Spacecraft/Rover Hybrids for the Exploration of Small Solar System Bodies

M. Pavone (PI)
J. Castillo, A. Frick, J. Hoffman, I. Nesnas (Co-Is)
B. Hockman, R. Reid

Stanford University, Jet Propulsion Laboratory, MIT
Small Bodies Exploration

...to prepare for human exploration

...to defend our planet

...as a key to our origins

...to understand how the Solar system formed and evolved

Deimos

2004 BL86

Phobos

Hartley 2

[Pavone et al., Aerospace '13]
## Motion in Low Gravity Worlds

<table>
<thead>
<tr>
<th></th>
<th>Surface Gravity (g’s)</th>
<th>Escape Velocity (m/s)</th>
<th>Freefall time from 1 m (s)</th>
<th>Your weight Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Itokawa</strong></td>
<td>$10^{-5}$</td>
<td>0.2</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td><strong>Phobos</strong></td>
<td>$10^{-4}$</td>
<td>11</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

**Itokawa Asteroid**

400 m

**Phobos (Mars’ moon)**

20 km
The Big Question

How would you change the design for LOW gravity environments?
Mobility Challenges in Microgravity

- Getting there
- Remaining “attached”
- Very limited traction
- Uneven/uncertain terrain

[Koenig et al., ICRA ’14]
Spacecraft/rover hybrids

Develop mission architecture that allows the **systematic** and **affordable in-situ** exploration of small Solar System bodies

**Key philosophy:** Exploit low gravity

- Minimalistic platform **specifically designed** for microgravity:
  - **Systematic** exploration (all access mobility and scalability)
  - 3 mobility options: 1) tumbling, 2) hopping, 3) shuffling
Basic concept

Key idea: Swapping angular momentum [Allen et al., ICRA '13]
From Phase I to Phase II

NIAC Phase I [Pavone et al., NIAC ’11]

- Scientific rationale
  ⇒ 10-20% motion accuracy

- Feasibility assessment
  ⇒ 2–5 Watts for cm/s speed in 6 to 600 µg gravity

NIAC Phase II

- Planning and control
- Localization and navigation
- System’s engineering and mission to Phobos
Outline

1. Planning and Control
2. Localization and Navigation
3. System’s engineering and Mission to Phobos
Outline

1 Planning and Control

2 Localization and Navigation

3 System’s engineering and Mission to Phobos
Controls

Hybrid control:

- **Flywheel Spin-up:** Slowly accelerate flywheels in direction of heading
- **Coast (default):** No torque applied
- **Flywheel Braking:** Apply rapid braking torque, producing tumbling or hopping motion

Controlled mobility:

3D Trajectory of Center of Mass

2D Path of Center of Mass
- Initial Position
- CoM Path
- Waypoint
Planning:

Tumbling:

Hopping:
Prototypes

Stanford prototype

JPL prototype
6 DoF Micro-Gravity Test Bed

[Diagram of a 6 DoF Micro-Gravity Test Bed with labels for Force Sensor, Spring Mechanism, X, Y, Z, 3-axis gimbal, Prototype, Yaw, Pitch, and Roll]
Hopping at 0.002 g
Outline

1 Planning and Control

2 Localization and Navigation

3 System’s engineering and Mission to Phobos
# Localization and Navigation

<table>
<thead>
<tr>
<th></th>
<th><strong>Global Location</strong></th>
<th><strong>Regional Location</strong></th>
<th><strong>Incremental</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lost somewhere on surface</td>
<td>Lost in small area &lt;1% of surface</td>
<td>Refining pose during/after controlled motions</td>
</tr>
</tbody>
</table>

| **Mothership Only** | • RF link  
• Flash LIDAR, retro-reflectors on rover\(^{(2)}\) | • Exhaustive visual search with narrow FOV camera\(^{(1)}\) | • Narrow FOV camera\(^{(1)}\) |
|---------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| **Synergistic Mothership & Hybrid** | • LED/laser strobe on hybrid, synchronized visual search  
• RF ranging | • LED/laser strobe on hybrid, visual search with mothership narrow FOV camera | • Multiple camera observations/tracking during motions  
• Visual SLAM |
| **Hybrid Only** | • Matching surface images during hops\(^{(1)}\)  
• Star tracker and accelerometers with gravity model\(^{(3)}\) | • Matching surface images during hops\(^{(1)}\) | • Visual odometry  
• Stereo vision  
• Visual SLAM  
• Surface image velocity est. during large hops |

Assumes a mapping phase prior to hybrid deployment:

1) Imaged 100% of the body (less than 1 meter/pixel)
2) Determined a surface shape model
3) Determined a gravity model from mass and density estimates
Outline

1 Planning and Control

2 Localization and Navigation

3 System’s engineering and Mission to Phobos
Building upon Cubesat’s Legacy

Hybrid Spacecraft/Rovers will build on JPL’s interplanetary CubeSat developments.

MarCO provides heritage, expertise, and risk reduction for further JPL interplanetary missions.

- **2014**: + C&DH + IRIS 1 + Environment + JPL Expertise
- **2016**: + IRIS 2 + Propulsion + Structure + ACS + Environment + JPL Expertise + Facilities + Distance
- **2017-2018**: + Flight Heritage + radio + space qualified parts + expertise
- **2020+**: + Flight Experience + Heritage + High TRL components

As a leader in interplanetary Cubesats, JPL continues to innovate and push the boundaries of space exploration.
Preliminary System Architecture

8U design, scalable from 1U to 27U

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

2. Cold/Warm Gas Propulsion (Optional)
   • ~20 m/s for assisted soft landing (e.g. Phobos)
   • Alternatively, volume can be used to increase battery capacity or payload
   • Leverages: INSPIRE, MarCO, NEA Scout

3. Telecom
   • UHF Relay to Mothership
   • 4 mutually orthogonal antennas embedded in spikes
   • Leverages: INSPIRE

4. GNC Sensors/Actuators
   • 3 mutually orthogonal flywheels
   • 3+ wide angle navigation cameras
   • Sun Sensors + IMU
   • Optional LEDs for localization
   • Leverages: JPL Visual Odometry frameworks & VSLAM algorithms

5. Science Platform
   • X-Ray Spectrometer
   • Thermocouple (embedded in spikes)
   • Microscope
   • Cameras + Accelerometers
   • Leverages: Pathfinder/MER/MSL

6. Electrical Power System
   • Lithium secondary or primary batteries; >200 W-h @ 12V
   • Optional solar panels
   • Leverages: INSPIRE, MarCO, NEA Scout
Reference Mission to Phobos

Fractionated payload and targeted mobility

- Origin of Phobos’ materials?
- Water and organics at Phobos?
- Structure of Phobos’ soil?
- Surface dynamics?

In situ Resource Package

Regolith/Risk assessment Package

NIR/BG Ratio
Conclusion

• Robotic exploration of small bodies:
  • Will be one of the main NASA focus in the years to come
  • Requires disruptively new mobility concepts ad hoc for low gravity environments

• Spacecraft/rover hybrids:
  • New paradigm for in-situ exploration of small bodies
  • Technology to obtain new science at an affordable cost
  • Proof of concept successfully demonstrated

• Work in Phase II:
  • Planning and control for fine mobility
  • (Synergistic) localization and navigation
  • Systems engineering
  • Conceptual study of mission to Mars’ moon Phobos
  • Experimental validation (test beds and parabolic flights)