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

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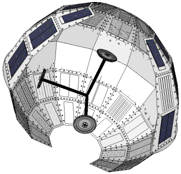

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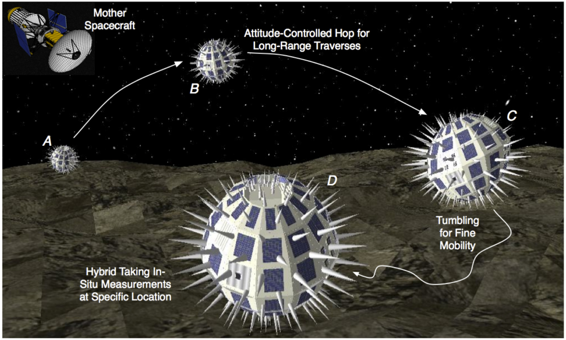
NASA Innovative Advanced Concepts Program

The objective

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

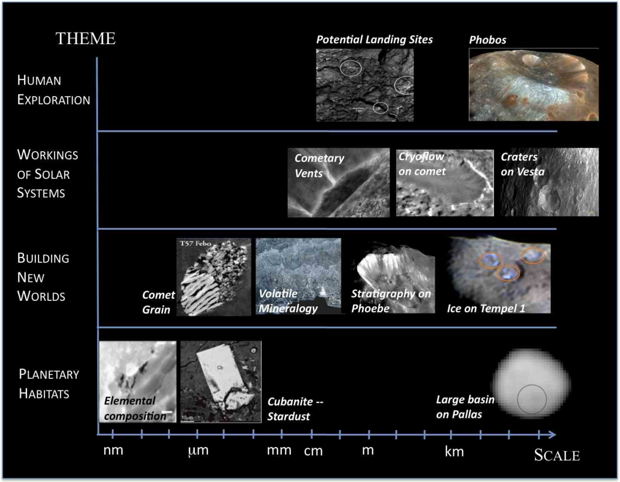
Key idea: minimalistic, internally-actuated mobile robotic platforms



Outline

1. Science requirements
2. Robotic platform
3. Mission architectures & operations: mission to Phobos
4. Conclusion

Small bodies & planetary decadal survey



J. Castillo, M. Pavone, I. Nesnas, and J. Hoffman "Expected Science Return of Spatially-Extended In-Situ Exploration at Small Solar System Bodies," in 2012 IEEE Aerospace Conference.

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Robotic platform

"Traditional" approaches:

- Wheeled rovers
- Legged rovers
- Spring-actuated hoppers
- Thruster-actuated hoppers

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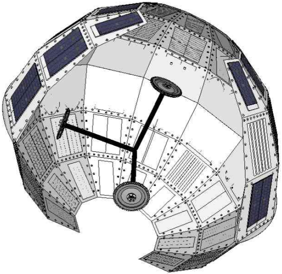
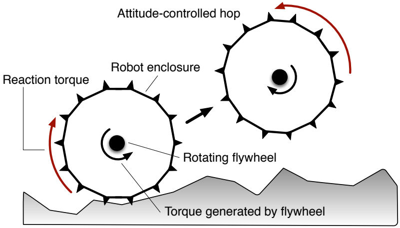
Key philosophy: Exploit low gravity, rather than facing it as a constraint



- Minimalistic platform specifically designed for microgravity (inspired by JAXA's MINERVA mini-lander, which however did not succeed during its deployment):
  - Systematic exploration (all access mobility, versatility and scalability)
  - 3 mobility options: 1) tumbling, 2) hopping, 3) pseudo-orbital flight

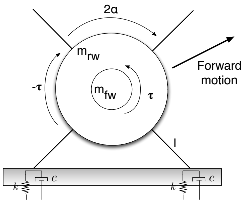
Basic concept: Swapping angular momentum

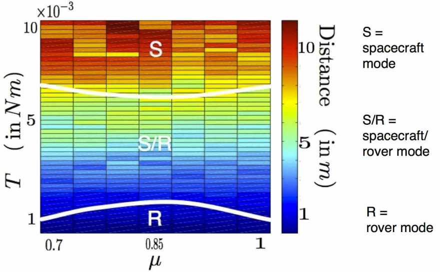
$$\mathbf{H} = \mathbf{I}_{\text{platform}}\,\boldsymbol{\omega}_{\text{platform}} + \sum_{i=1}^{3} \mathbf{I}_{\text{flywheel},i}\,\boldsymbol{\omega}_{\text{flywheel},i}$$



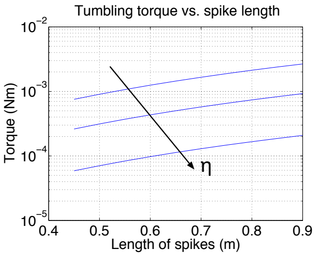
Required torques

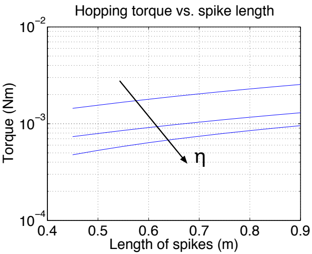
Spring-damper model $(g = 0.0001\, m/s^2,\ m = 1\, Kg)$:





Impulsive model $(g = 0.001\, m/s^2,\ m = 1\, Kg)$:



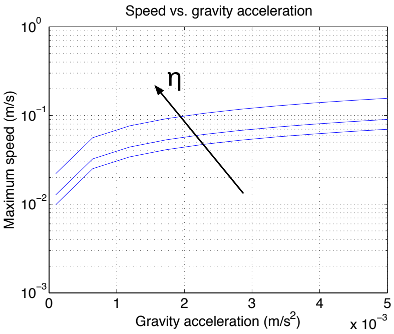


Maximum speed

Maximum speed is upper bounded by

1. Escape velocity
2. Intrinsic limitation of performance

$$v_{\max} \leq \frac{2l\sin(\alpha)\sqrt{(m_{rw}+m_{fw})\,g\,l\,\sin(\alpha)}}{\sqrt{2\alpha\,(1-\eta)[(m_{rw}+m_{fw})l^2+I_{rw}]}}$$

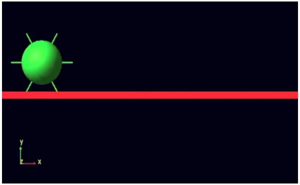


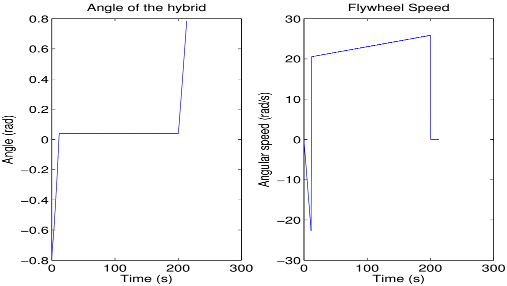
FAQ: what about momentum build-up?

With constant torque...

$$N_{\max} = \frac{2\,\dot{\varphi}_{\max}\, I_{\text{fw}}}{\sqrt{[(m_{\text{rw}} + m_{\text{fw}})l^2 + I_{\text{rw}}](1/\eta^2 - 1)}}\,\frac{1}{\sqrt{2(m_{\text{rw}} + m_{\text{fw}})g\, l(1 - \cos(\alpha))}}$$

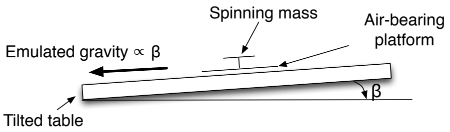
...but by exploiting gravity one can avoid momentum build-up:





Prototype and initial experiments

Testbed:



Tumbling

Hopping

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Science questions at Phobos

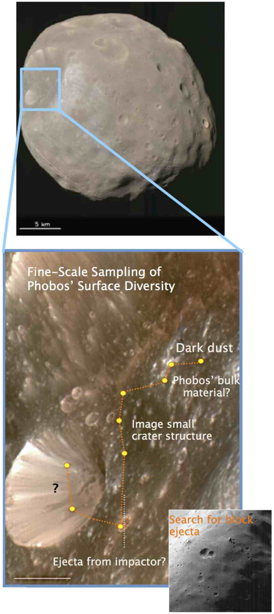
Main questions:

1. What is the origin of Phobos materials?
   - Phobos comes from Mars?
   - Phobos is a captured asteroid?

2. Water and organics at Phobos?
   - "Blue" spectral unit water-rich?
   - Putative phyllosilicates associated with organics?

3. What is the structure of Phobos soil?
   - Degree of maturation of the regolith?

4. What is the nature of the surface dynamics?
   - Degree of mobility of the soil?



Delivery:

- JPL NEO Surveyor (50Kg payload)

Navigation:

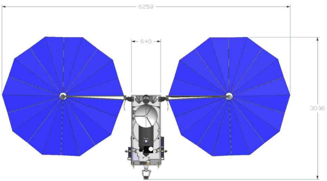
- Beyond the scope of Phase I

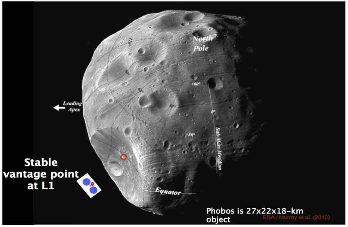
Deployment:

- Ballistic (3m/s impact) or TAG

Spacecraft operations:

- Stable vantage point at L1





Science payload

Theme	Objectives	Observable	Role	Instrument
Decadal Science: Origins **Precursor Science: Soil mechanics/risk**	Obtain regolith composition	Elemental	Mothership	GR&ND
		Mineralogical	**Hybrid**	XRS
	Evaluate regolith maturity	Microstructure	**Hybrid**	Microscope
	Constrain mechanical properties	Angle of repose	**Hybrid**	Camera
		Response to impulse	**Hybrid**	Accelerom.
		Crater morphology	Mothership	HRSC
	Constrain dust dynamics	Measure dust flux	Mothership	Dust analyzer
Decadal Science: Processes **Precursor Science: risk**	Topography mapping	Photoclinometry	Mothership	HRSC
	Gravity mapping	Doppler tracking	Mothership	RSS
		Acceleration	**Hybrid**	Accelerom.
	Assess surface dynamics & electrostatic environment	Dust interaction with spikes	**Hybrid**	Camera
Decadal Science: Habitability **Precursor Science: ISRU**	Distribution of water	Neutron detection	Mothership	GR&ND
		Mineralogical	**Hybrid**	XRS

Power and mass breakdown

	Instrument	Mass (g)	Power (W)
Science Package	Radiation monitor	30	0.1
	XRS	300	4
	Thermocouple	50	1
	Microscope	300	0.1
Operational and science support	Accelerometer/Tiltmeter	66	0.002
	Descent camera (WAC/PanCAM)	100	0.1
Subsystems	Transceiver	230	8
	Avionics (including OBDH)	250	0.25
	Thermal	200	1.5
	Antenna	200	0
	Motors and flywheels	400 (total)	3 (each)
Structural	Solar panels	300	
	Battery	222	
	Structure	1000	
	RHU (optional)	400	
		Total: $\sim 4Kg$	**Total**: $\sim 25W$

Operational modes

1. Initial reconnaissance of object
2. Deployment of hybrid
3. Initial “free roaming” by hybrid
4. Command and execute guided rolling/hopping trajectories
   - Day activity (3.5 hours): science, mobility, & battery recharging
   - Night activity (3.5 hours): science & survival
   - Night-day transition: telecom off and short tumbling

Outline

Conclusion

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 during NIAC Phase I
- Significant student involvement: R. Allen (SU), R. Kobrick and K. Patel (MIT)

Future plans

	Task	Phase I	Phase II
Robotic platform	3D motion in non-uniform gravity	○	●
	3D motion planning	○	●
	2D prototype and experiments	●	
	3D prototype and experiments		●
	Mechanical design	○	●
Science objectives	Synergies mothership/hybrids for several targets for new/increased science	○	●
	Flight opportunities		●
Mission architecture	Proximity operations		●
	Deployment	○	●
	Electrostatic and dust effects	○	●
	Architecture with multiple hybrids (e.g., Phobos)		●
	Localization for hybrids	○	●