Overview of Area-of-Effect Softbot (AoES) Surface Operations on Rubble Pile Asteroids

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6/14/2019

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- KRG members: Christoph Keplinger, Nick Kellaris, Shane Mitchell
- AoES Grad Project Team

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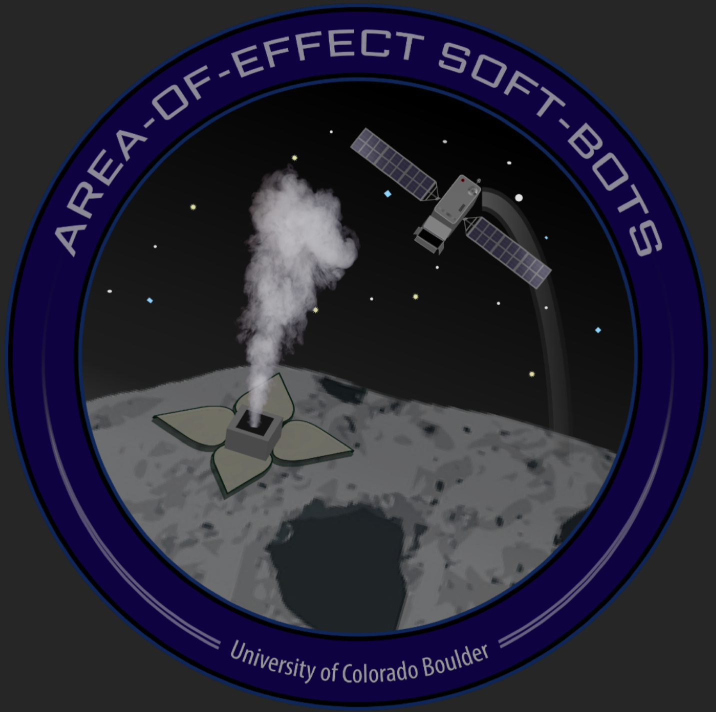
Overview

- Motivation and Overview
- AoES Bus Design
- Surface Mobility
  - Crawling
  - Hopping
- Future Work

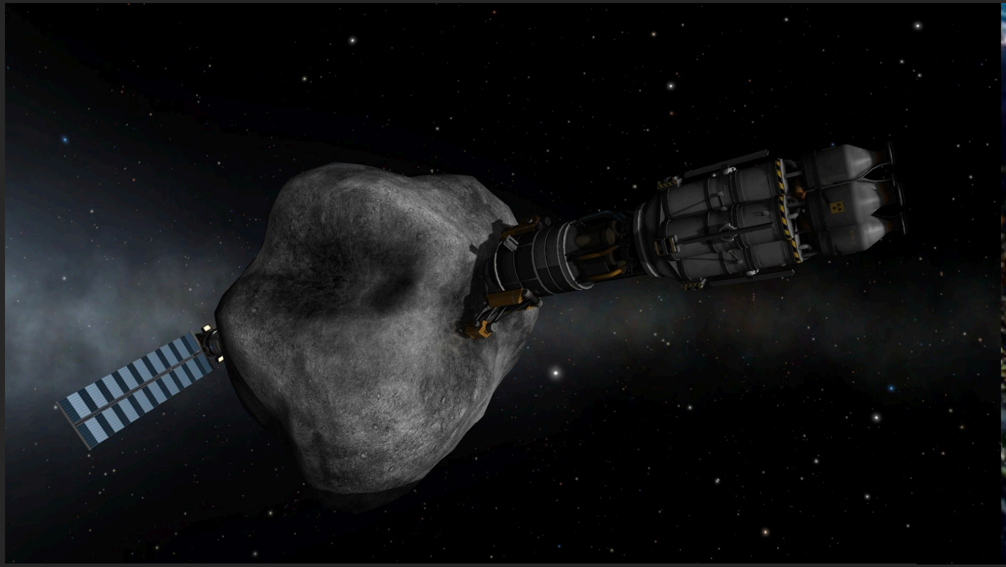


Why asteroids?

Science

Economics

Planetary Defense



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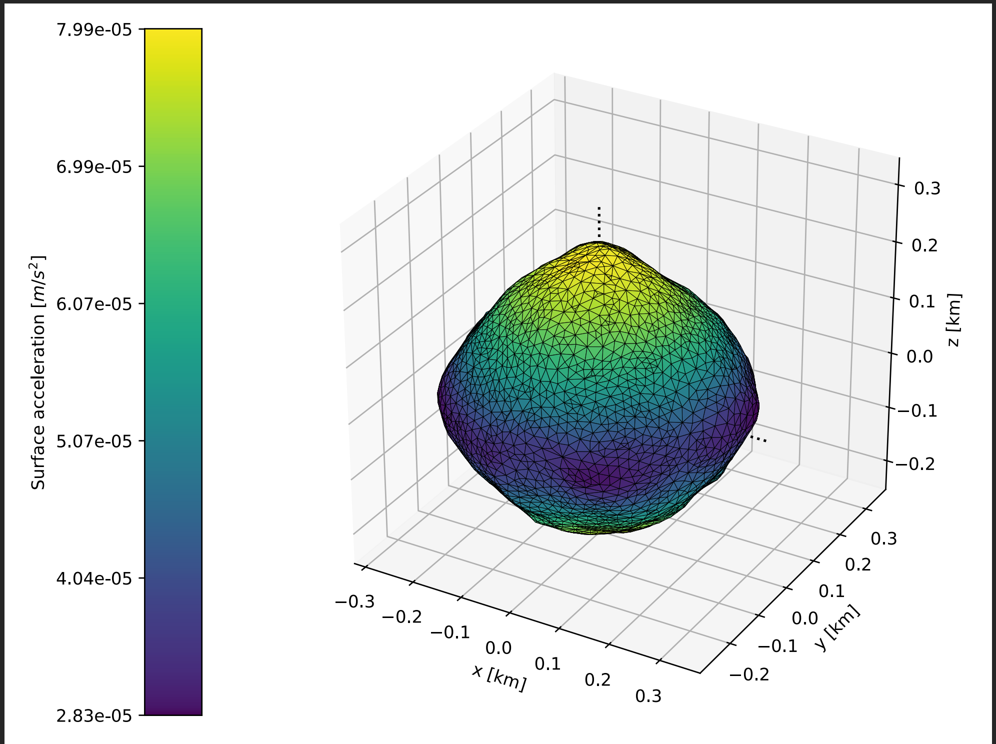
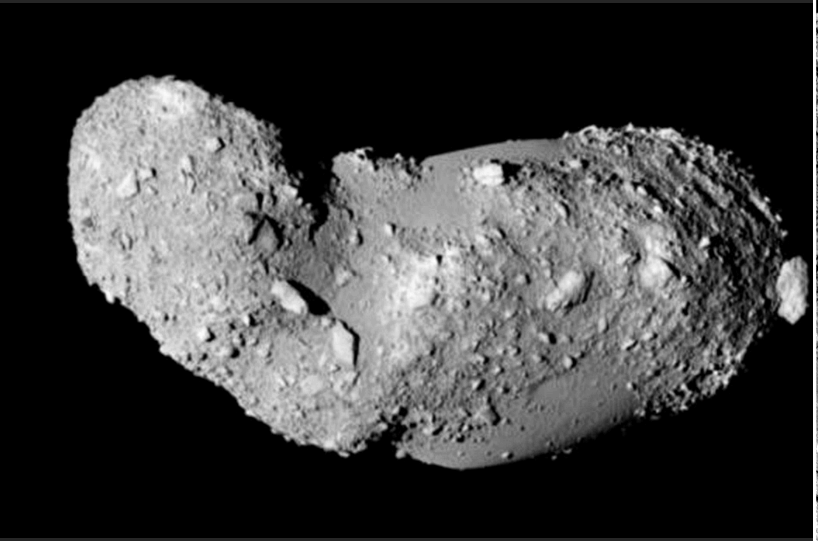
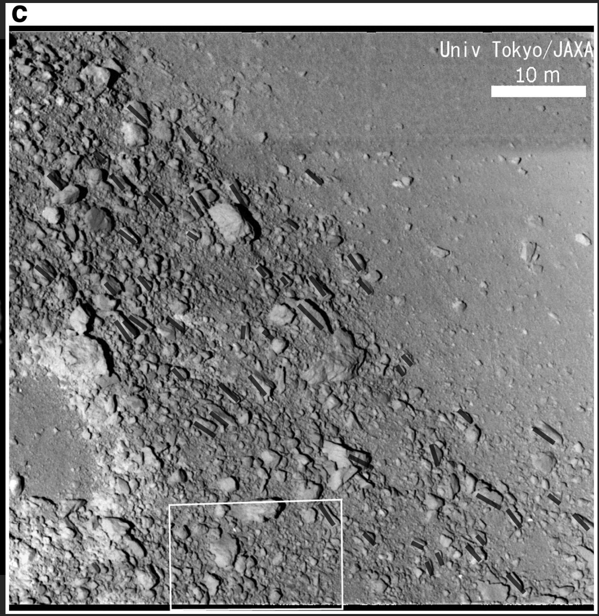
What are rubble piles?

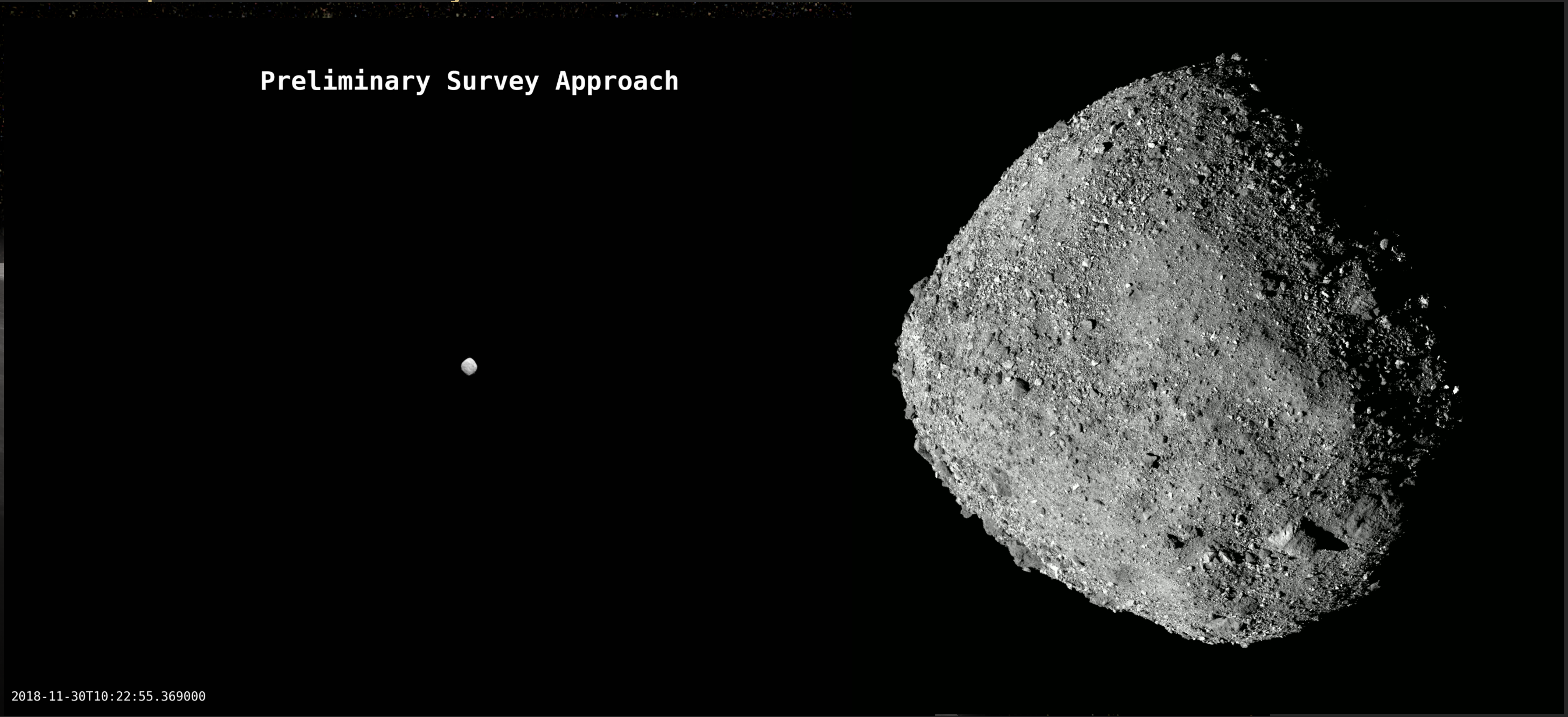
- Asteroid interior structures are unknown
- Cohesion plays an important role
- Surfaces could be boulders, rocks, pebbles… or dust
- How do we operate on these types of surfaces?







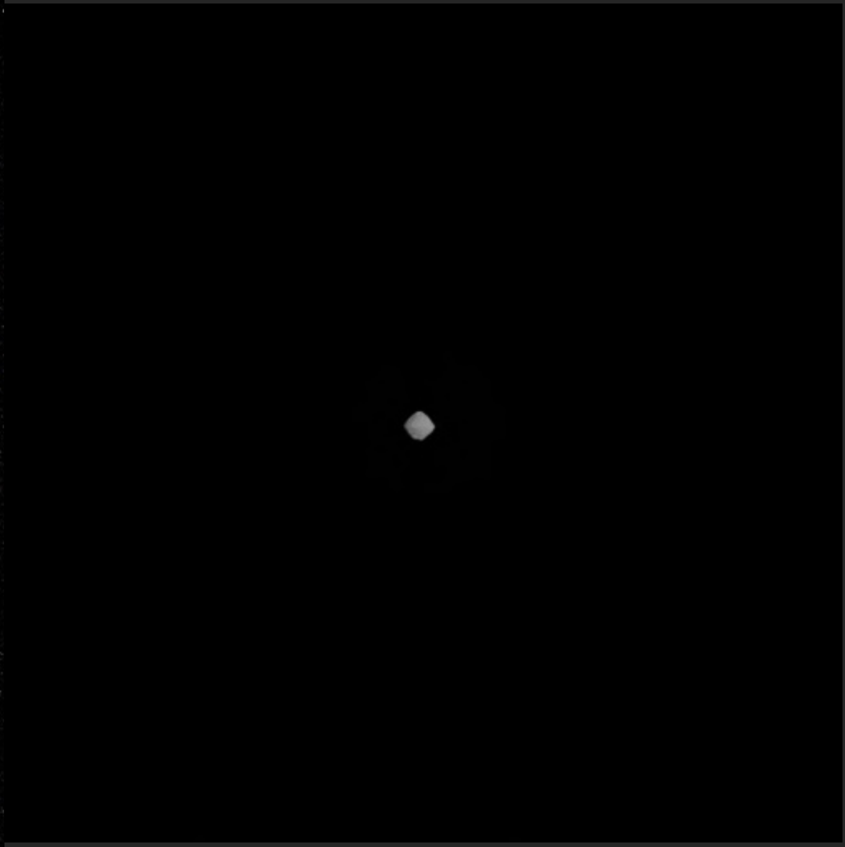
Exploration today: OSIRIS-REx



More information at: www.asteroidmission.org

Exploration today: Hayabusa 2

- Arrived at asteroid Ryugu last summer!



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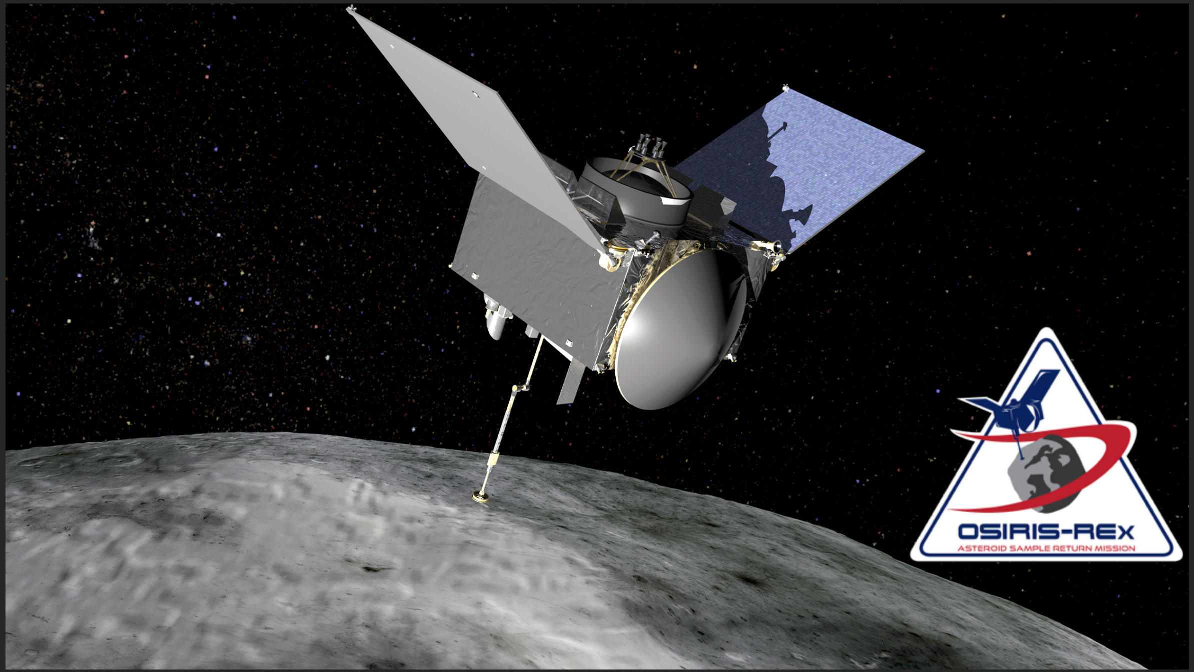
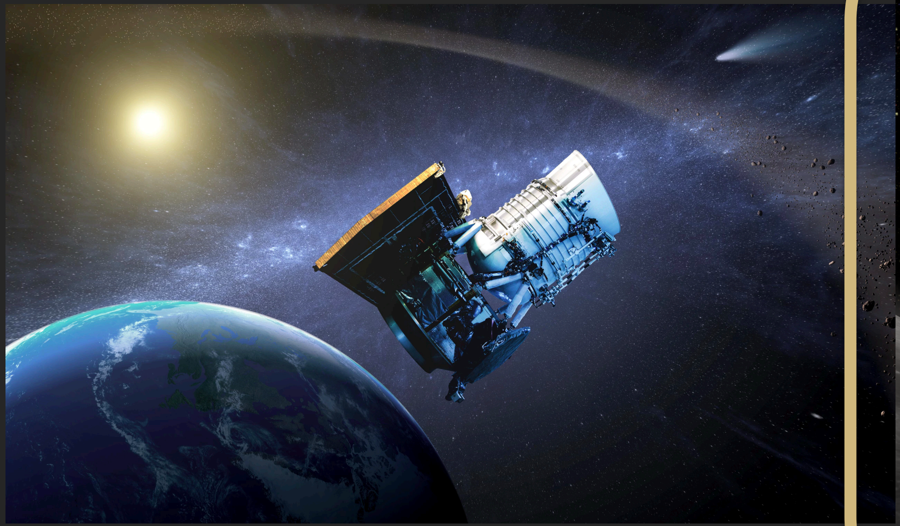
Current Asteroid Mission Con-ops

- Small body missions today require a slow, deliberate acquisition of knowledge about the body to enable proximity operations
  - OSIRIS-REx: approach -> distant flybys -> high orbit -> lower orbit -> TAG
  - Hayabusa2: approach -> inertial hovering -> low sorties -> TAG
- Operations are almost exclusively planned on the ground
- TAG sampling methods capture ~ 1kg MAX
- Alternative ARRM based methods – bagging, grabbing a boulder – are unproven and dangerous to the system

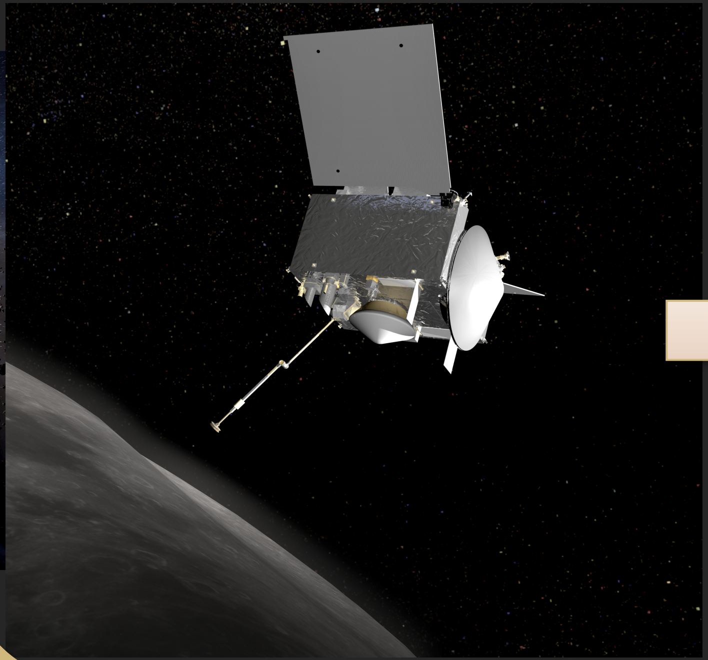


The Asteroid Mining Cycle

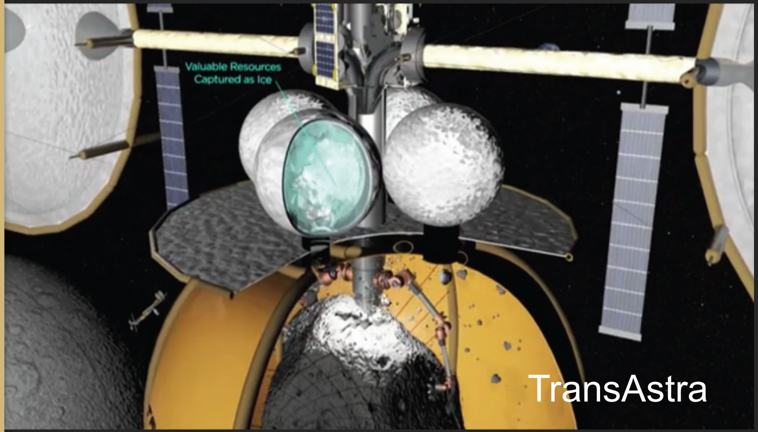
Prospect



Extract

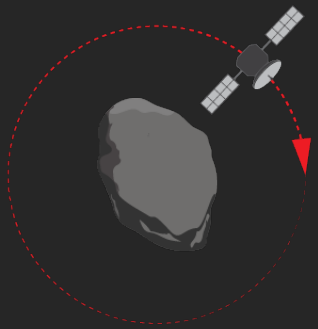


Refine



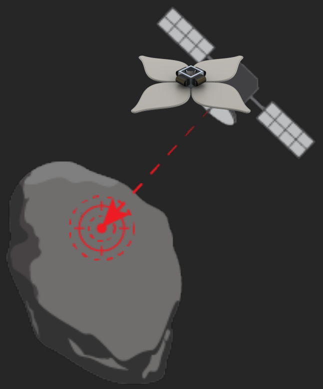
How do we get a lot of material from the surface to the refinery efficiently?

Dismantling Asteroids for Resource Acquisition

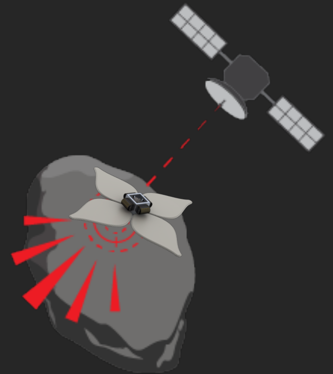


Mothership travels to target asteroid

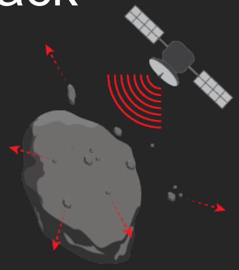
Deploy AoES



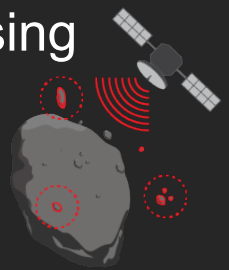
Dismantle and loft material



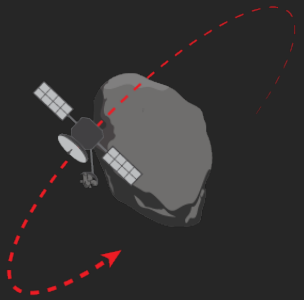
Track



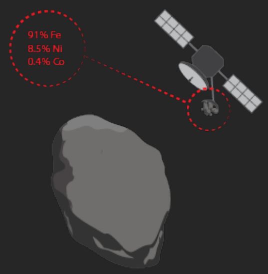
Remote Sensing



LoRS STTR



Capture



Analyze

The AoES project

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Problems and Solutions to Small Body Operations

Microgravity Mobility

Uncertain Substructure

Sinking into Regolith

Dusty Environment

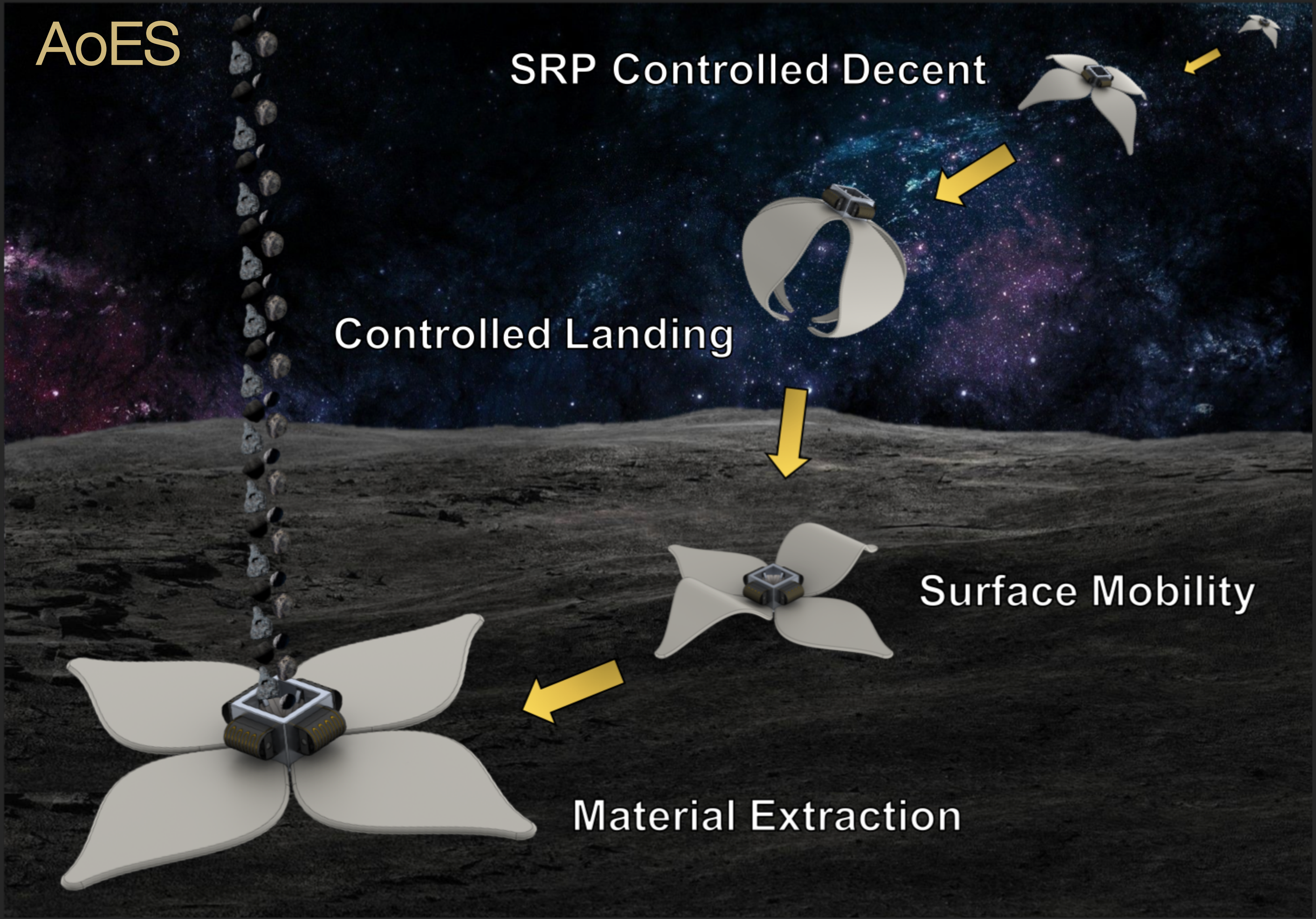
Crawling/Hopping Locomotion

Adhesive Surface Anchoring

Large Surface Area

RTG Powered

Encapsulated Mechanics



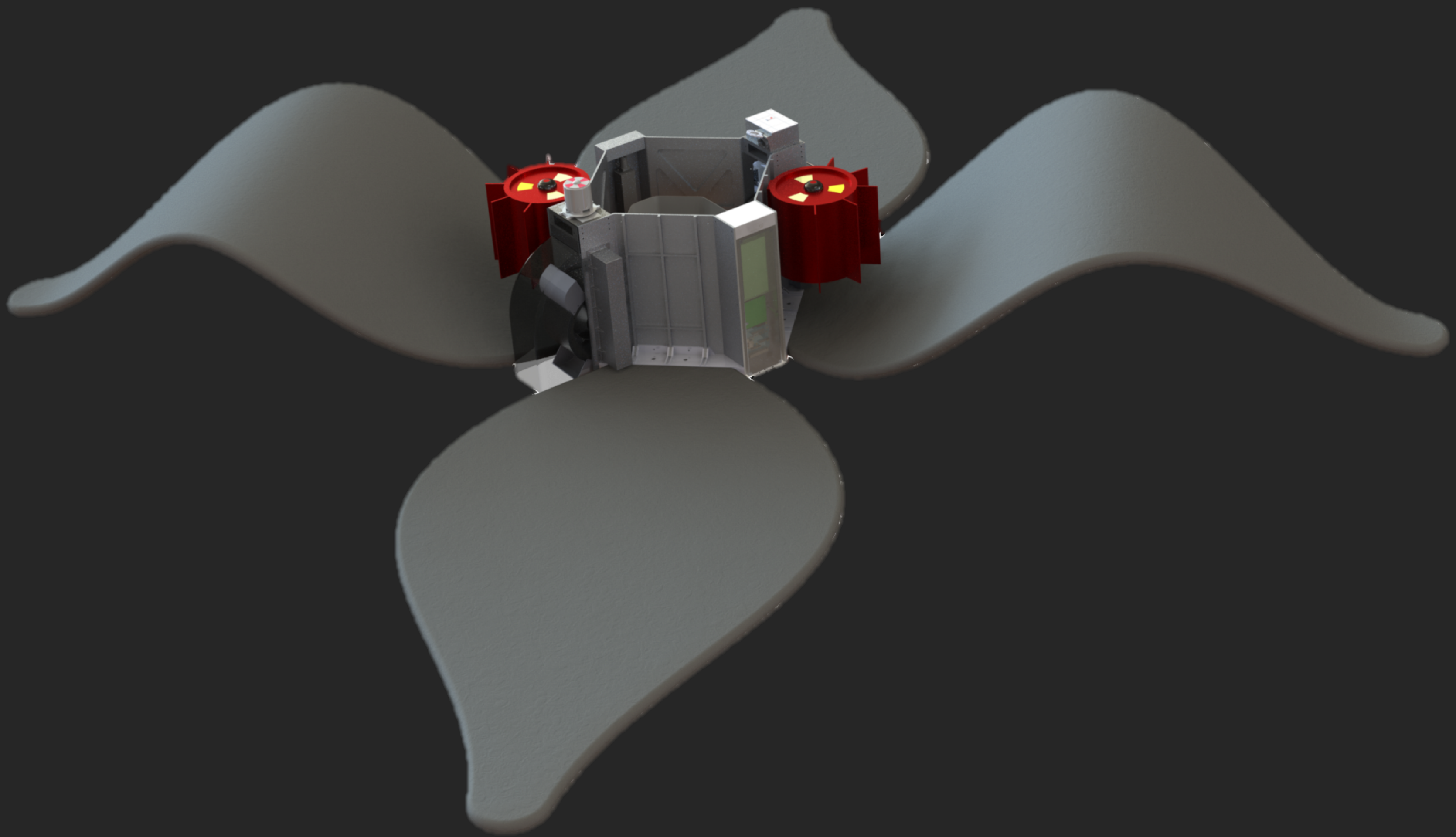
What are Area-of-Effect Softbots?

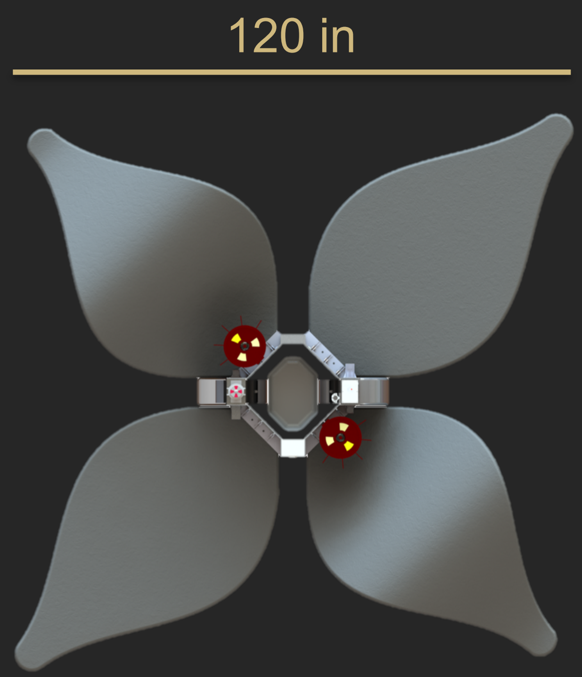
- Soft robotic spacecraft (AoES) with a large, flexible, actuated surface area uses adhesion to anchor to asteroid surfaces
- Large surface area also allows for solar sailing orbit control and hopping across the asteroid surface
- AoES support an ISRU mission by dismantling rubble pile asteroids by lofting material from the surface to be collected by an orbiting processing vehicle for resource extraction

UPDATED AOES BUS DESIGN

AOES GRADUATE PROJECT TEAM AY18-19

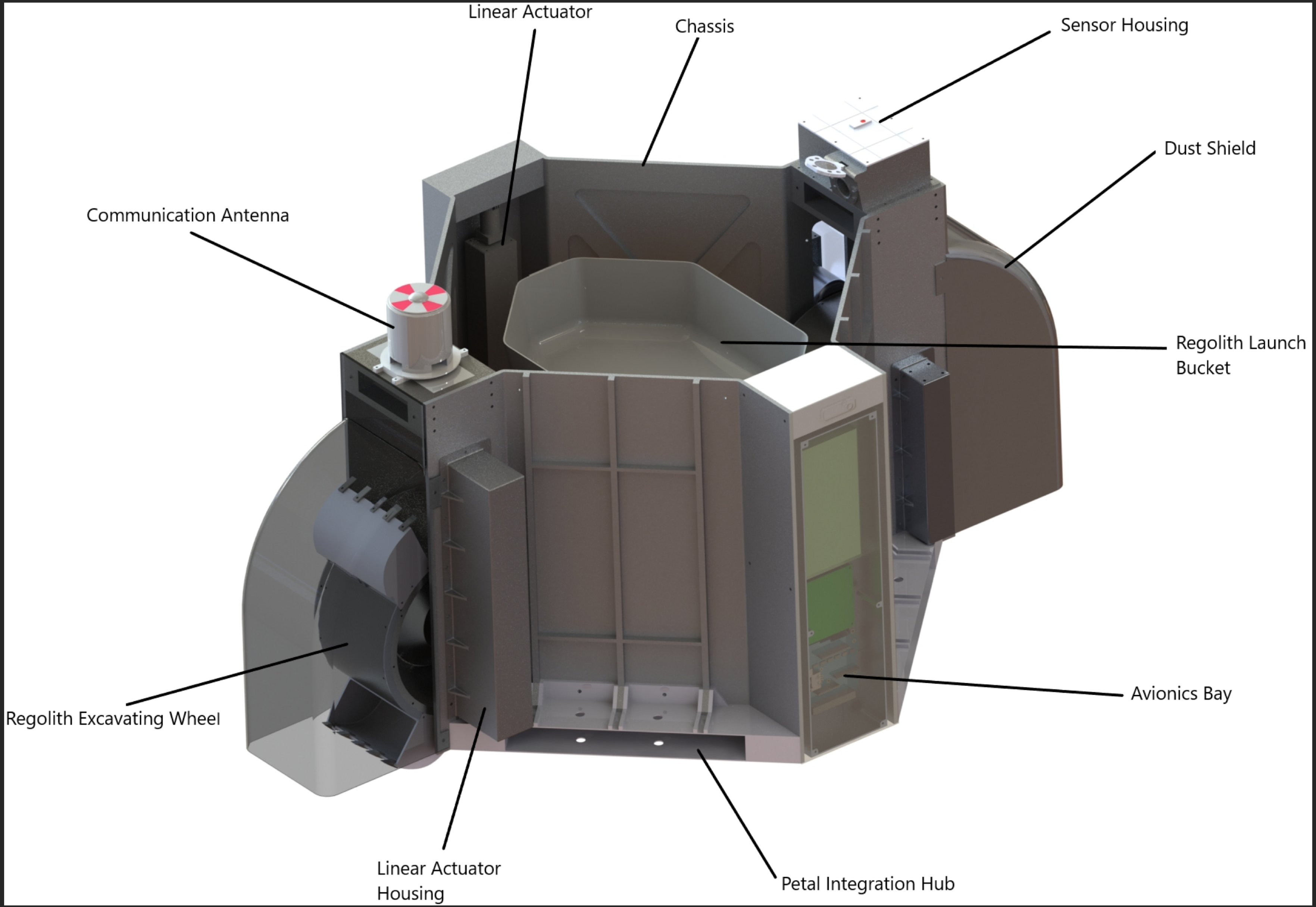
Area-of-Effect Softbots Current Design





Component	Value
Mass	116 kg
Power	93 W
Regolith Capacity	9500 cm^3
Digging Depth	15.5 cm
Launching	25 cm/s

AoES Design – Main Bus



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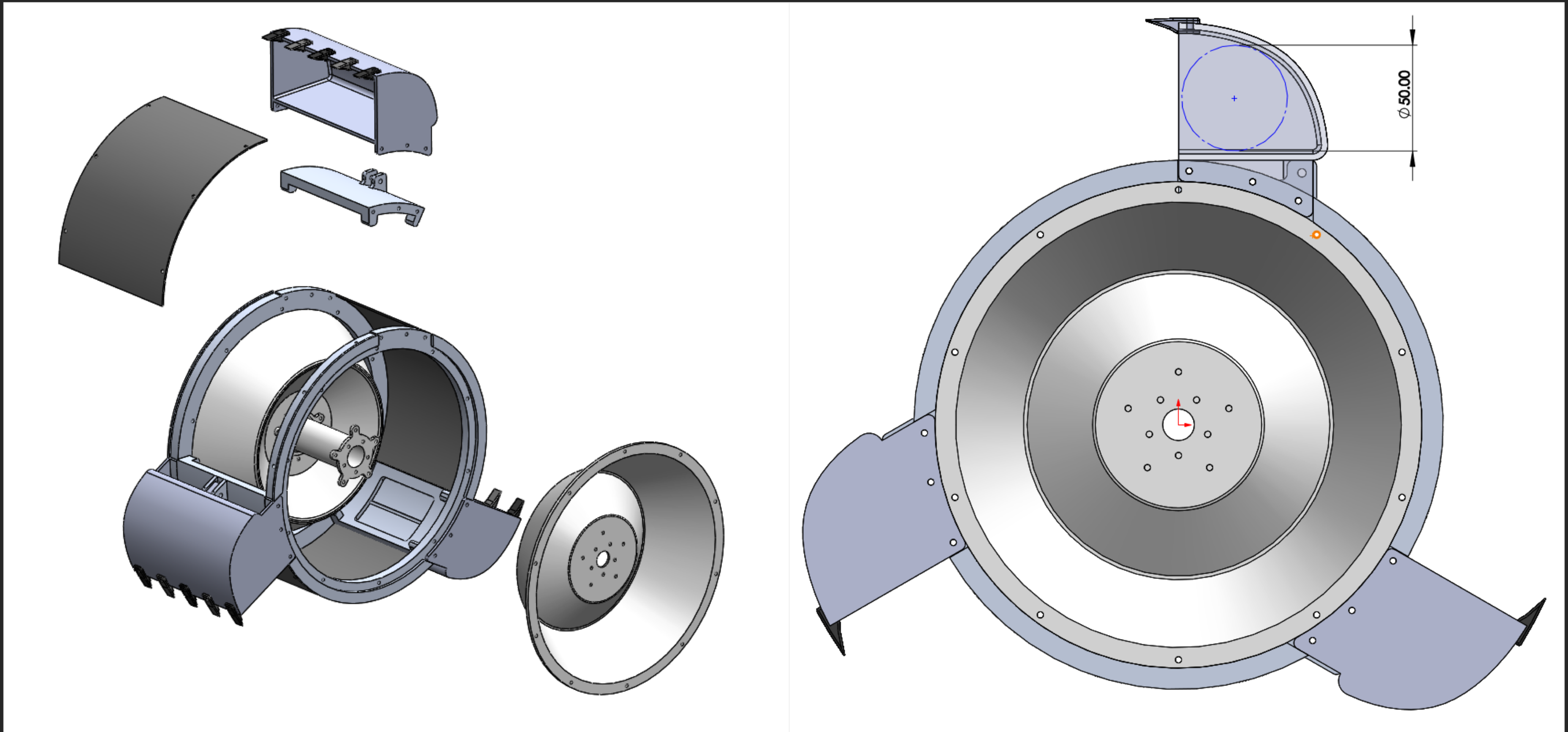
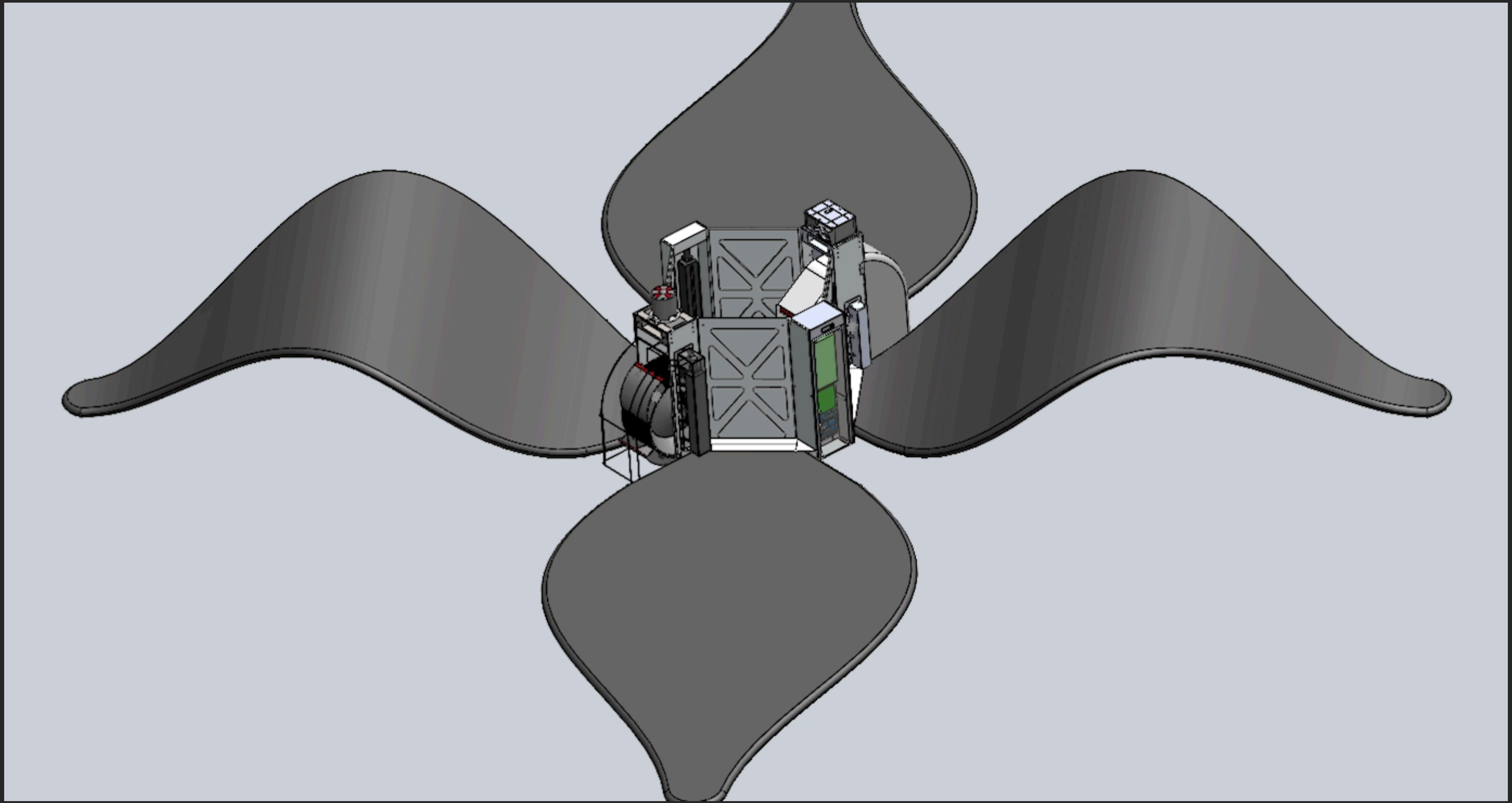
AoES Design – Bucket Wheel



Bus Operations



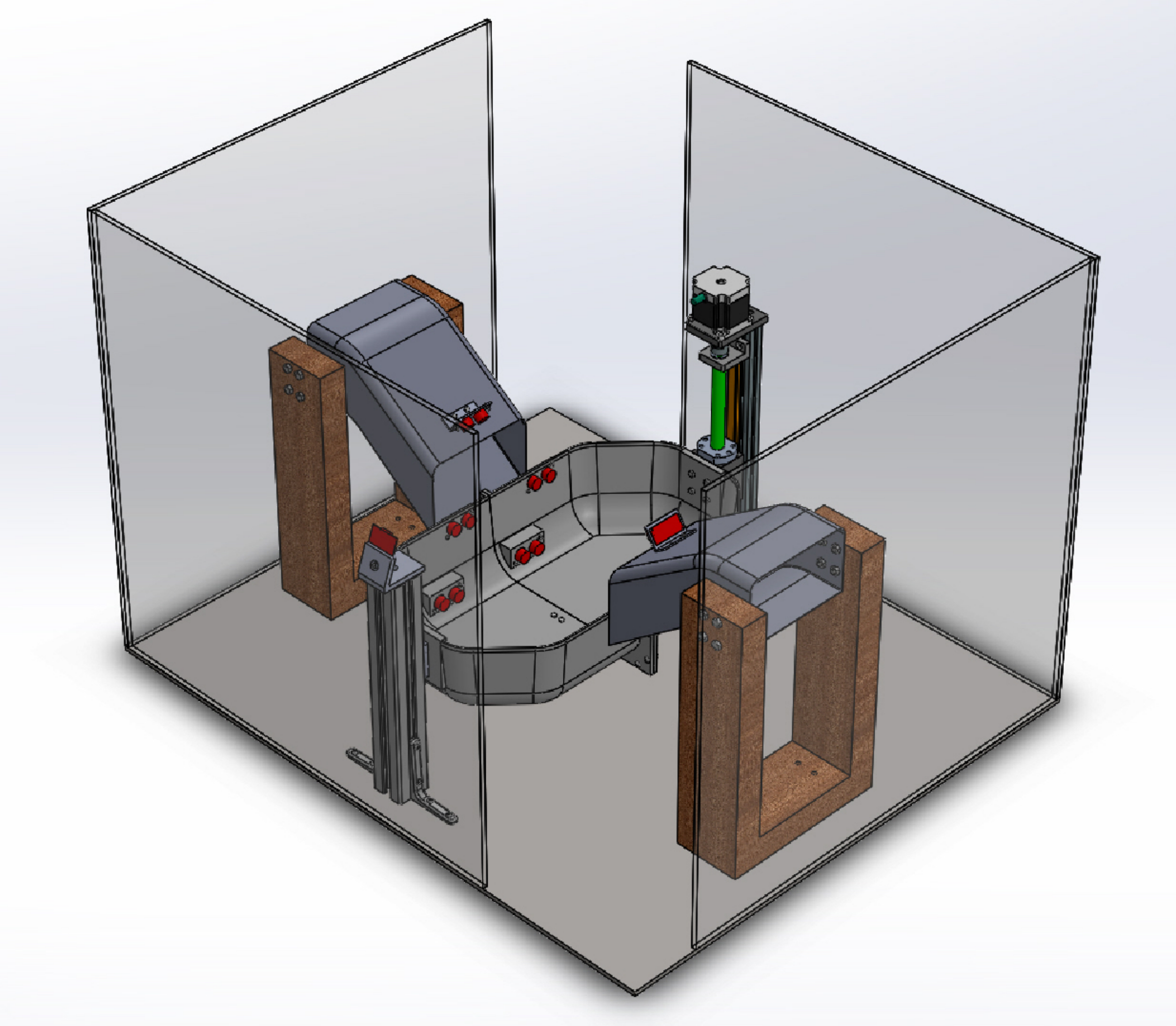
Launching Mechanism Prototype

Test Rig:

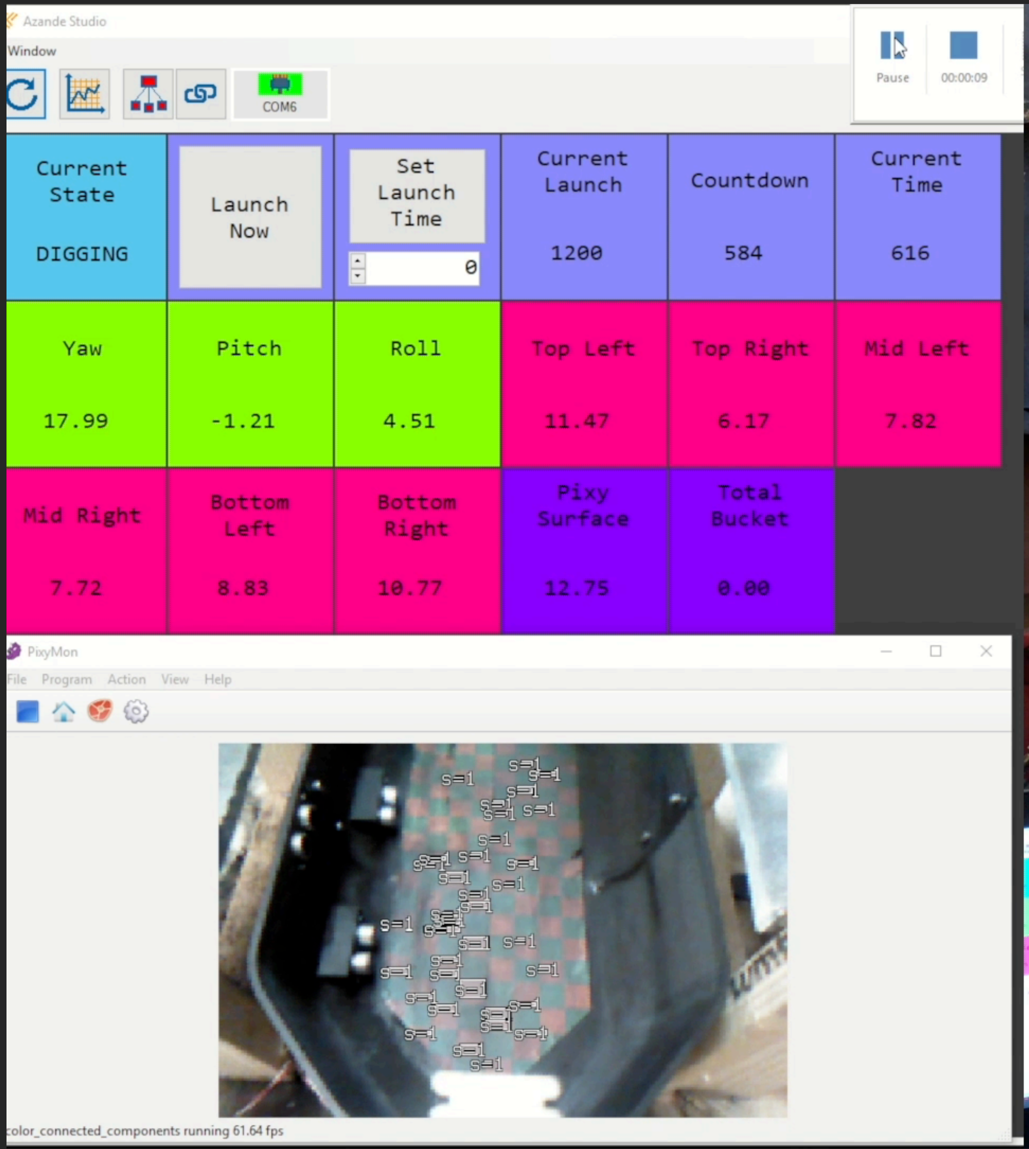
- Capable of 10 cm/s
- Meet max load requirement of 8 kg

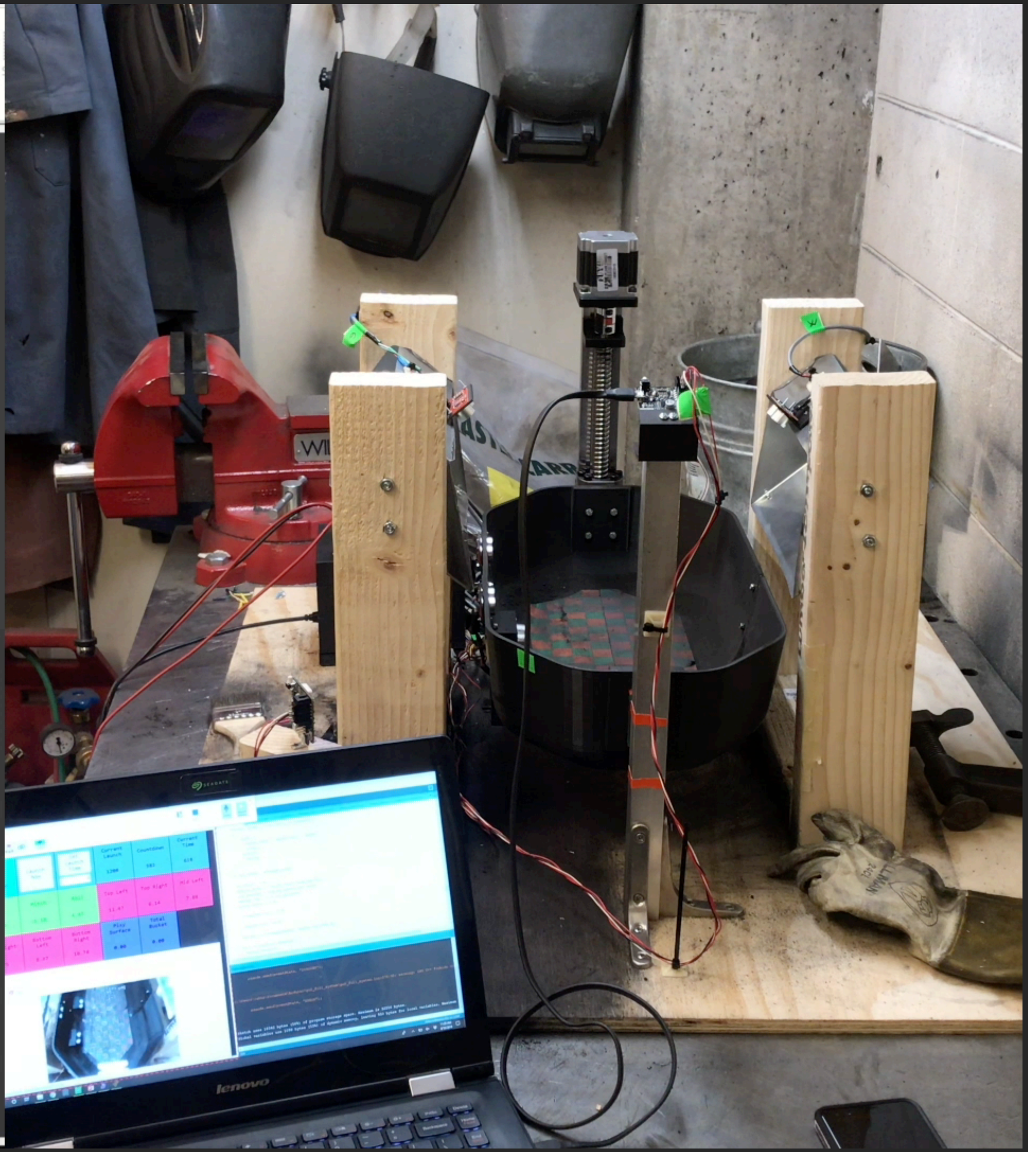
Final Design:

- Capable of 25 cm/s
- Higher torque motor
- Ball screw material resistant to abrasion from regolith
- Dust covers



Launching Mechanism Demo





AOES SURFACE MOBILITY

ORCCA, KRG

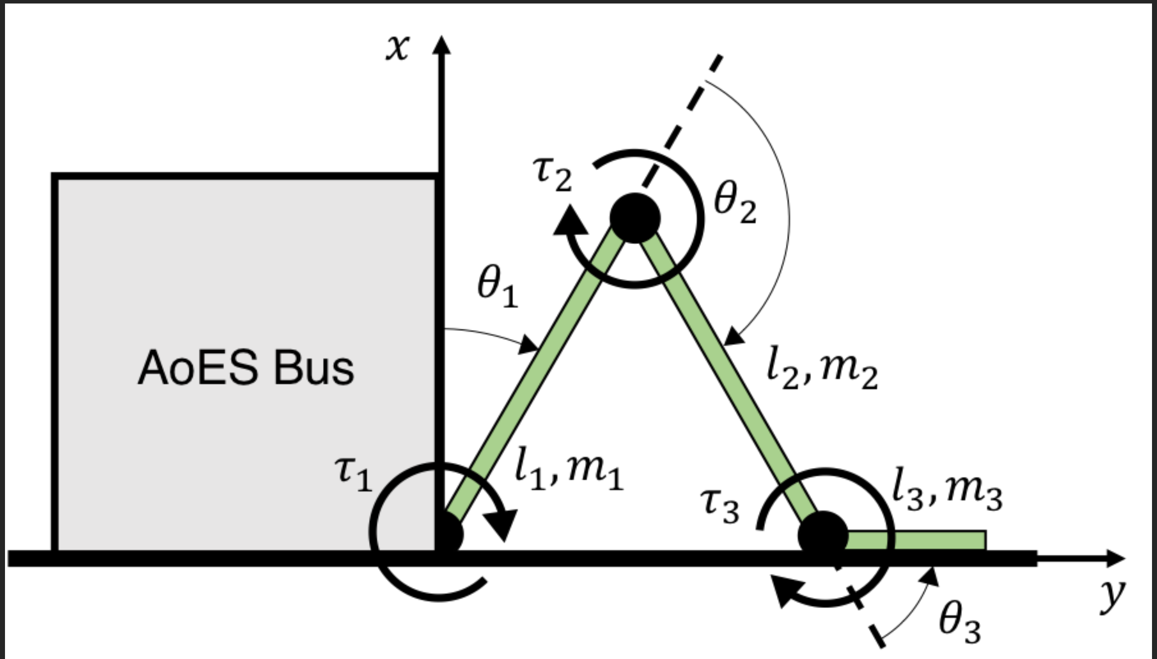
Surface Mobility

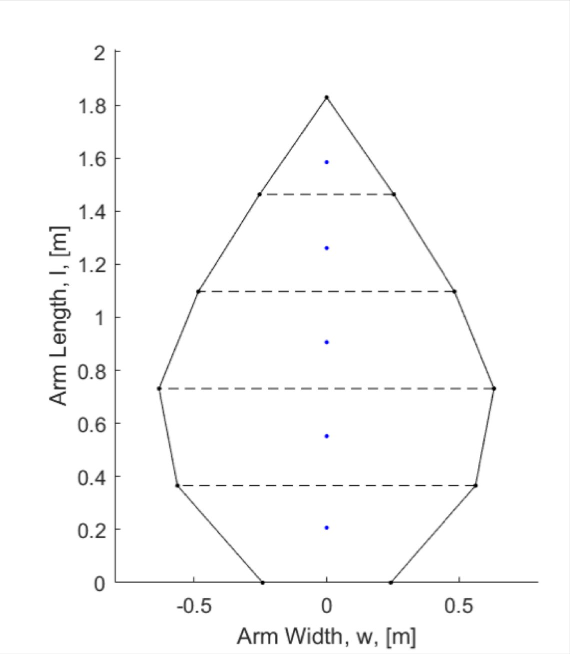
- Crawling
  - Short distance using AoES limbs
  - Move around excavation site

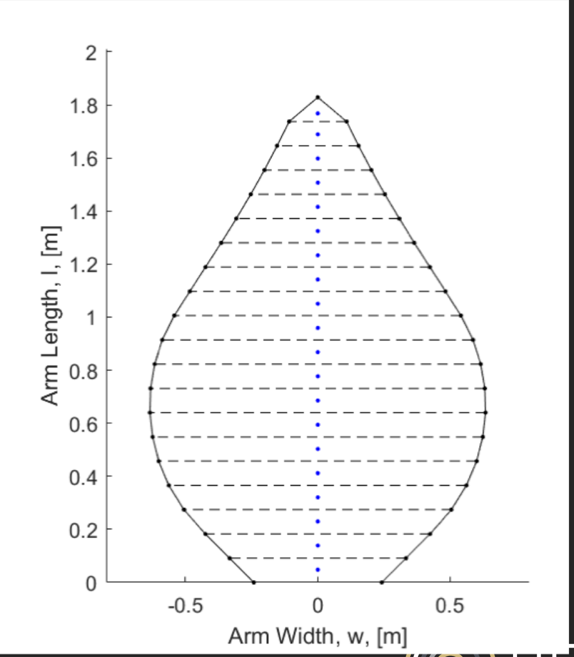
- Hopping
  - Long distance using the dynamics of the system (SRP)
  - Move between excavation sites

Crawling Modeling

- Flexible arm modeled as a series of rigid links
  - Torsional spring and damper at each link create passive material dynamics
  - Moment control at some joints using HASEL actuators
  - Forces along the length for contact dynamics and gravity







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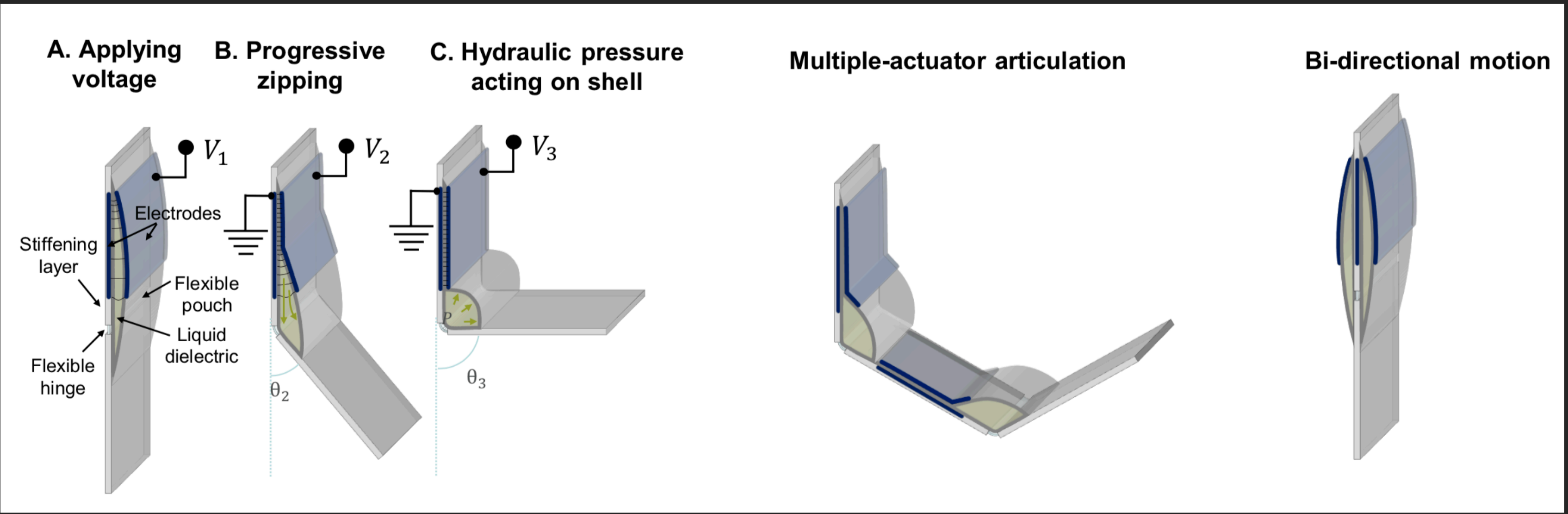
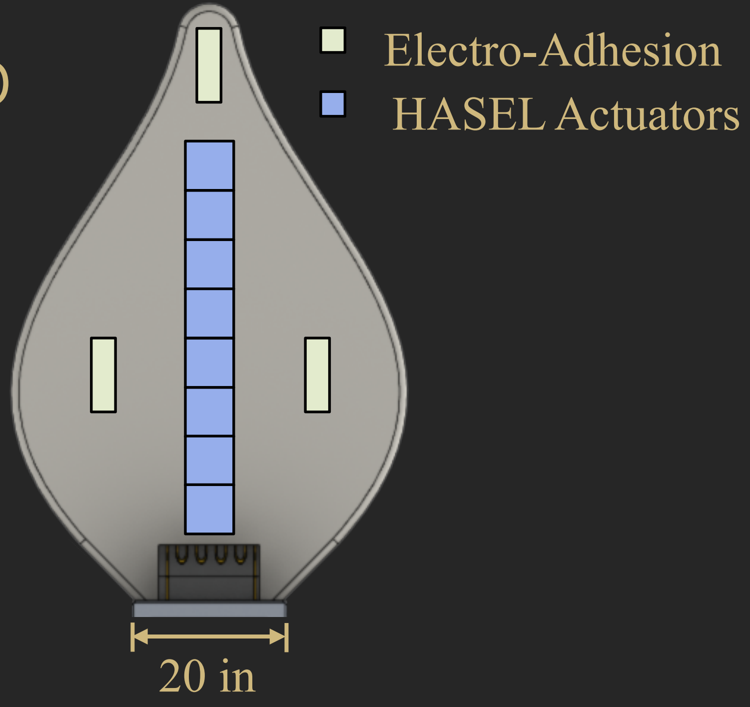
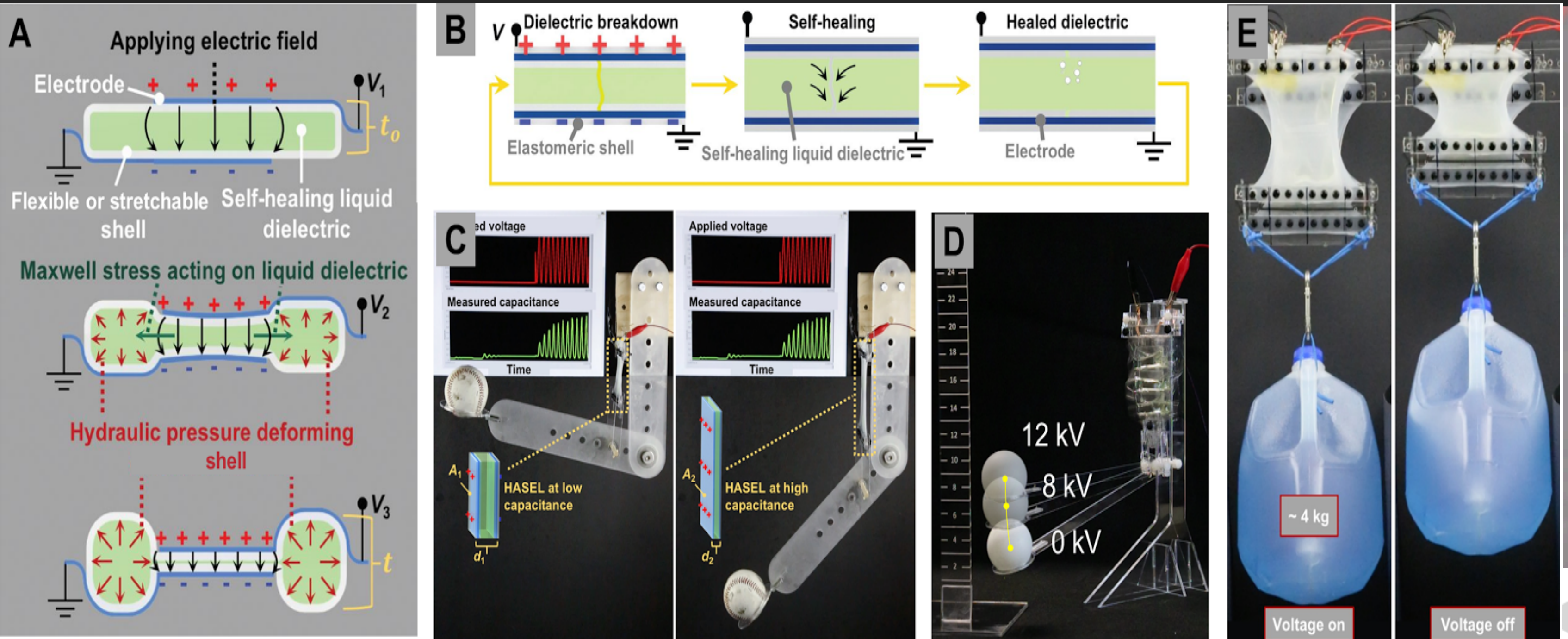
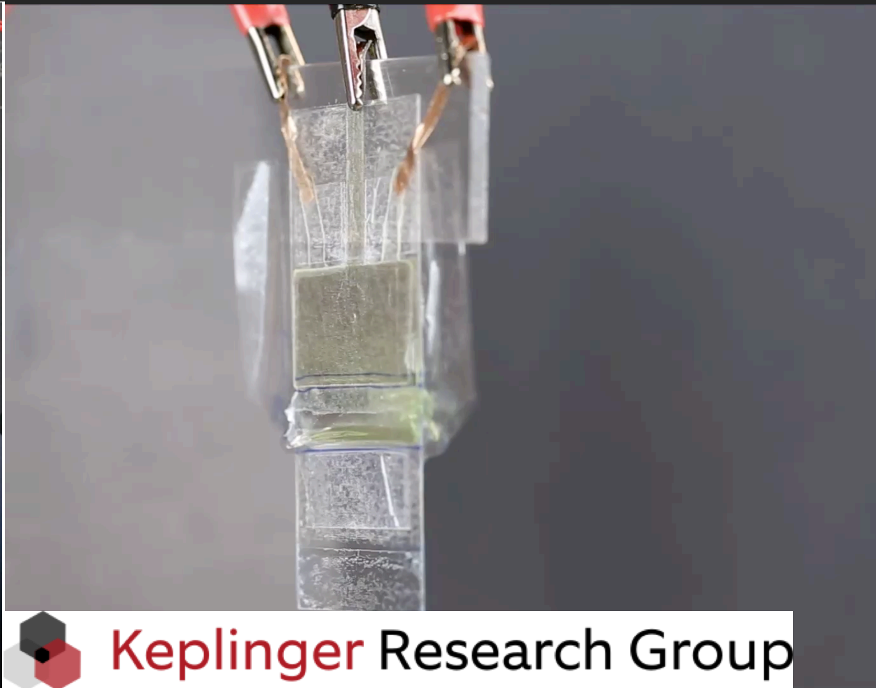
HASEL Actuators – Keplinger Research Group

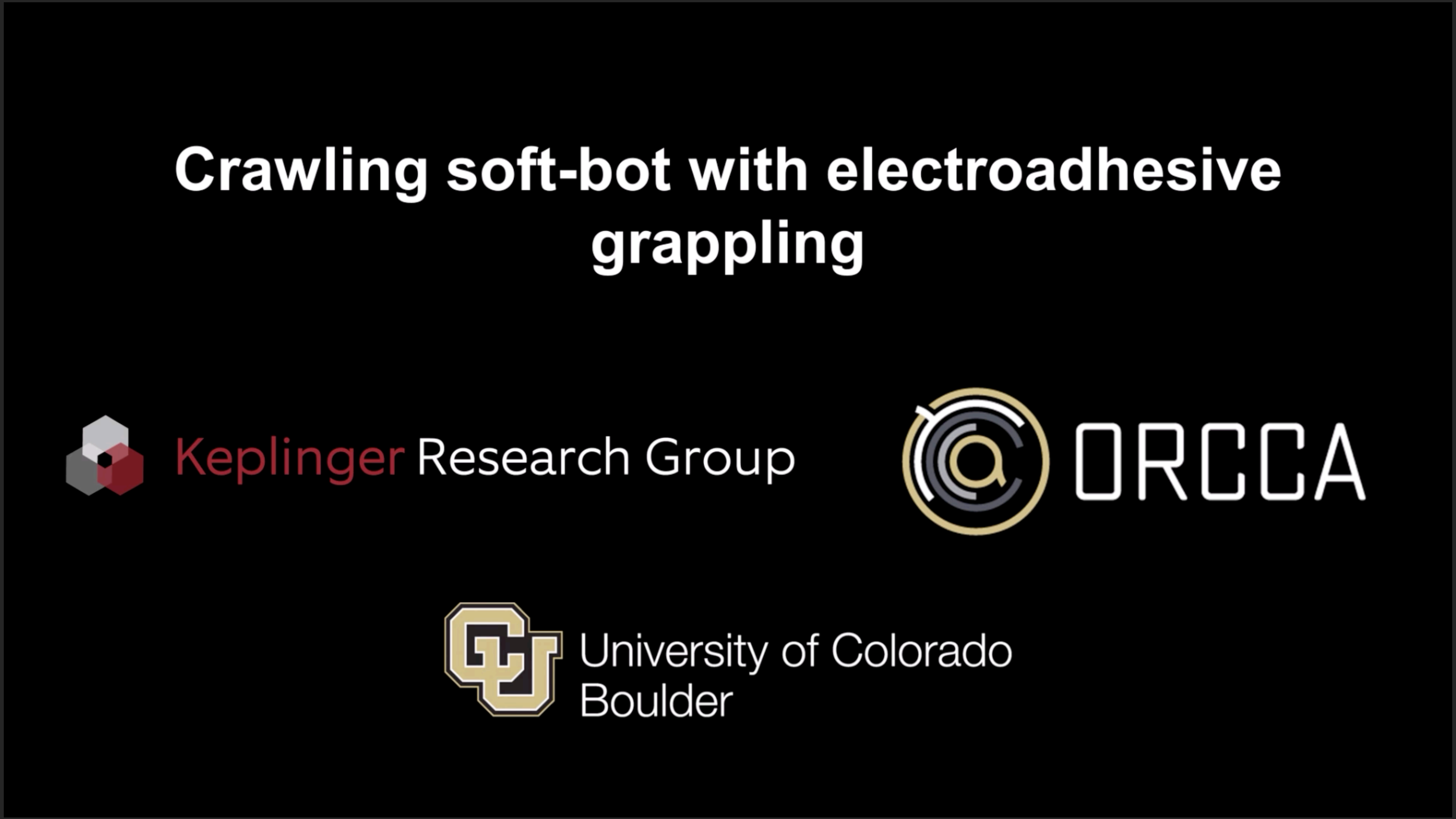








HASELs and Electro-Adhesion



Hopping Overview

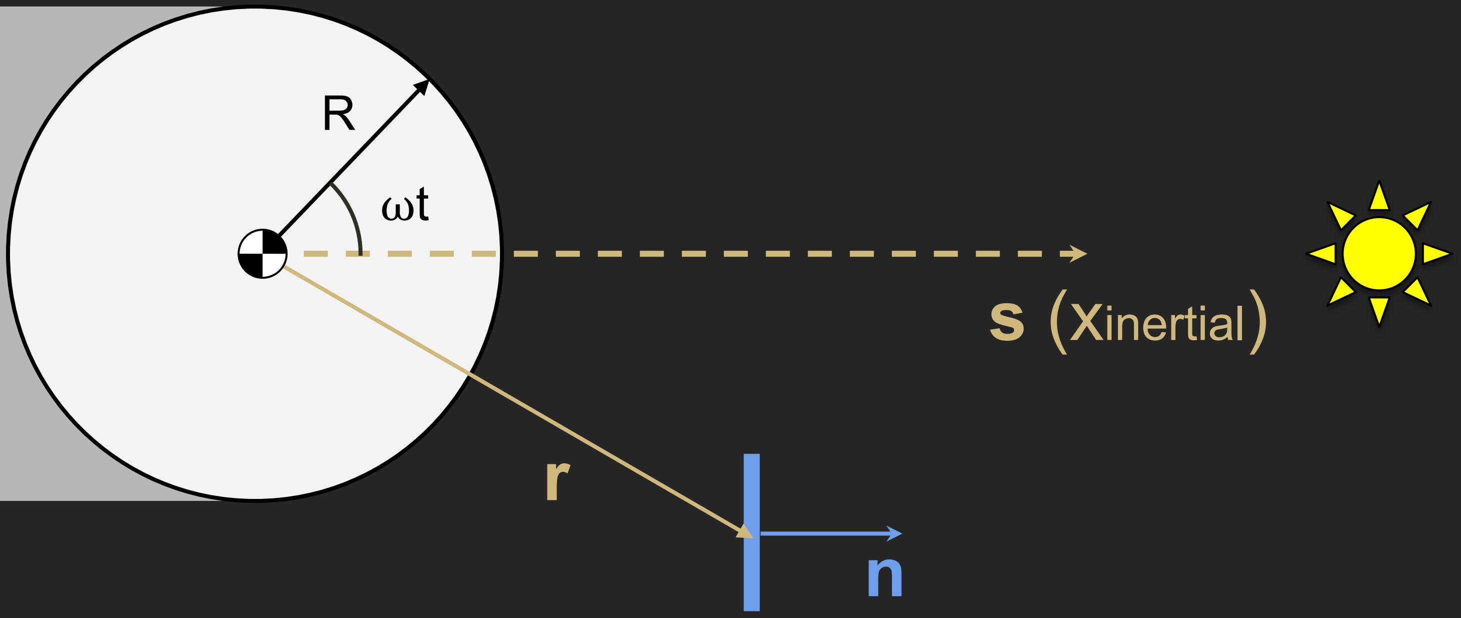
- Dynamics account for Bennu's rotation and flat plate solar radiation pressure

$$\ddot{\mathbf{r}} = -\frac{\mu}{r^3}\mathbf{r} - 2\boldsymbol{\omega} \times \dot{\mathbf{r}} - \boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r} + \ddot{\mathbf{r}}_{SRP}$$

Shadow Conditions

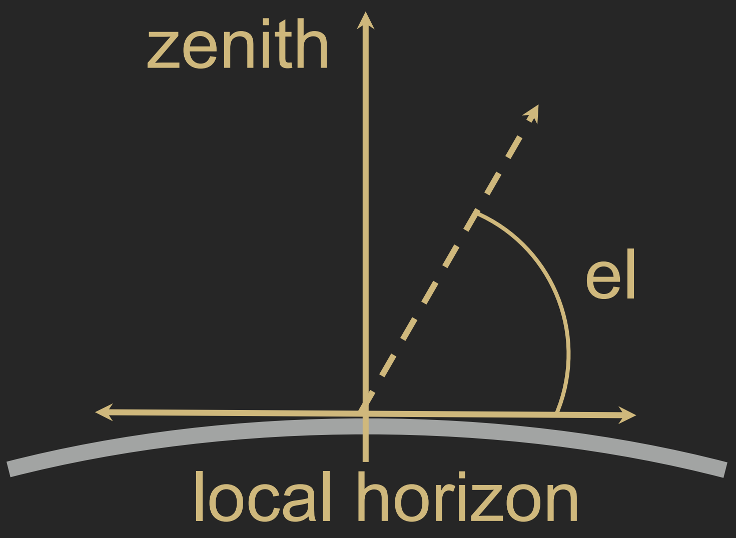
$$\boldsymbol{r}^T \hat{\boldsymbol{s}} < 0$$

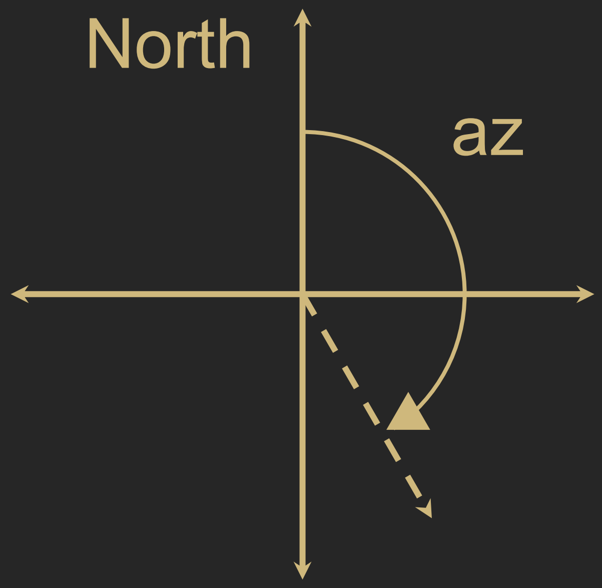
$$\| \left(\mathbb{I}_{3\times3} - \hat{\boldsymbol{s}}\hat{\boldsymbol{s}}^T\right) \boldsymbol{r} \| < R$$



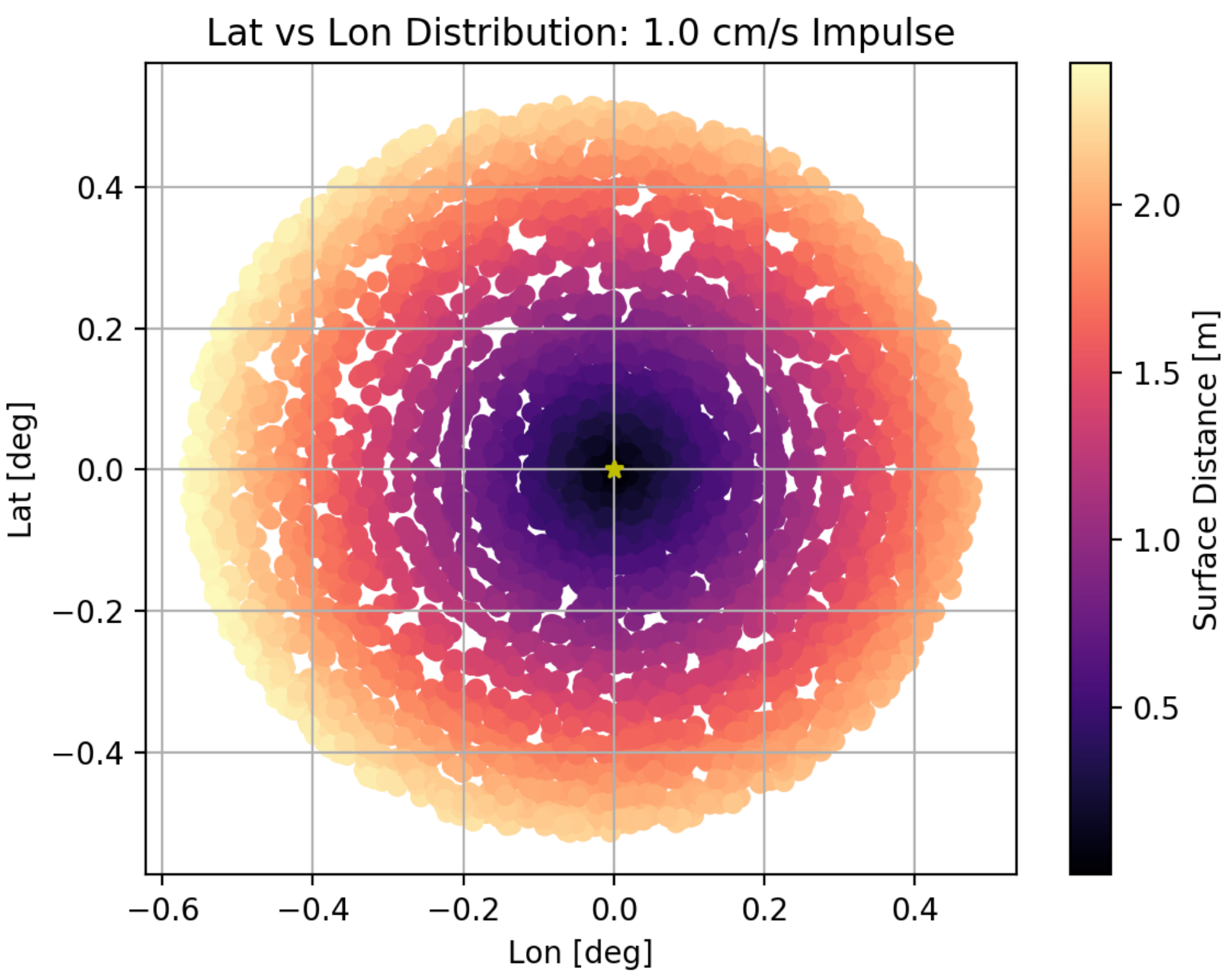
System Overview - Angles

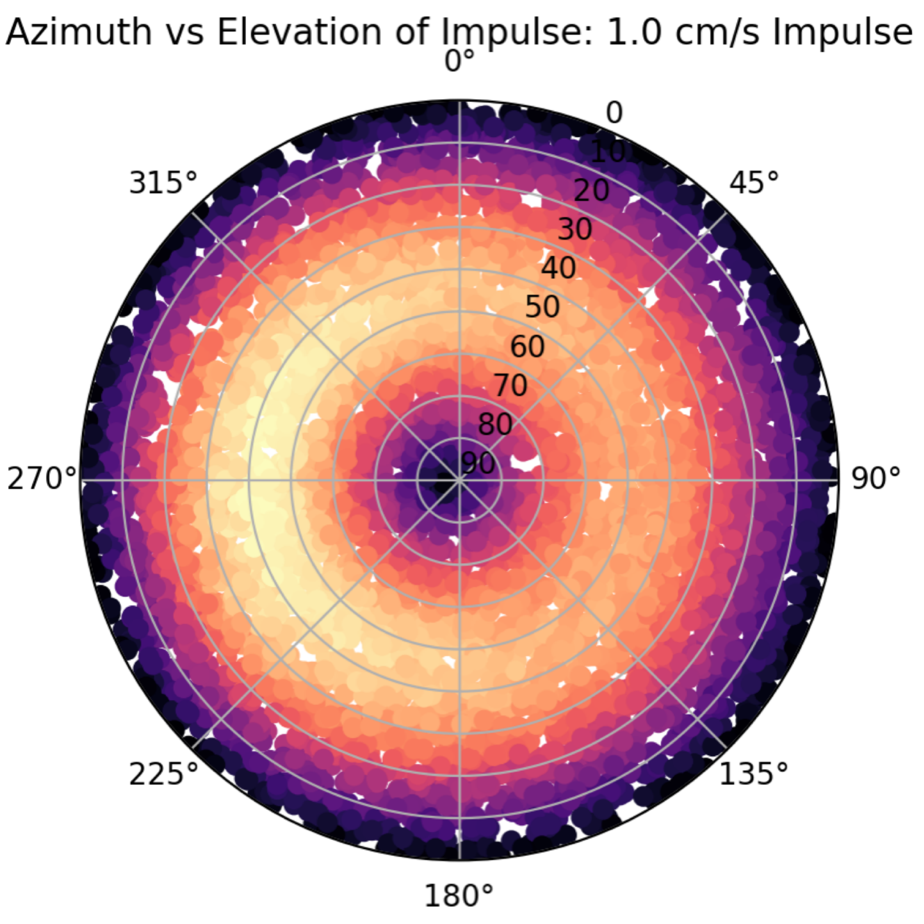
- Latitude and Longitude defined on Bennu's body-fixed frame
  - 0° initially aligned with the inertial *x*-axis
- Azimuth and Elevation defined from local horizon frame
- Random sampling over Az/El for hop impulse at given Lat/Lon



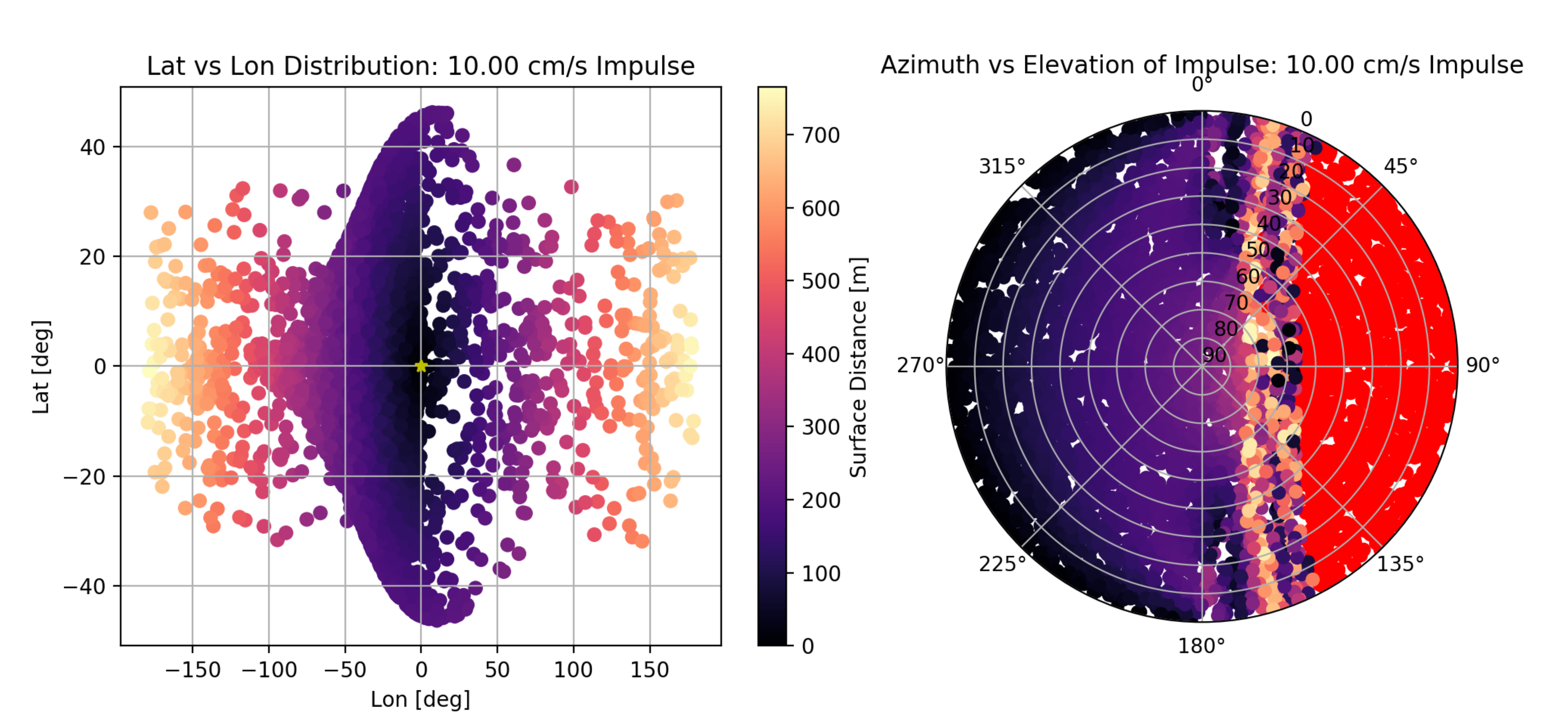


SRP (**s** = **n**): 1 cm/s Impulse at (0°, 0°)





SRP (**s** = **n**): 10 cm/s Impulse at (0°, 0°)



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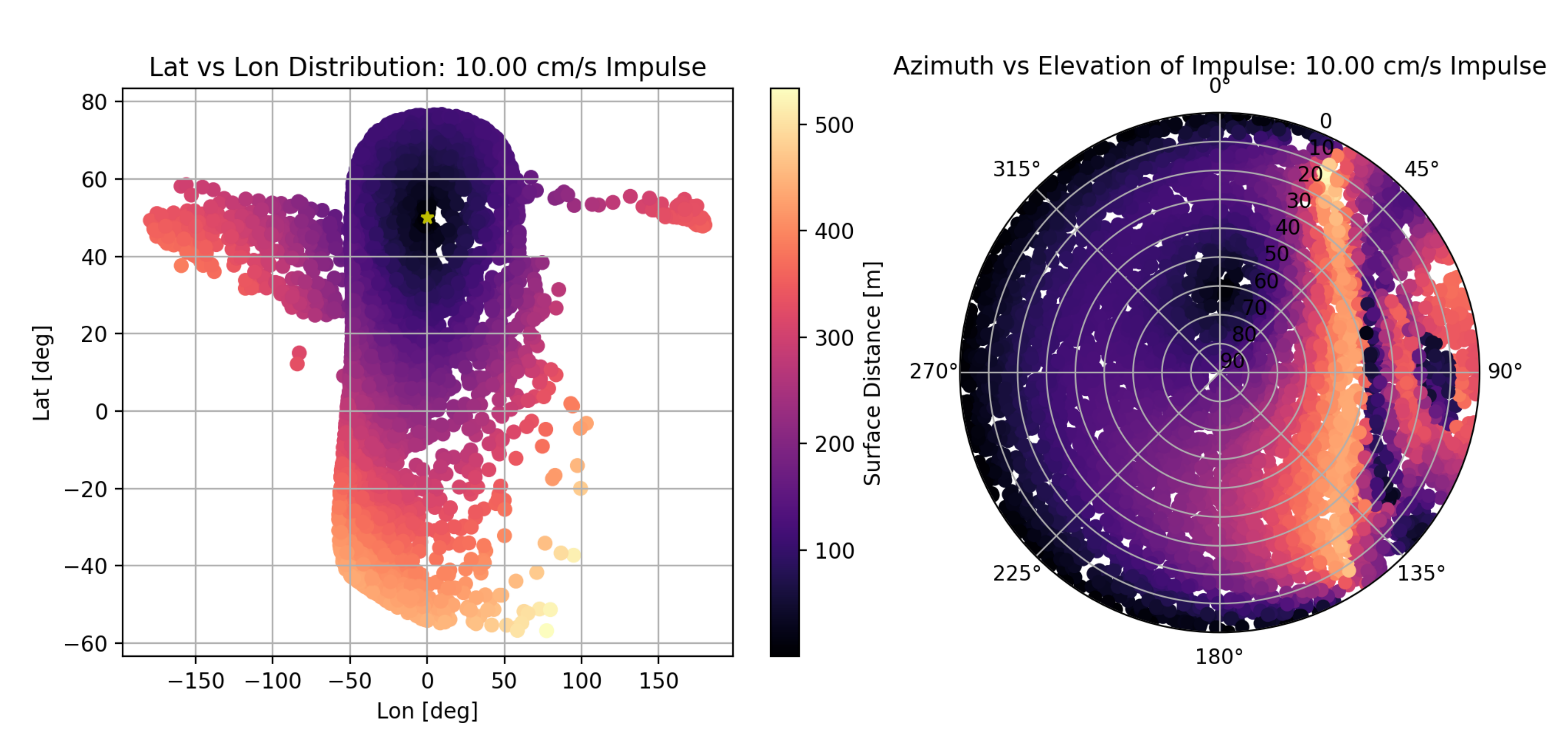
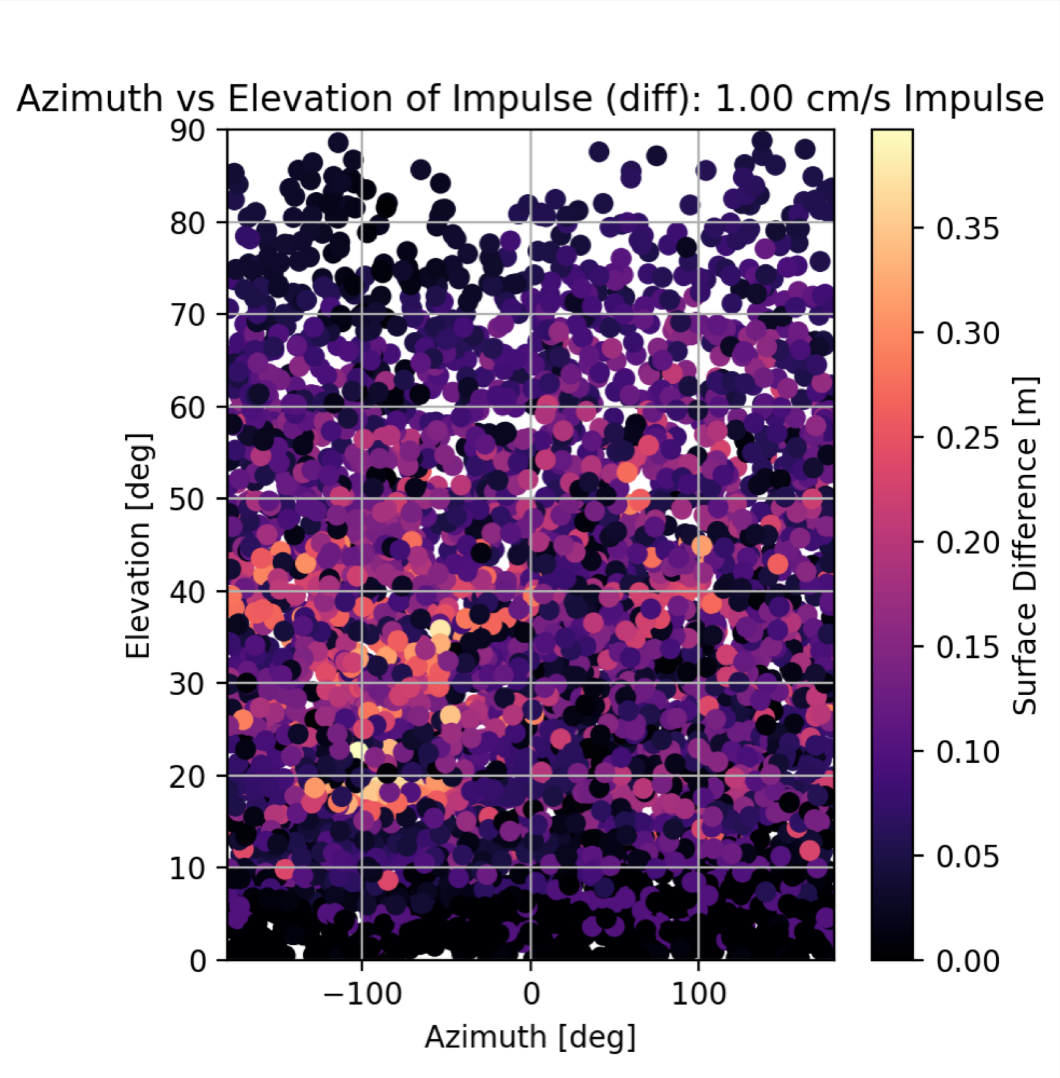
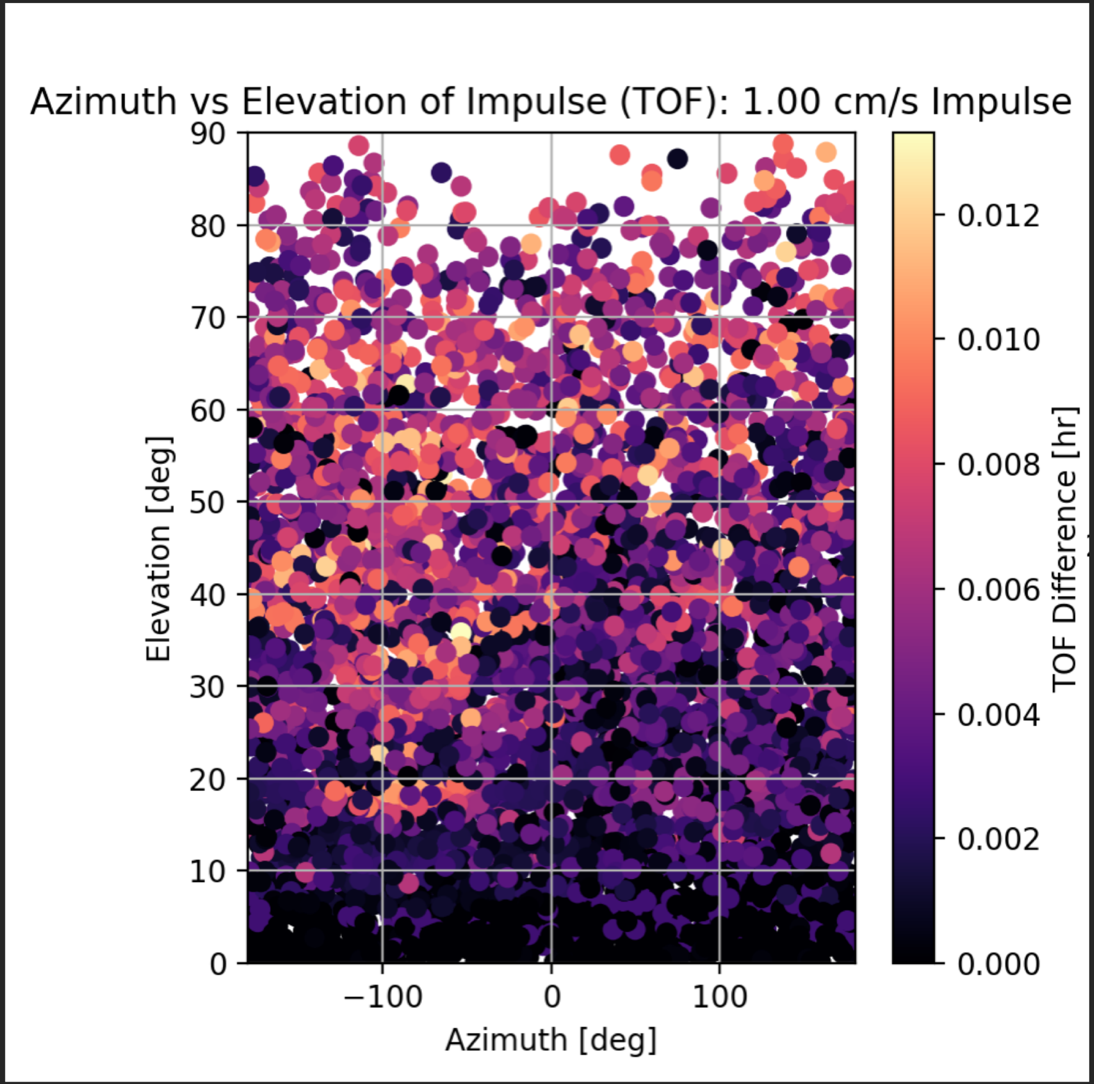
SRP (**s** = **n**): 10 cm/s Impulse at (50°, 0°)



1 cm/s Impulse at (0°, 0°) - Difference Plots





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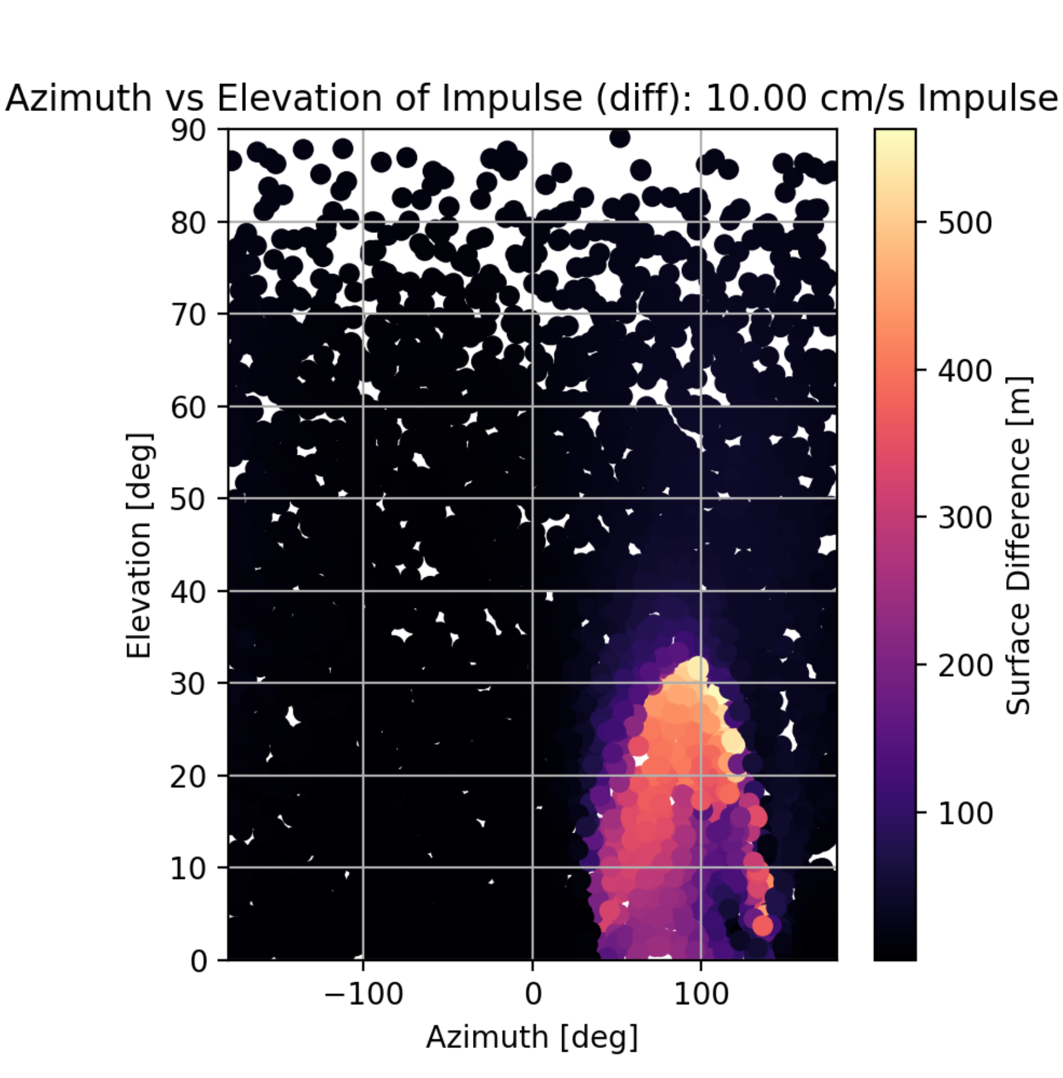
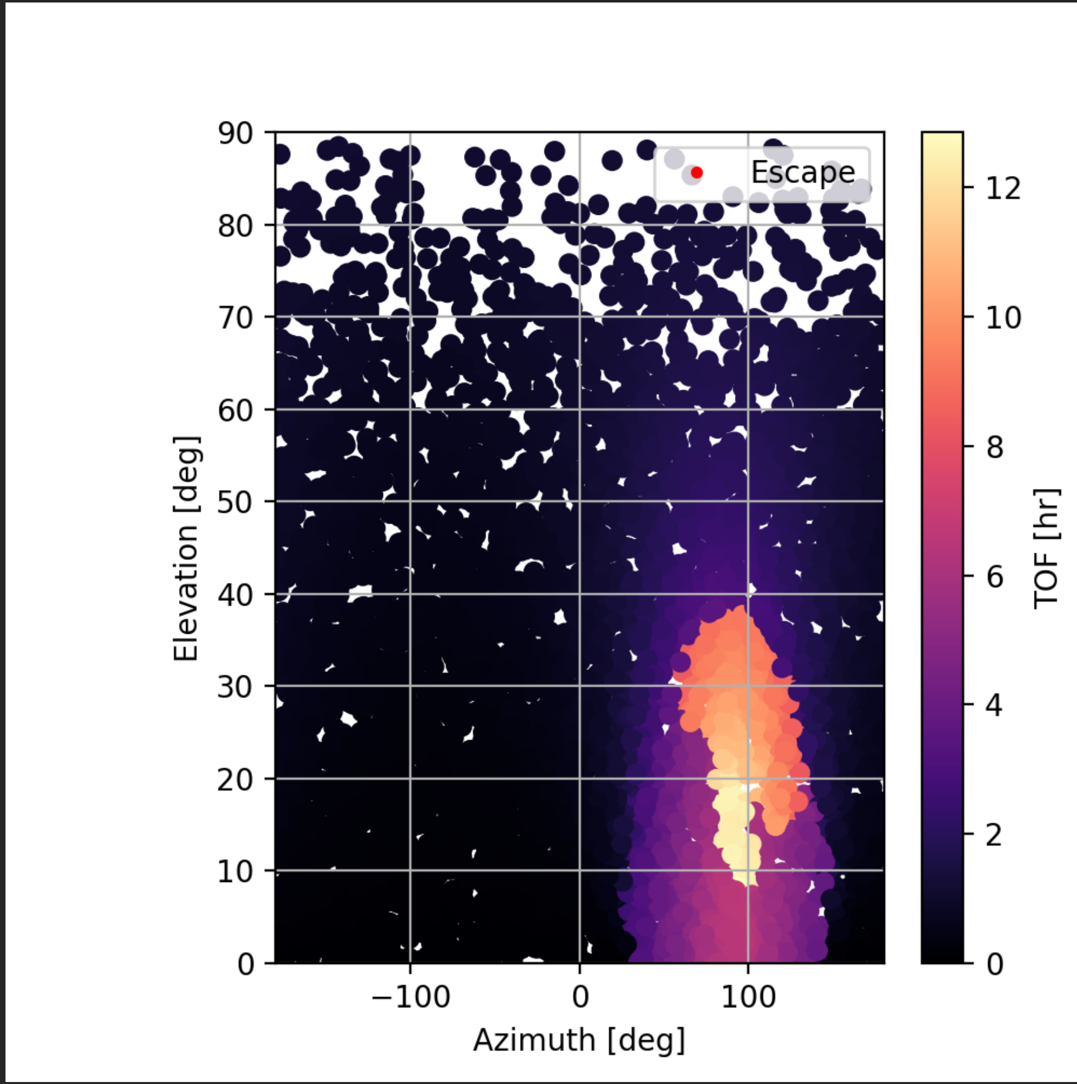
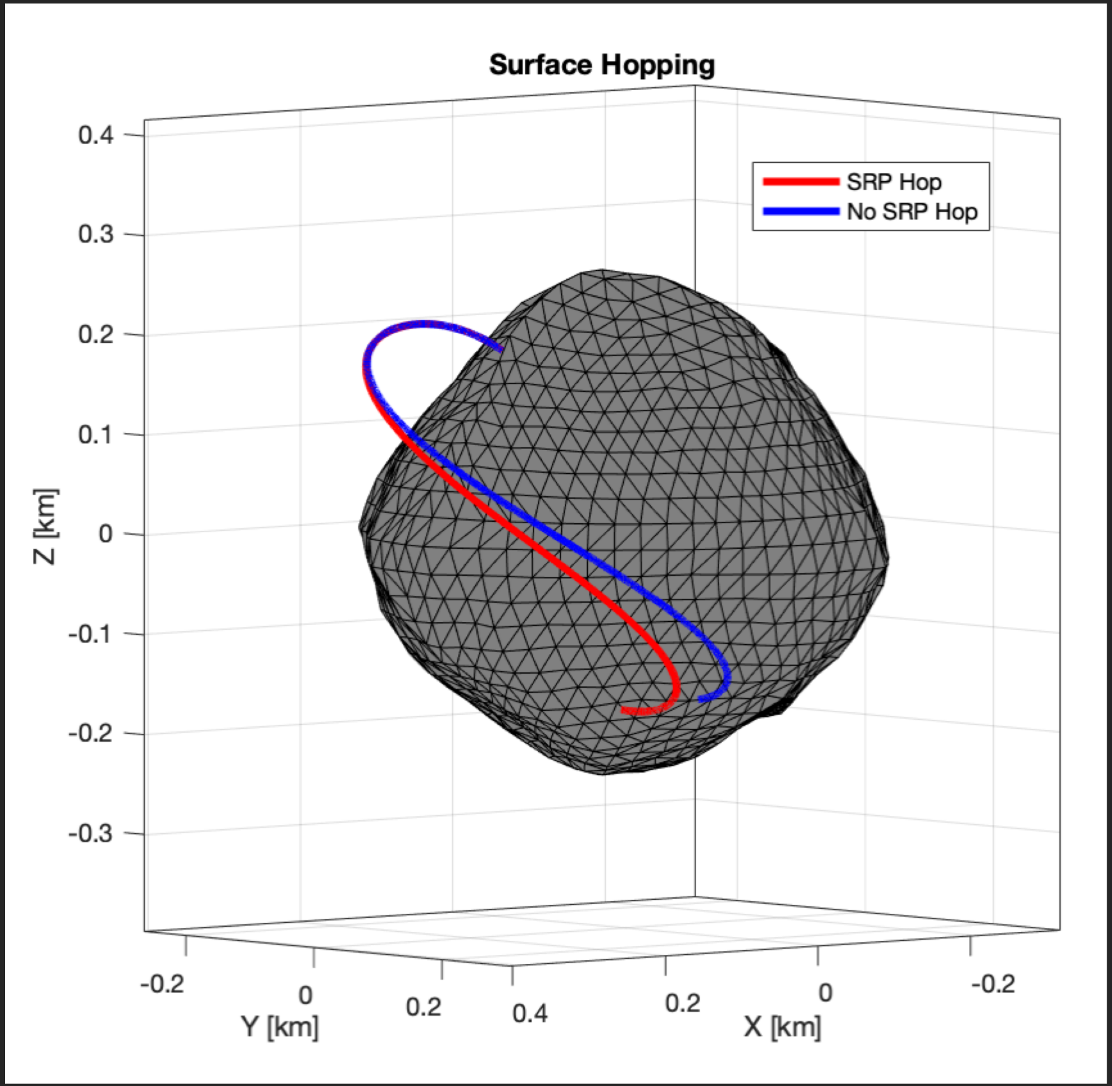
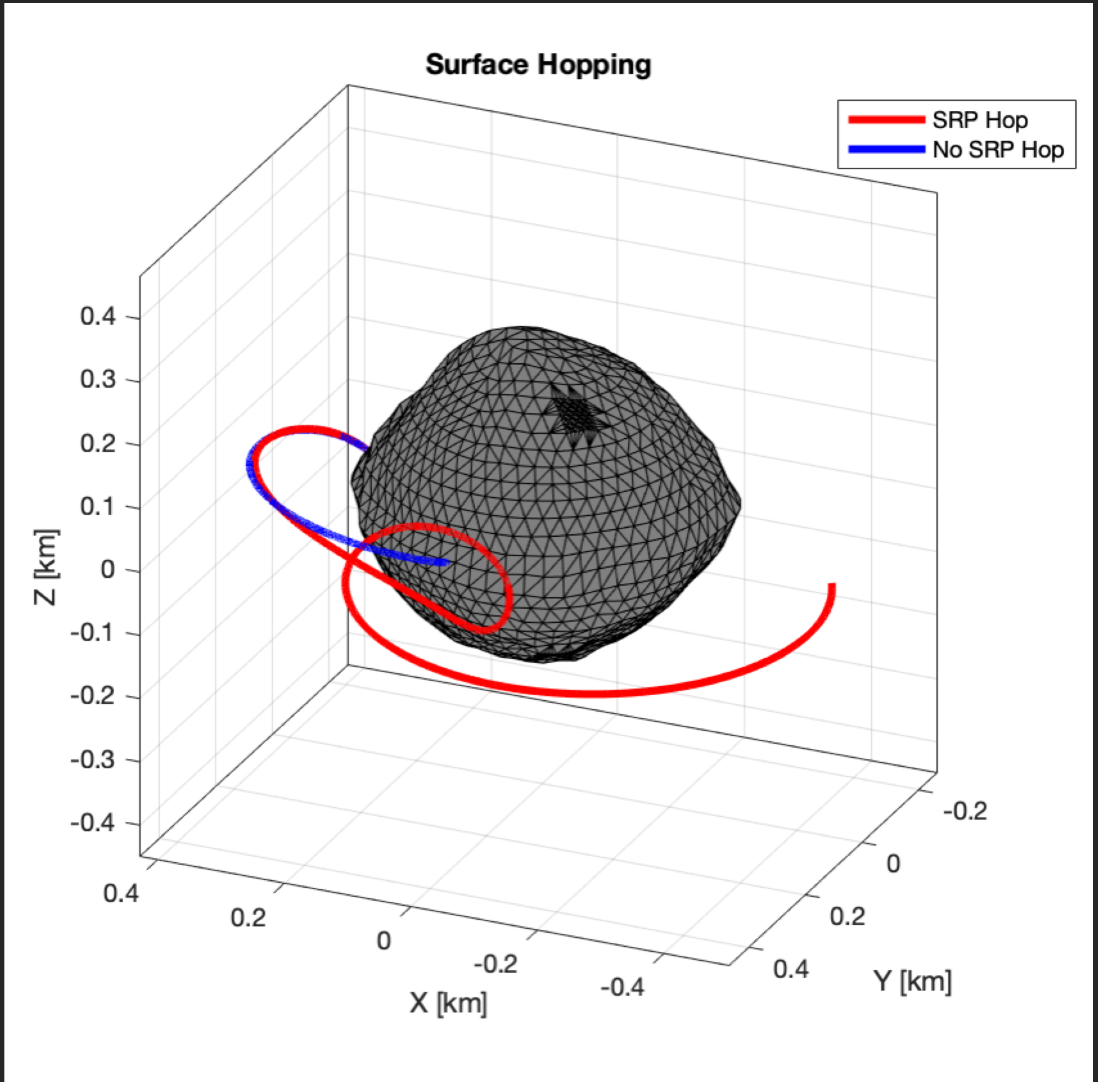
10 cm/s Impulse at (50°, 0°) - Difference Plots





Example Trajectories





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How much regolith can we get?

How much regolith can we get?

- Assume 10 excavation sites randomly distributed on Bennu
  - Radius: $\mu = 5$ m, $\sigma = 1$ m
  - Depth: $\mu = 1$ m, $\sigma = 0.25$ m

6.73e+05 kg → 56251 launch cycles

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6.73e+05 kg → 56251 launch cycles

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- Assuming 1 regolith launch per hour → 363 days to excavate

- Assuming a collection efficiency of 30%, 15% hydrated minerals, and a 50% refining efficiency

1.51e+04 kg of water

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FUTURE WORK

Collaborations

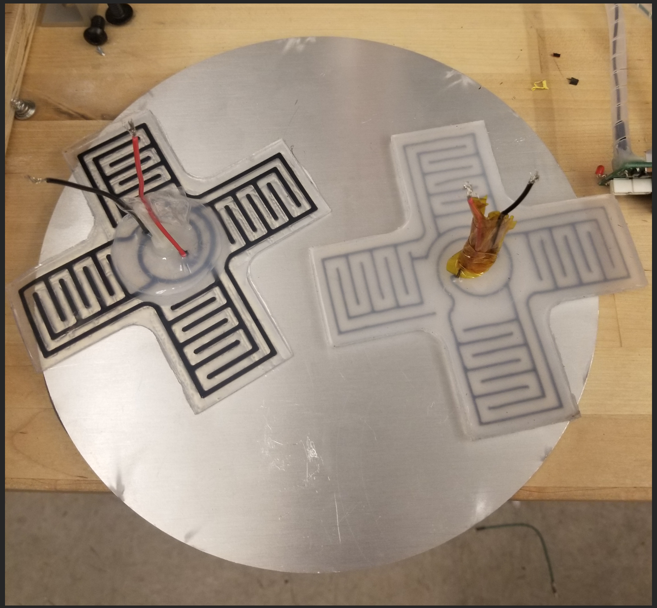
Keplinger Research Group

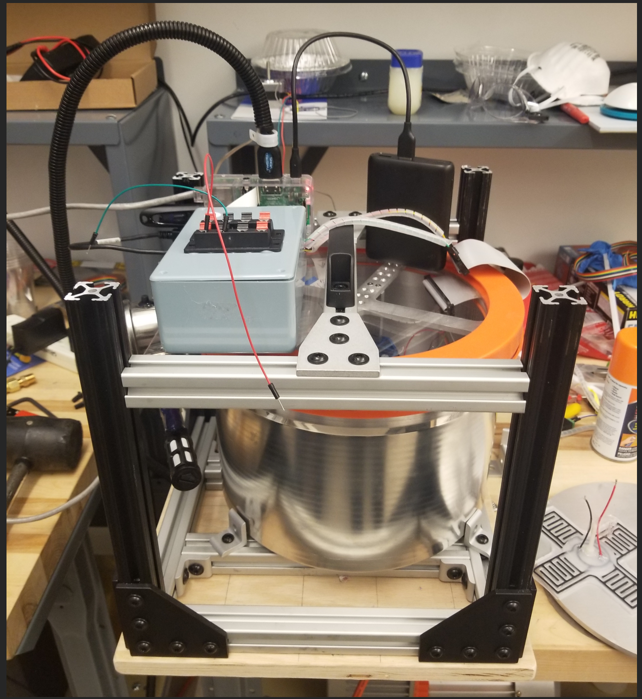
Project ESPRESSO

Alex Parker
SWRI

Center for Lunar & Asteroid Surface Science
CLASS

Dan Britt
UCF





CI Simulant

CM Simulant

Parabolic Flight Experiments

- Testing AoES electro-adhesion

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Future Work

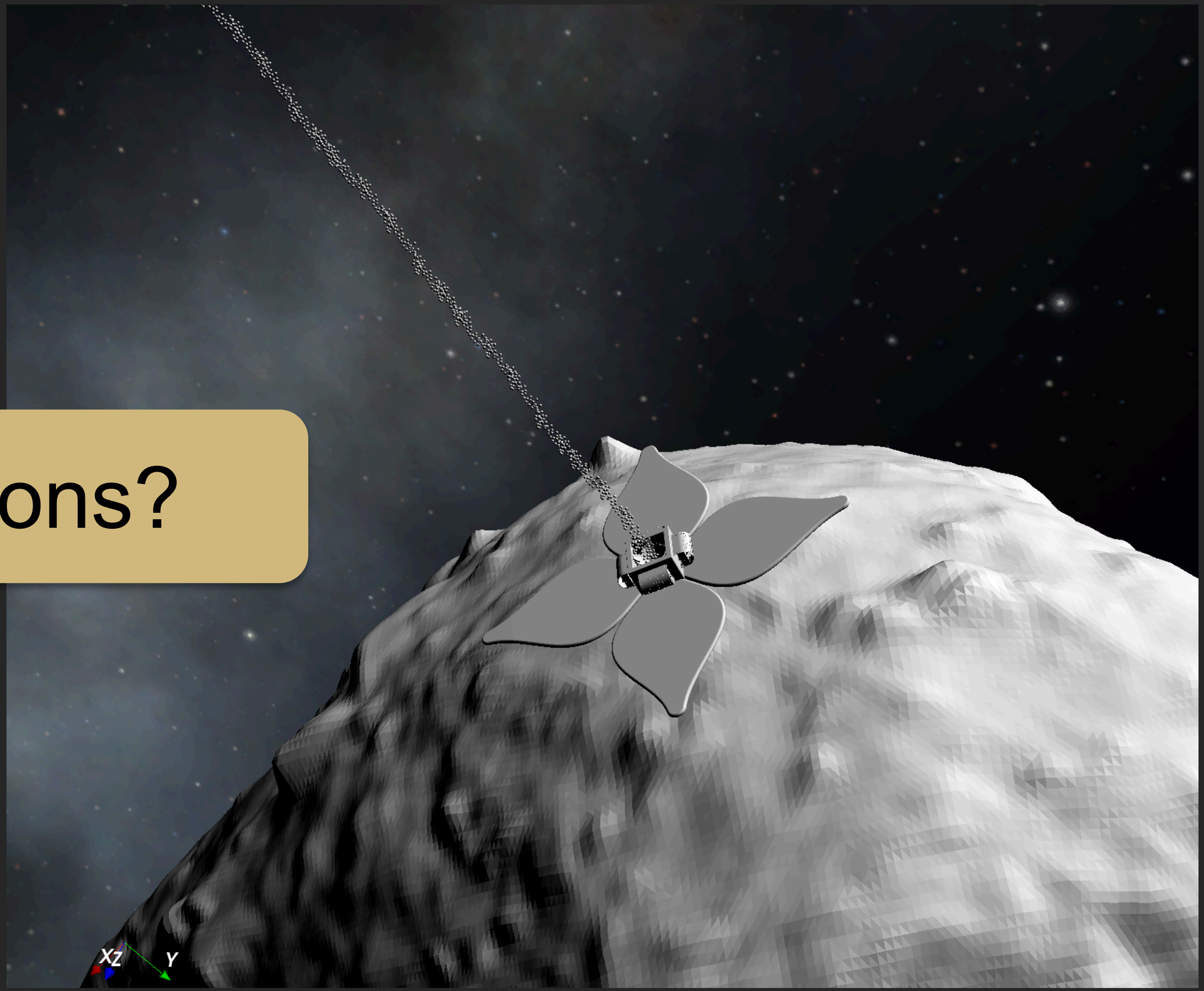
- Further work on the AoES bus and limb design
  - Rigorous thermal analysis
  - HASEL actuators and AoES limb integration

- Increased model fidelity for SRP hopping simulations
  - Implementing an SRP controller for guidance
  - Include autonomous surface mobility planning for excavation site selection

- Increased fidelity of AoES crawling model
  - Implement contact forces and surface conditions

- Electro-adhesion experiments and other prototypes

Area-of-Effect Softbots to the Rescue!



Questions?

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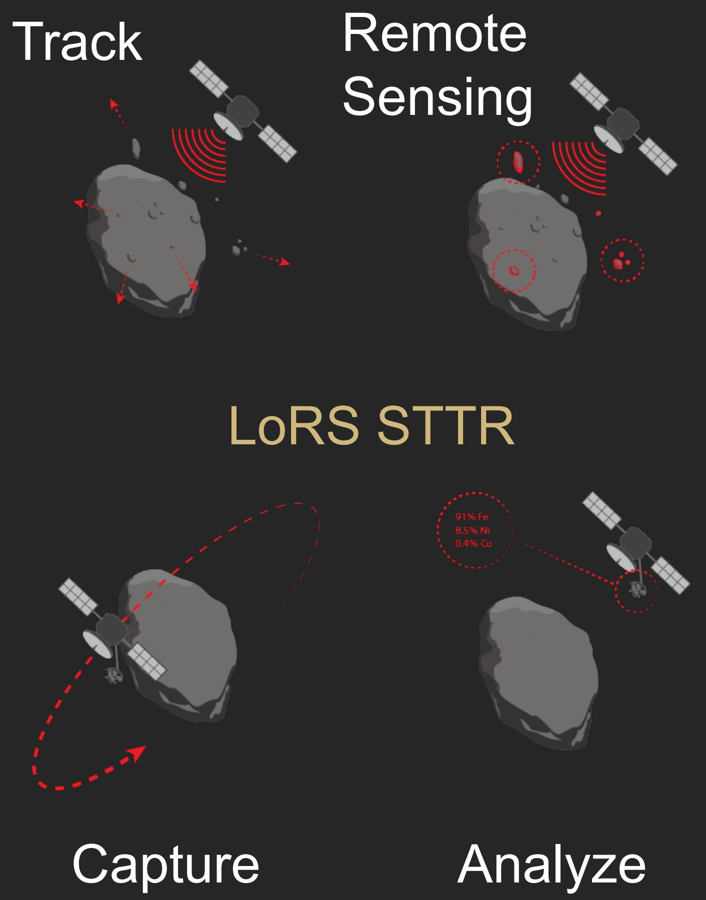
BACK-UP SLIDES

Dismantling Asteroids for Resource Acquisition

What about the mothership capturing this lofted material??



Debris Propagation

- What happens to material lofted from a small body?
  - it generally escapes or re-impacts
- To show this, we explored the parameter space with over 80,000 trajectories
- Bennu sized asteroid at 1AU

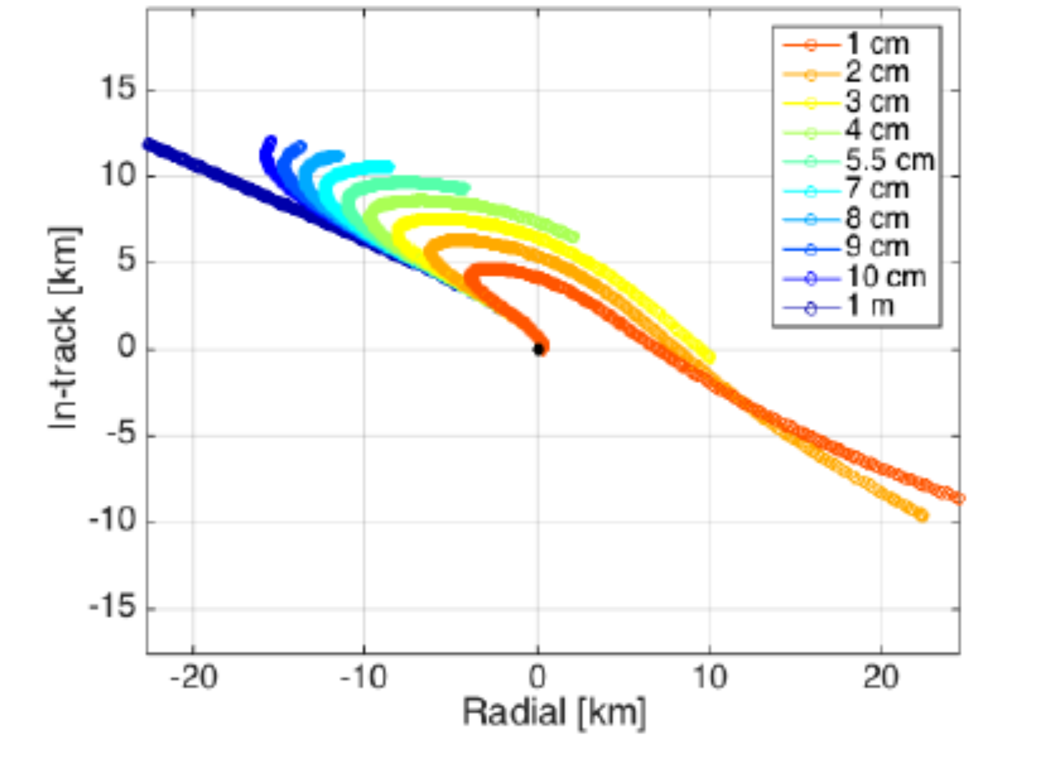


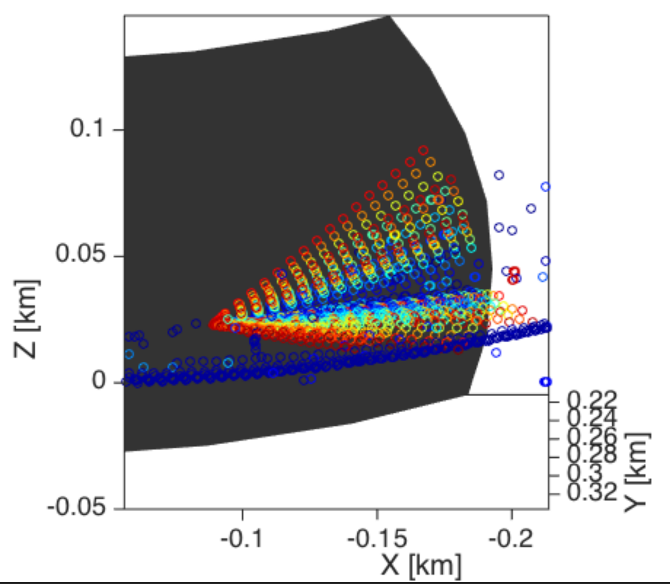
Table 1: Parameter space for lofted regolith trajectories

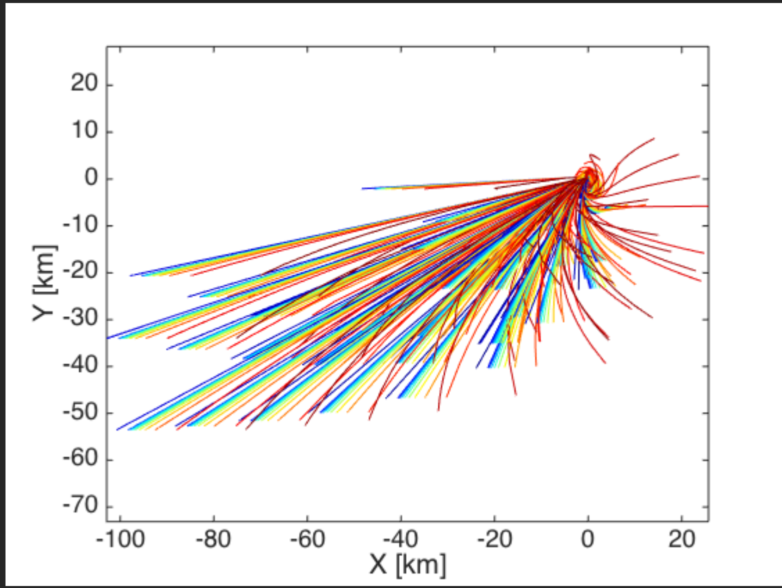
Parameter	Values Tested
Particle Radius	[100, 10, 8.9, 7.8, 6.6, 5.5, 4.4, 3.3, 2.1, 1] cm
Latitude	[80, ±64, ±48, ±32, ±16, 0] deg
Longitude	[0, 36, 72, 108, 144, 180, 216, 252, 288, 324] deg
Launch Azimuth	[0, 90, 180] deg
Launch Elevation	[10, 30, 45, 90] deg
Launch Velocity	[3, 5, 7, 9, 11, 13, 15] cm/s

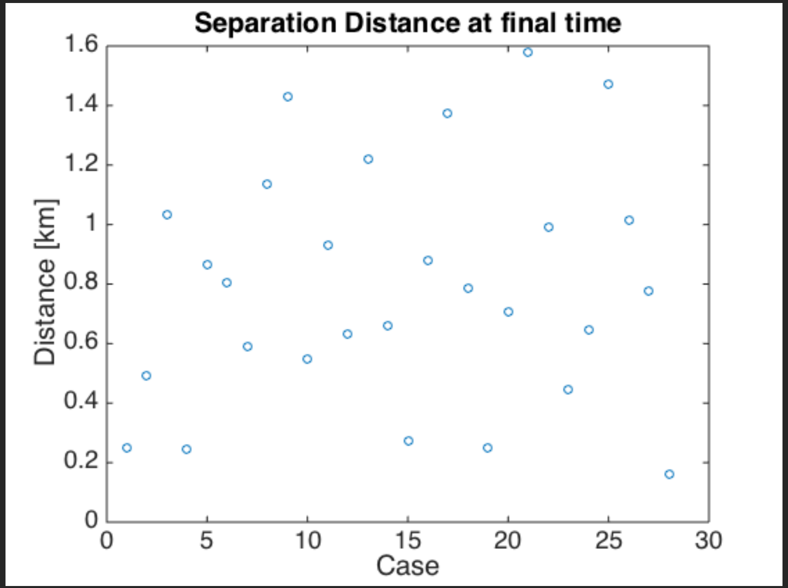
Debris Propagation

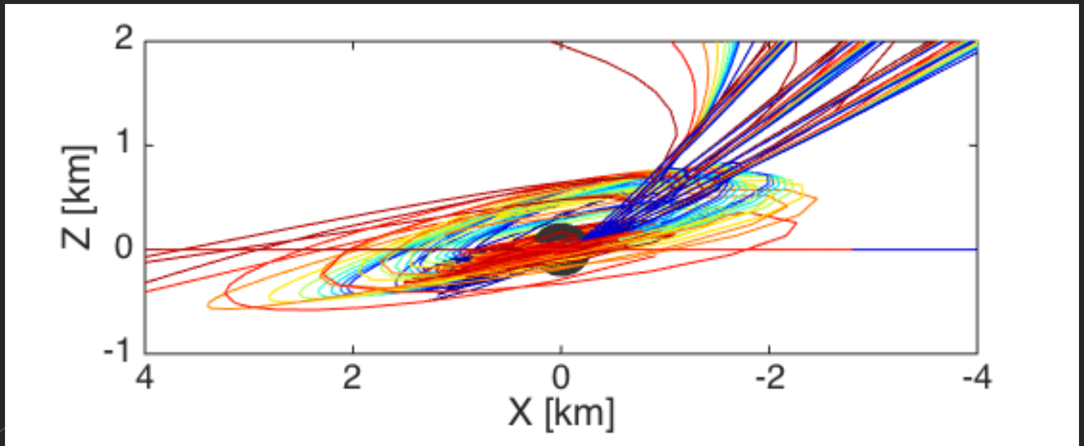
- 5 days
- 1 site, 108 longitude, 0 latitude

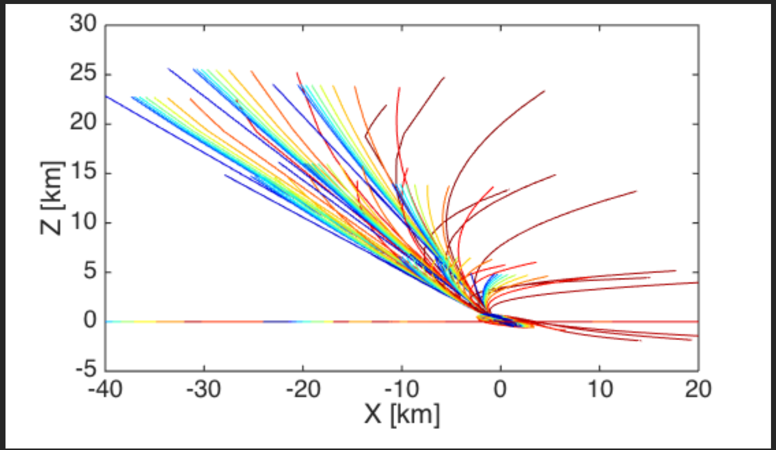
- SRP sorts material by size
- Although some trajectories appear close, they are separated when looking at time











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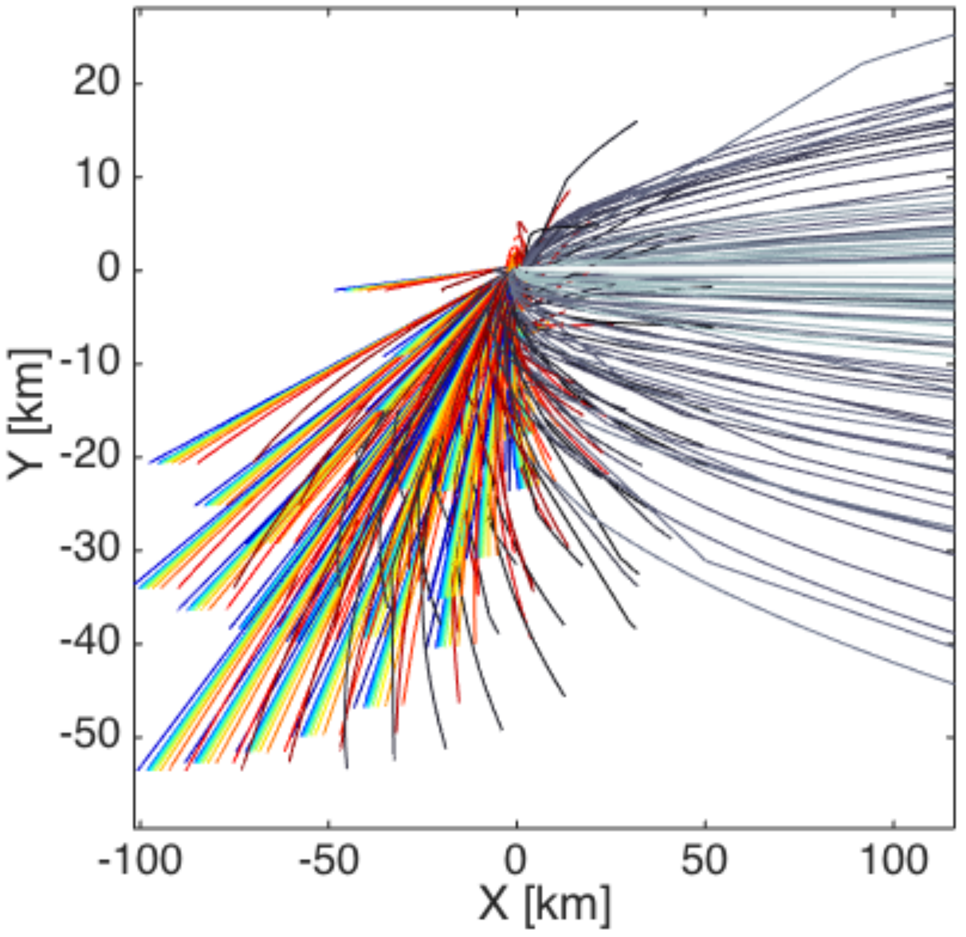
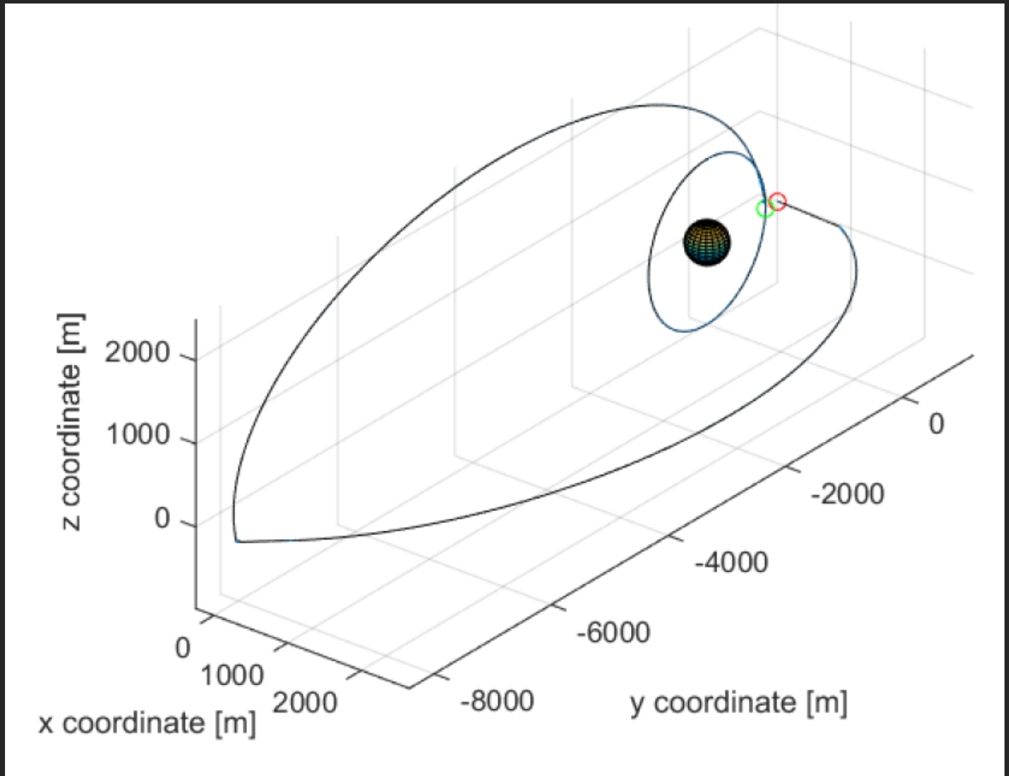
Dust Mitigation

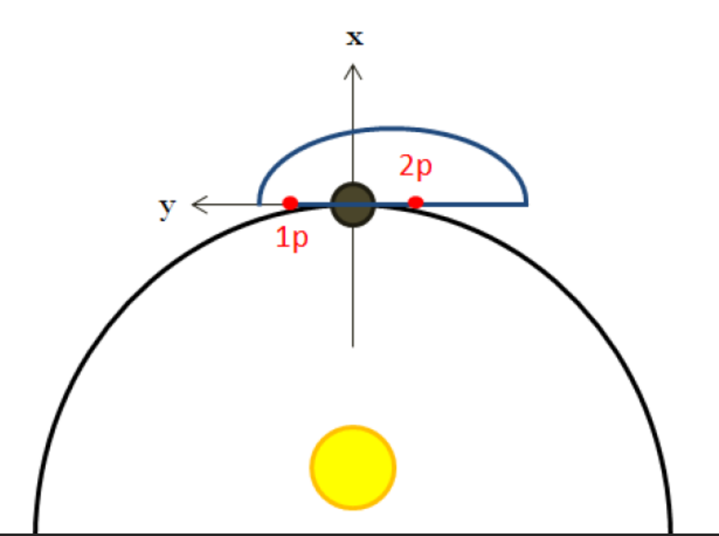
- What about all the dust?
  - it goes away - FAST
- Looked at 1 μm - 5 mm dust
  - 33,000 more trajectories
- In all cases, the dust either immediately re-impacts, or reaches 100s of km in days
  - the plot is cut off at the right, dust reaches this distance in ~1 day
- Not worried about significant residual dust



Maneuverability is *cheap*

- 7 cm/s to raise apoapse to 8km
- 3 cm/s to change inclination 90 degrees!
- ~6.5g of fuel with Dawn's ion engine and a 2000 kg s/c

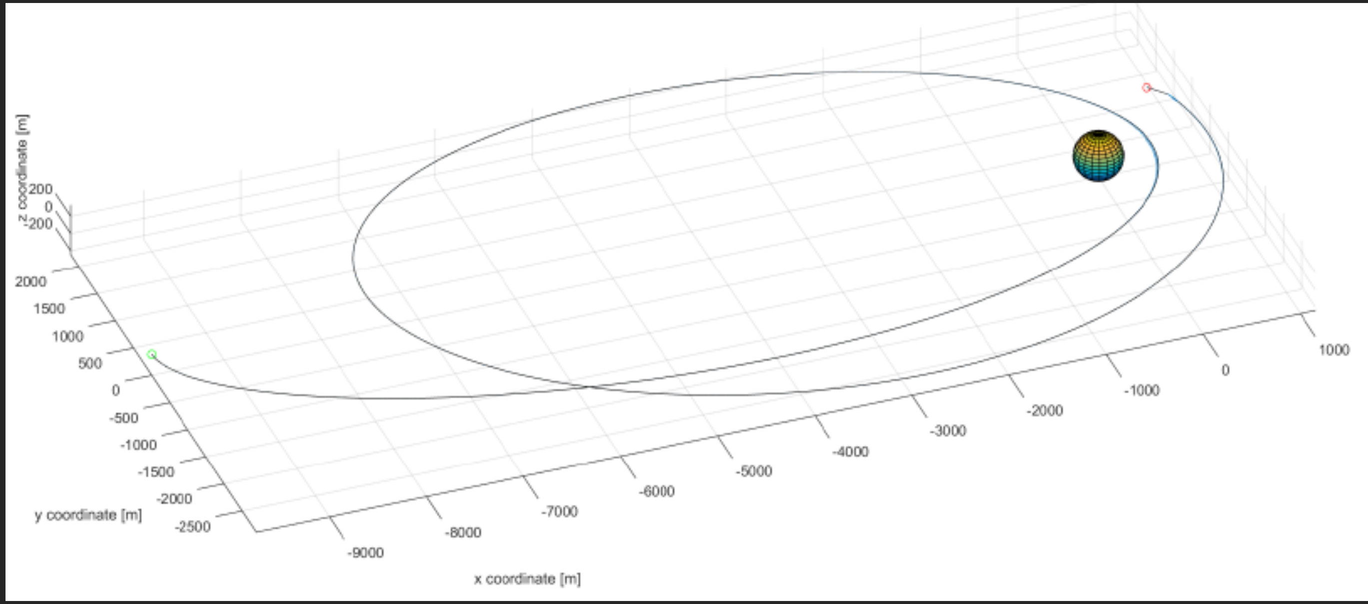


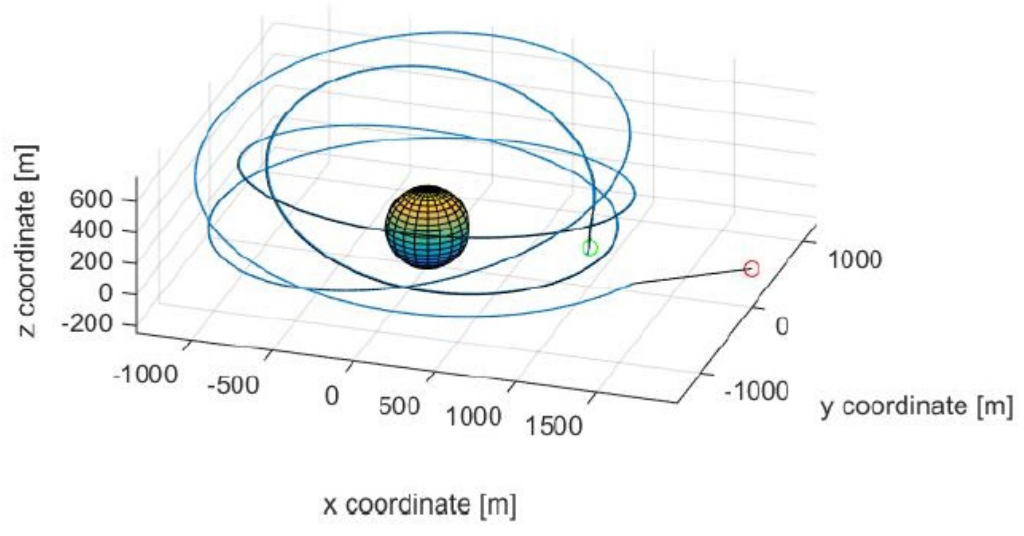


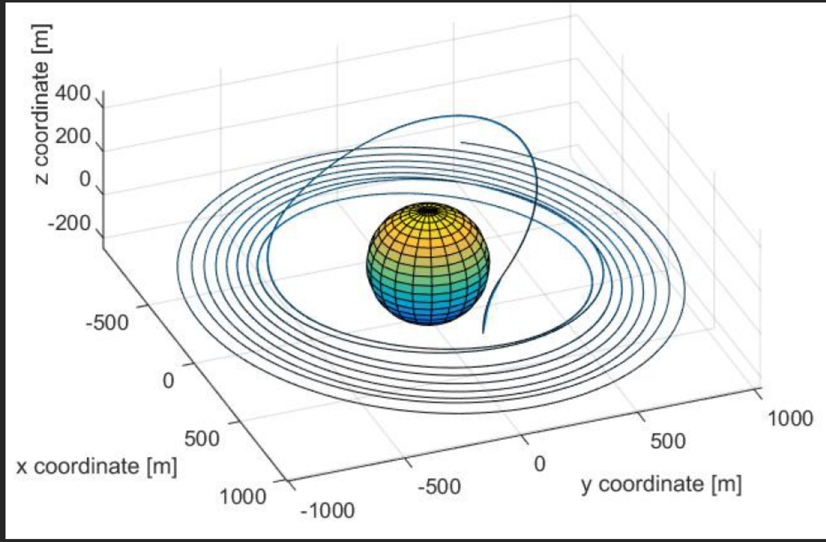
Spacecraft's propulsion characteristics used in the simulation

Parameter	Symbol	Value
Maximum thrust force	T_{max}	0.090 [N]
Specific impulse	I_{sp}	3100 [s]

Other fun, and feasible, trajectories







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Terminal Intercept Guidance

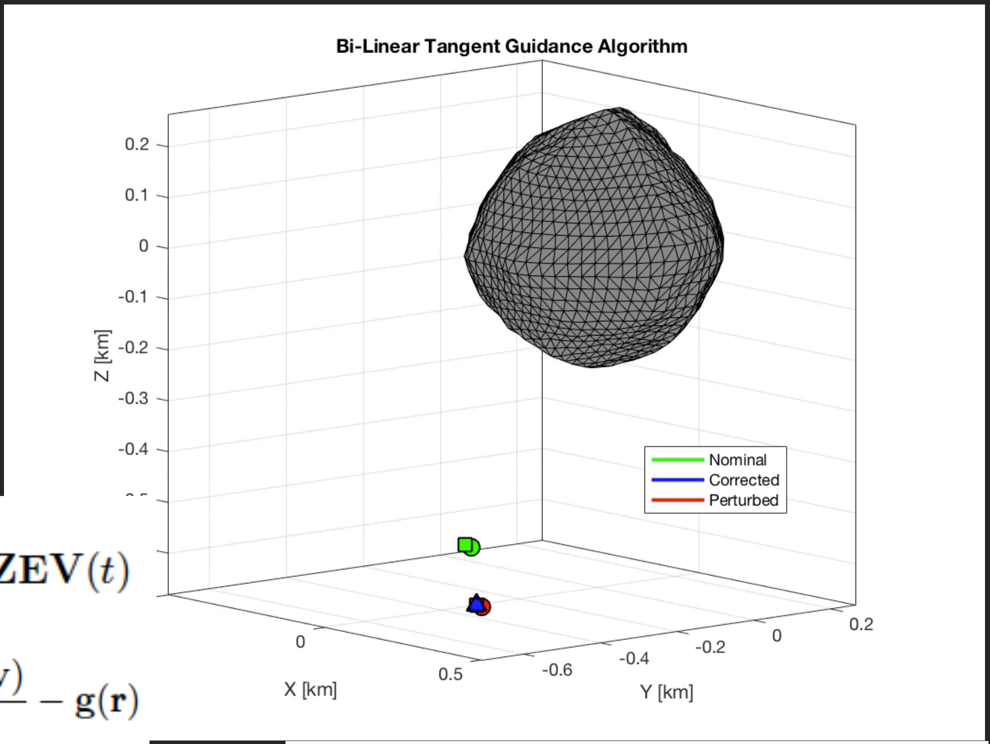
- Implemented ZEM/ZEV guidance algorithm
- Investigated a wide variety of conditions
- Minimal fuel required
  - on the order of grams

$$\mathbf{ZEM}(t) = \mathbf{r}_F - \left[\mathbf{r}(t) + \mathbf{v}(t)t_{go} - \int_t^{t_F}\int_{\tau'}^{t_F} \mathbf{g}(\mathbf{r},\tau')d\tau' d\tau\right]$$

$$\mathbf{ZEV}(t) = \mathbf{v}_F - \left[\mathbf{v}_t \int_t^{t_F} \mathbf{g}(\mathbf{r},\tau)d\tau\right]$$

$$\mathbf{a}_{comm}(t) = \frac{6}{t_{go}^2}\mathbf{ZEM}(t) - \frac{2}{t_{go}}\mathbf{ZEV}(t)$$

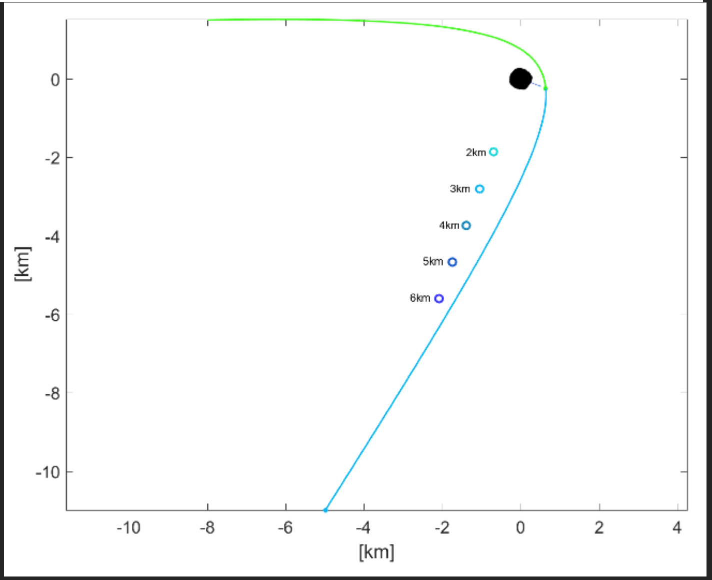
$$\mathbf{a} = \frac{6\left[\mathbf{r}_F - (\mathbf{r} + t_{go}\mathbf{v})\right]}{t_{go}^2} - \frac{2\left(\mathbf{v}_F - \mathbf{v}\right)}{t_{go}} - \mathbf{g}(\mathbf{r})$$



- Now implementing Bilinear Tangent Guidance for more robust general maneuverability
  - Comes from the launch vehicle world

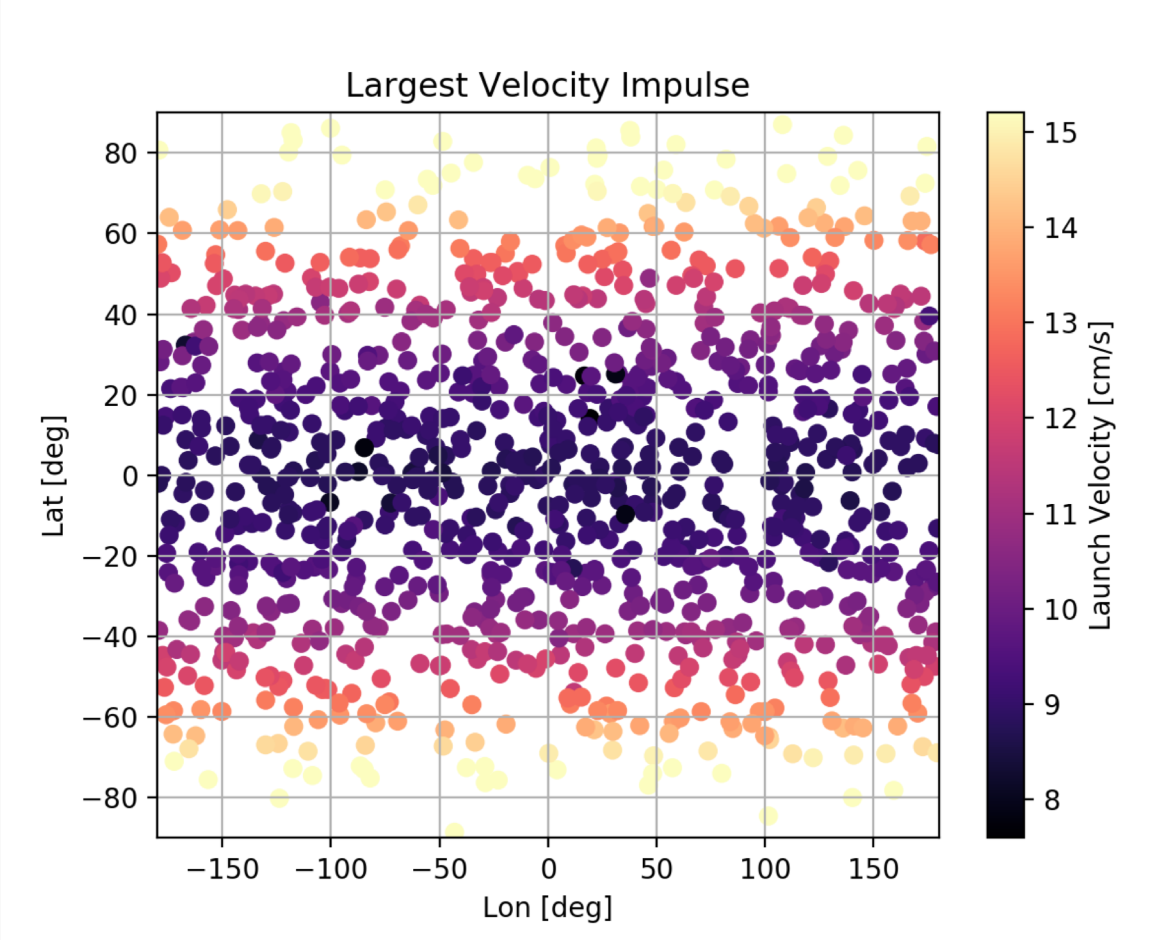
$$\tan\theta = \frac{A_z + B_z t}{A_x + B_x t}$$

$$\tan\alpha = \frac{A_y + B_y t}{A_x + B_x t}$$

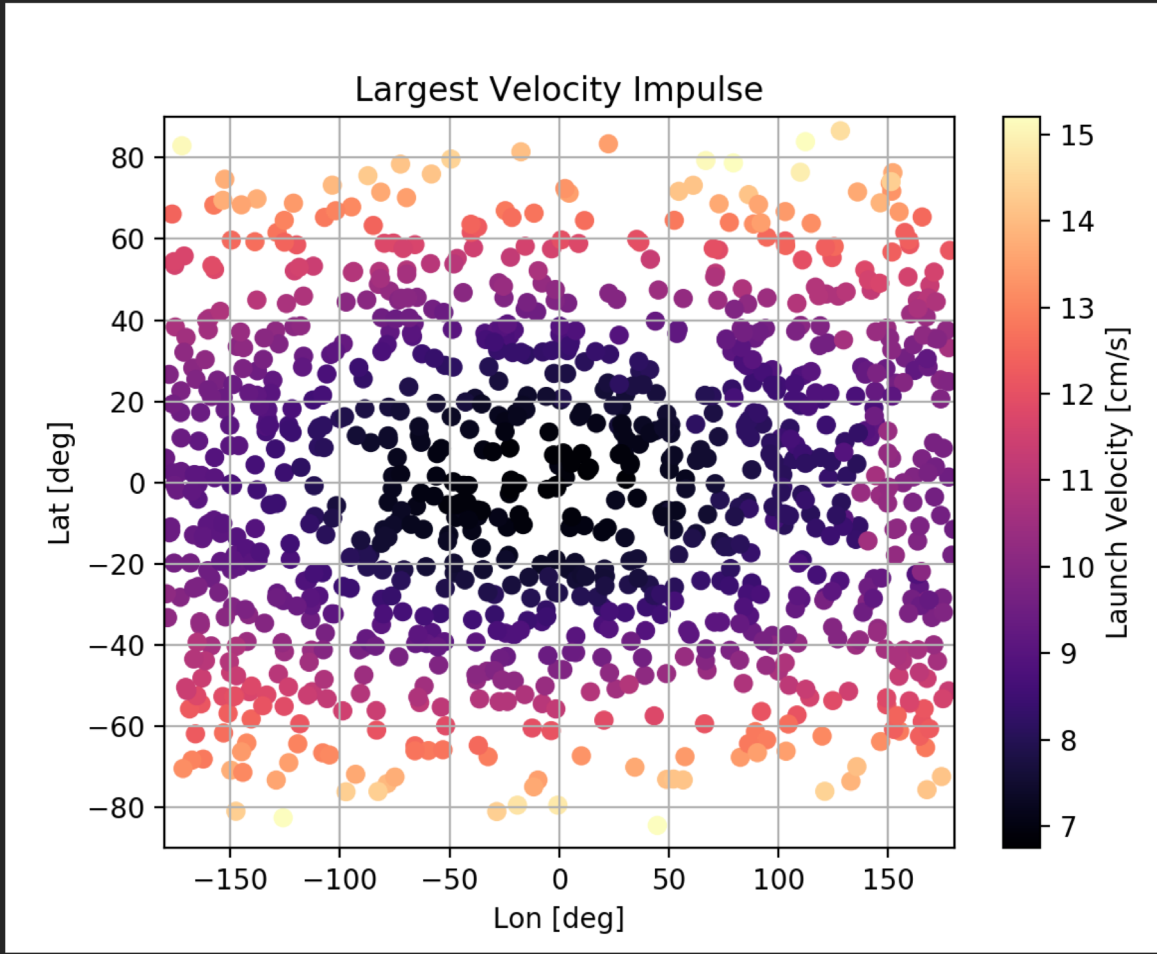


Max Impulse that Returns to Surface in 24 hrs

No SRP



SRP (**s** = **n**)



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Using Adhesion for Anchoring