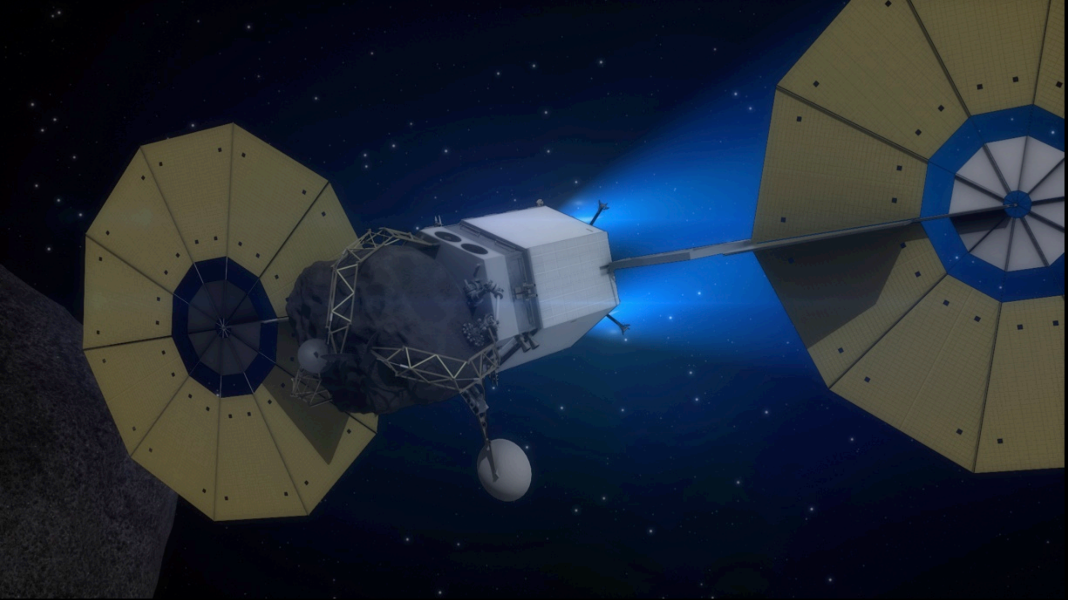

Key Challenges in Capturing a Boulder for the Asteroid Redirect Robotic Mission

15th International Planetary Probe Workshop

Benjamin D. Cichy[1] and Suparna Mukherjee[2]

[1] NASA Goddard Space Flight Center (GSFC)
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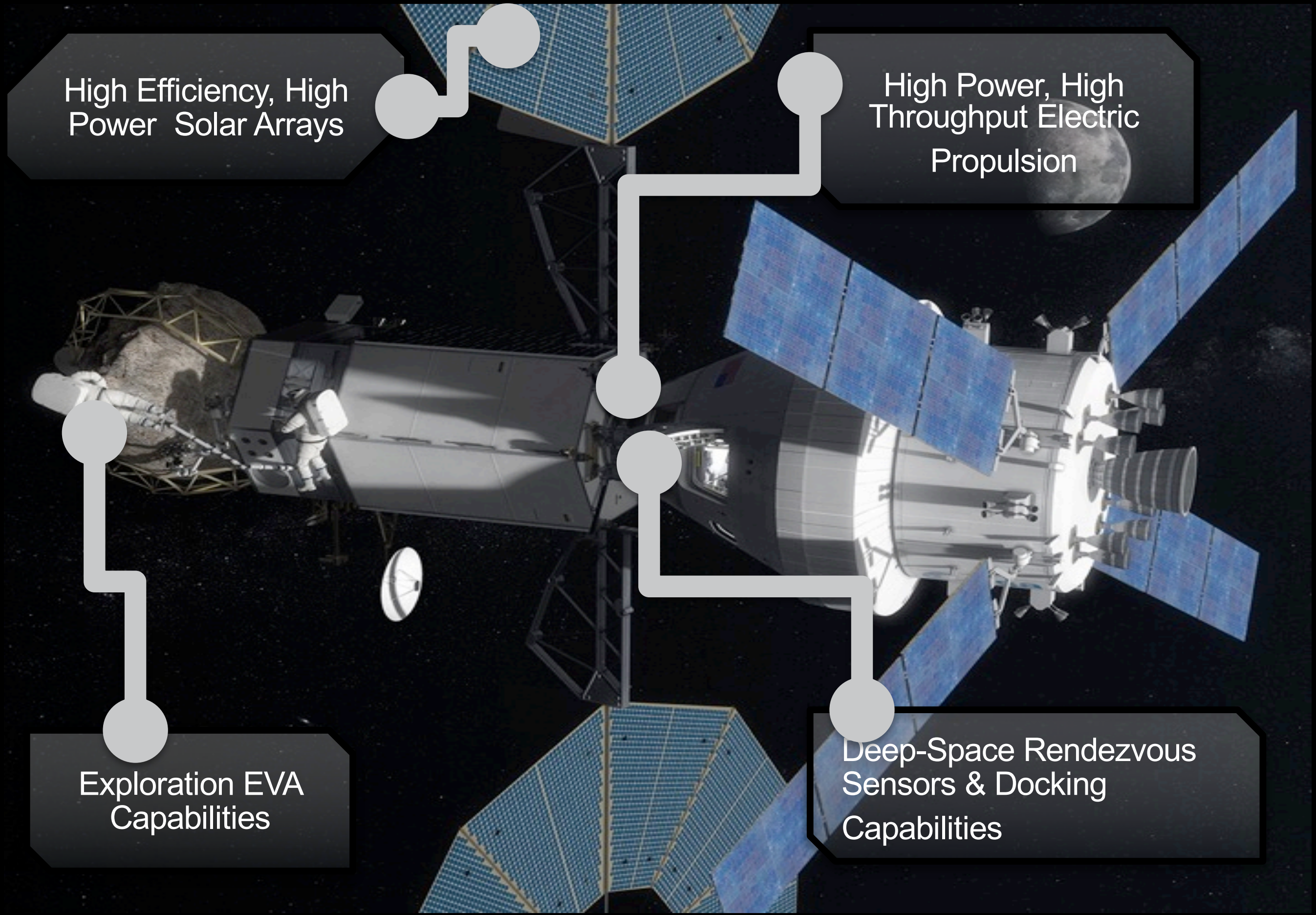
Asteroid Redirect Robotic Mission

Asteroid Redirect Mission (ARM)



"A Capability Driven Mission"

Transporting multi-ton objects with advanced solar electric propulsion

Integrated crewed/robotic vehicle operations in deep space staging orbits

Advanced autonomous proximity operations in deep space and with a natural body

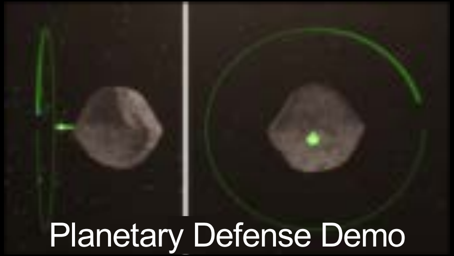
Astronaut EVA for sample selection, handling, and containment

Robotic Segment Boulder Collection Operations Concept

Approach
2 weeks

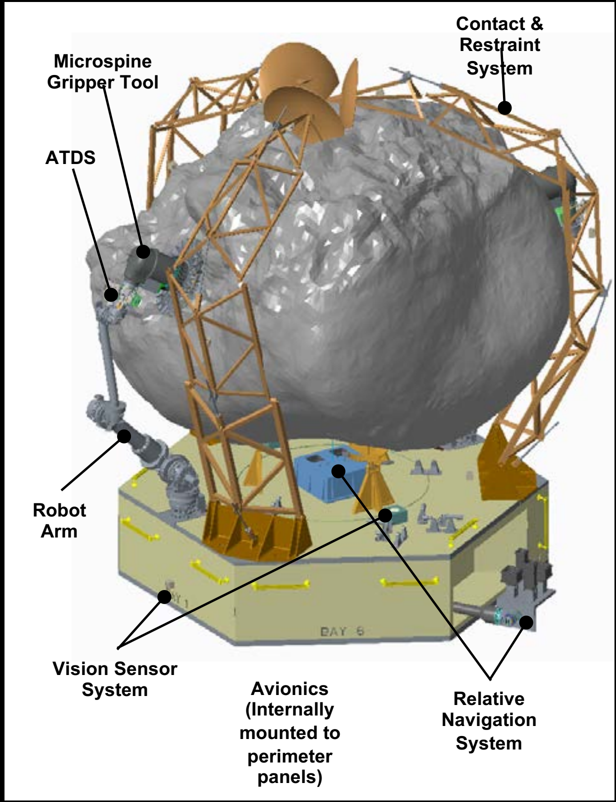
Characterization
2 months

Boulder Collection
~5 hours per attempt, 3 attempts over 2 months



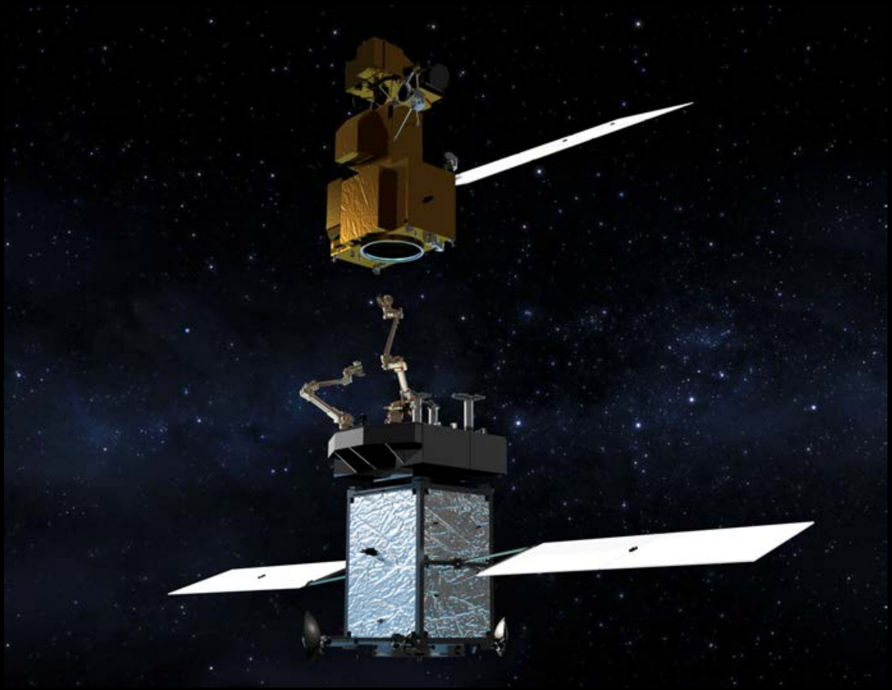
Planetary Defense Demo
5 months

The "Capture" Module



ARM Capture Module (CAPM)

“Capability Driven”

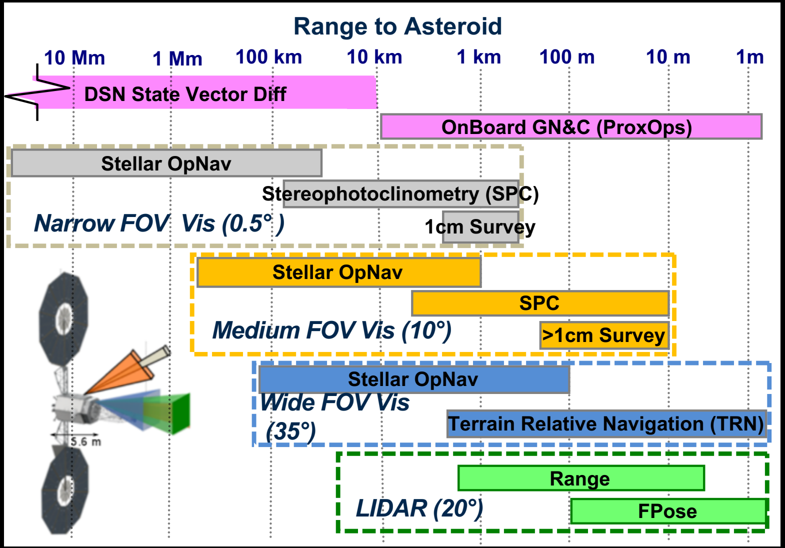


Restore-L Satellite Servicing Mission

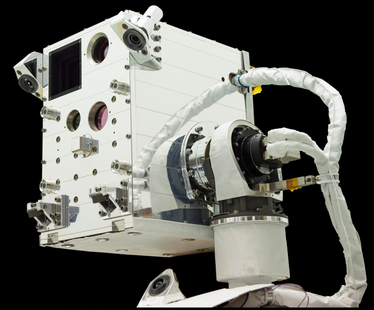
Asteroid Redirect Robotic Mission

Key Challenge 1: Precision Landing

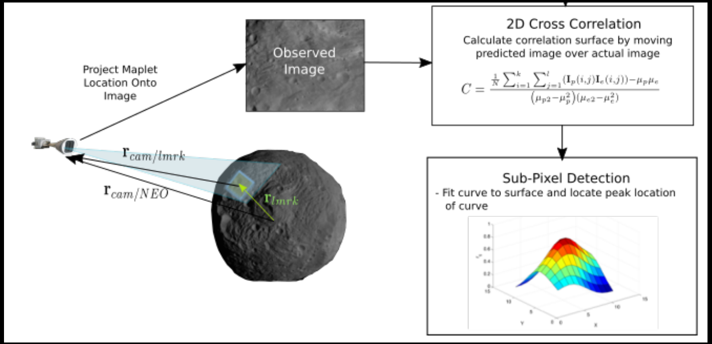
Autonomously land a 10 t vehicle with 50 m solar arrays to a pre-identified target with 50 cm accuracy and 10 cm/s touchdown velocity



ARRM relative navigation sensor ranges



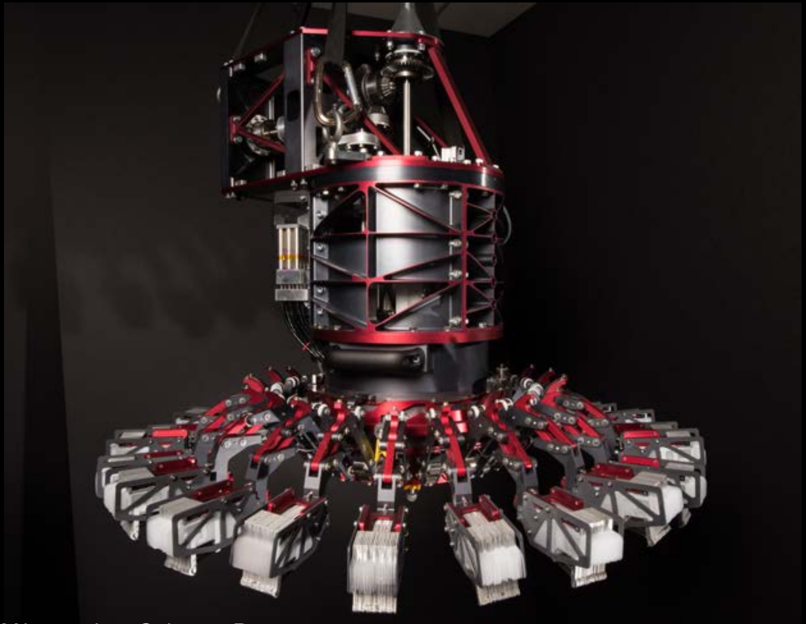
RAVEN Autonomous Rendezvous and Docking (AR&D) demo



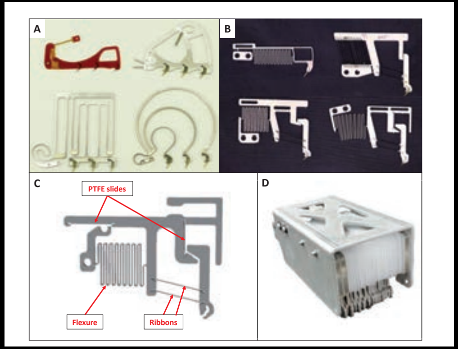
C. Wright, et al "Relative Terrain Imaging Navigation (RETINA) Tool for the Asteroid Redirect Robotic Mission (ARRM)", AAS GN&C 2016

Key Challenge 2: ”Docking” to Boulder

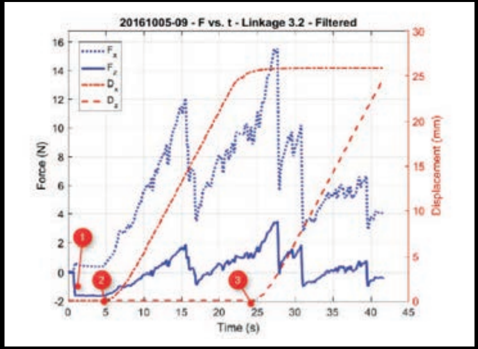
Autonomously grasp and anchor to natural rock surface



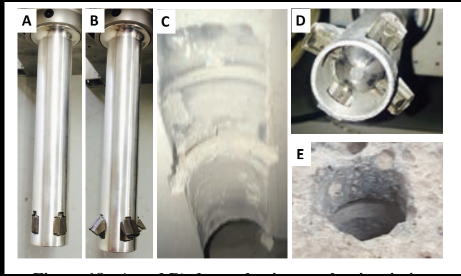
Microspine Gripper Prototype



Microspine design evolution



Microspine performance testing

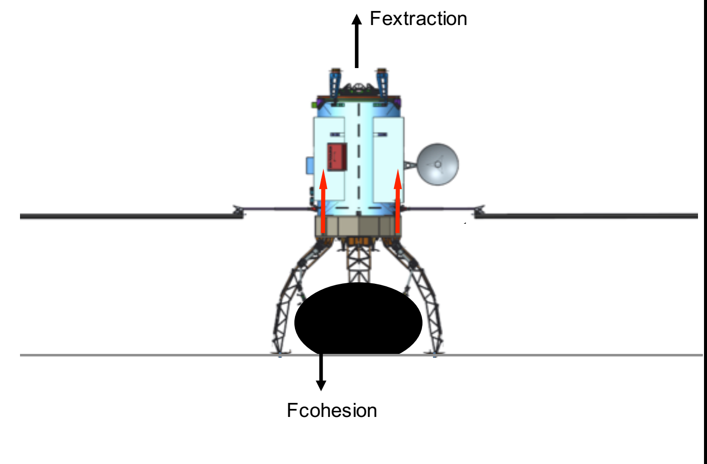


Drill anchor testing

A. Parness et al, “A Microspine Tool: Grabbing and Anchoring to Boulders on the Asteroid Redirect Mission”, IEEE Aerospace 2017

Key Challenge 3: Boulder Extraction

Autonomously extract the boulder breaking attachment / cohesion to surface



Forces during extraction

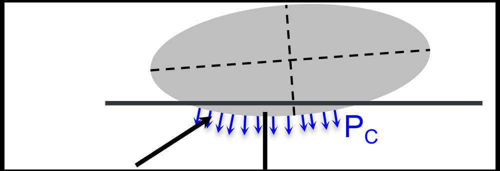
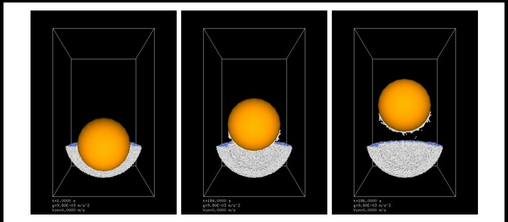


Illustration of surface area in contact



DEM simulation of boulder extraction, Sanchez and Sheeres 2014

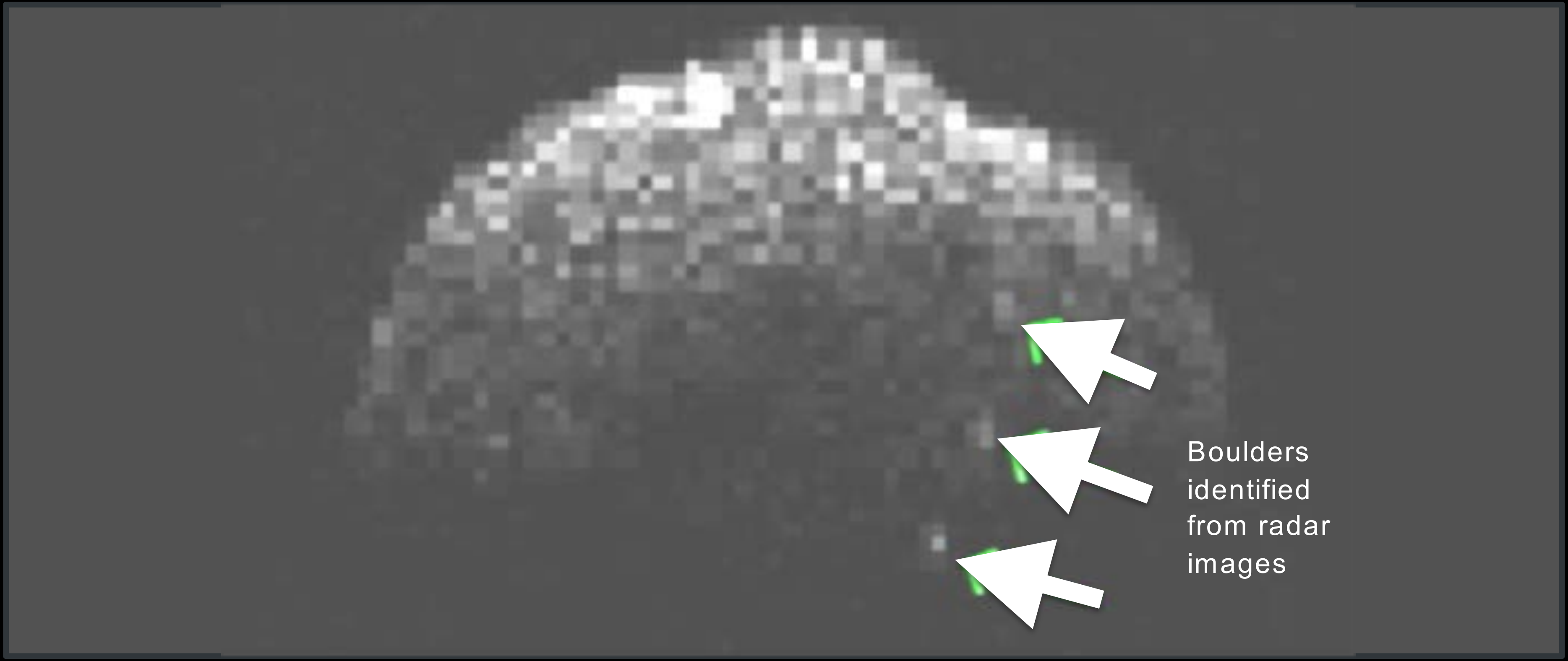
$$F_{cohesion} = S_{boulder\ in\ contact} * P_{cohesion}$$

$$\text{For } P_{cohesion} = 25 - 250 \text{ Pa}$$

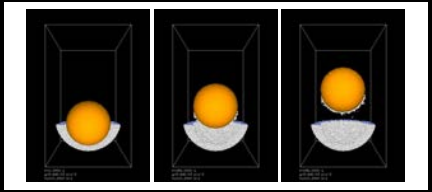
$$F_{cohesion} \sim= 500 \text{ N}$$

Classical calculation of required extraction force

Reference Target 2008 EV_5

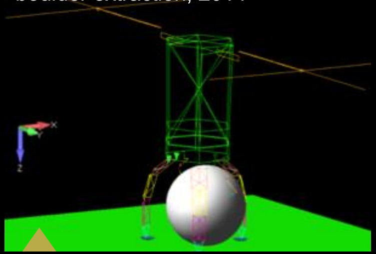


Heritage Capabilities, Uncertain Environments, Evolving Requirements

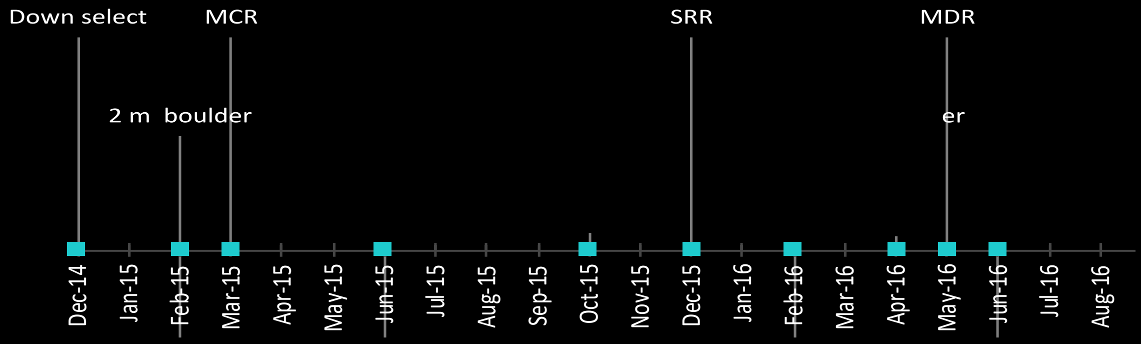


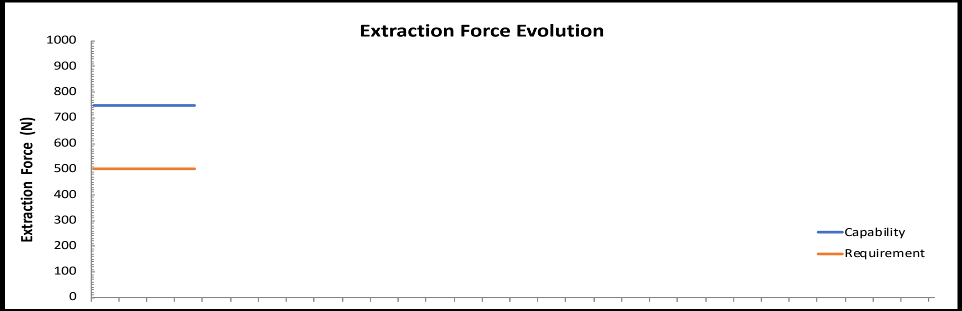
DEM simulation of boulder extraction, Sanchez and Sheeres 2014

KSC Swamp Works full-scale testing of boulder extraction, 2014

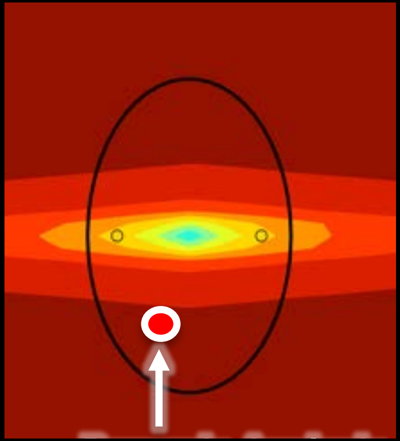


ADAMS simulations of extraction fore capability, 2014

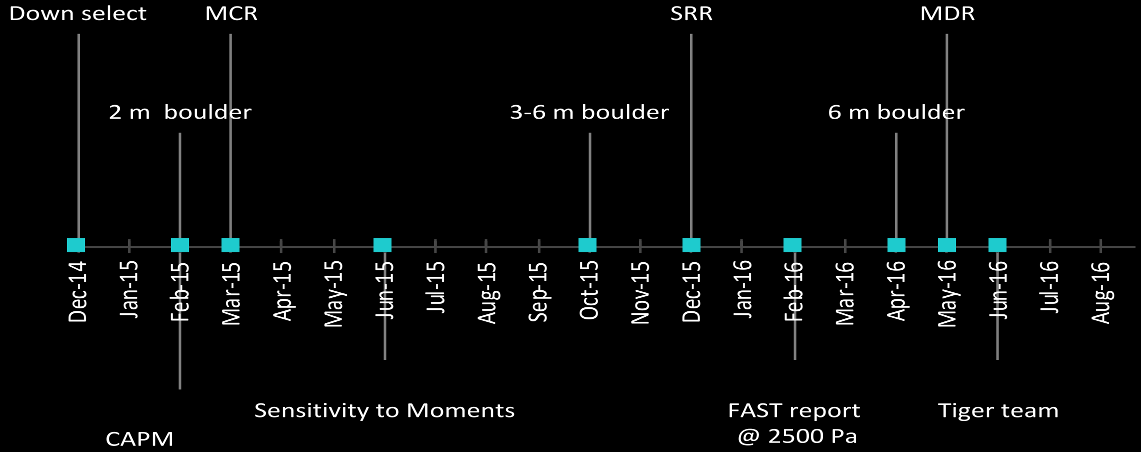


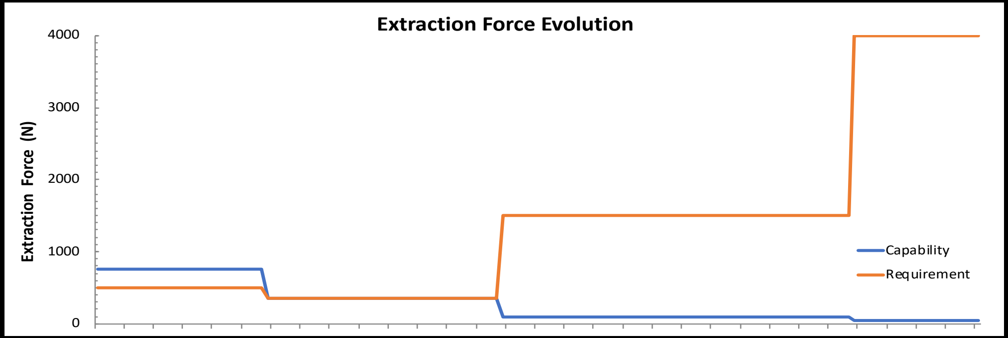


Heritage Capabilities, Uncertain Environments, Evolving Requirements

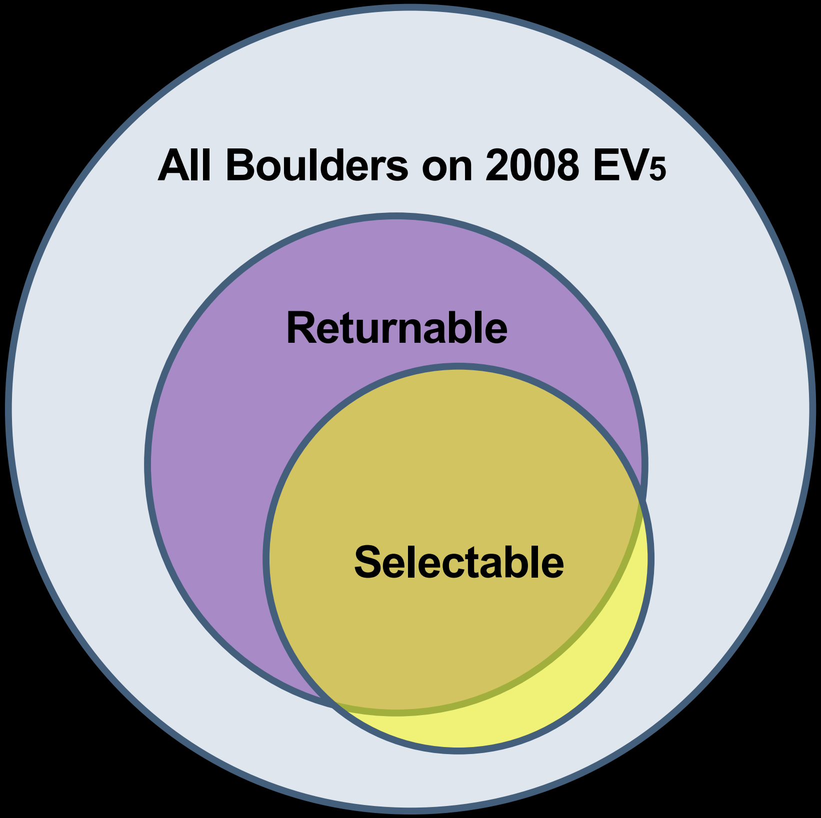


Sensitivity to cohesion offset





Mission Performance Monte Carlo Analysis



We need to analyze the probability of success – that we *find, extract,* and *return* a boulder of the required size

Simple Monte Carlo analysis would estimate by iteratively evaluating a randomly selecting boulder. However this is not correct because the mission will get to select the boulder to extract

When we model selection, we need to take into account uncertainty in knowledge, and the conservatism of the operations team – won't select a boulder unless there is a high confidence we will be successful. Thus *selectable* not a proper subset of *returnable*

$$P_{success} = P(Returnable \mid Selectable) * P_{one\ selectable}$$

where

$$P_{returnable} = \text{Probability a boulder can be extracted and returned}$$
$$P_{selectable} = \text{Probability a boulder would meet selection criteria (95\%)}$$
$$P_{one\ selectable} = [1-(1-P_{selectable})]^{\text{number of boulders}}$$

Probability of success formulation

Mission Performance Scorecard

<table>
<tr><th rowspan="2">Boulder Size</th><th colspan="4">100 N</th><th colspan="4">200 N</th><th colspan="4">500 N</th><th colspan="4">1500 N</th></tr>
<tr><th>CI</th><th>CM</th><th>CK</th><th>CR</th><th>CI</th><th>CM</th><th>CK</th><th>CR</th><th>CI</th><th>CM</th><th>CK</th><th>CR</th><th>CI</th><th>CM</th><th>CK</th><th>CR</th></tr>
<tr><td>1 m +0.5 m</td><td colspan="4">Robust</td><td colspan="4" rowspan="2">Robust</td><td colspan="4" rowspan="3">Robust</td><td colspan="4" rowspan="3">Robust</td></tr>
<tr><td>2 m +/- 0.5 m</td><td colspan="4">Some</td></tr>
<tr><td>3 m +/- 0.5 m</td><td colspan="4" rowspan="2">No Capability
Force Limited</td><td colspan="4">Some</td></tr>
<tr><td>4 m +/- 0.5 m</td><td colspan="4">No Capability</td><td>M</td><td>M</td><td>N*</td><td>N*</td><td>R</td><td>S*</td><td>N*</td><td>N*</td></tr>
<tr><td>5 m +/- 0.5 m</td><td colspan="16" rowspan="2">No Capability*
Mass Limited</td></tr>
<tr><td>6 m - 0.5 m</td></tr>
</table>

Key Assumptions

99% number of boulder estimates derived from radar data and SFD

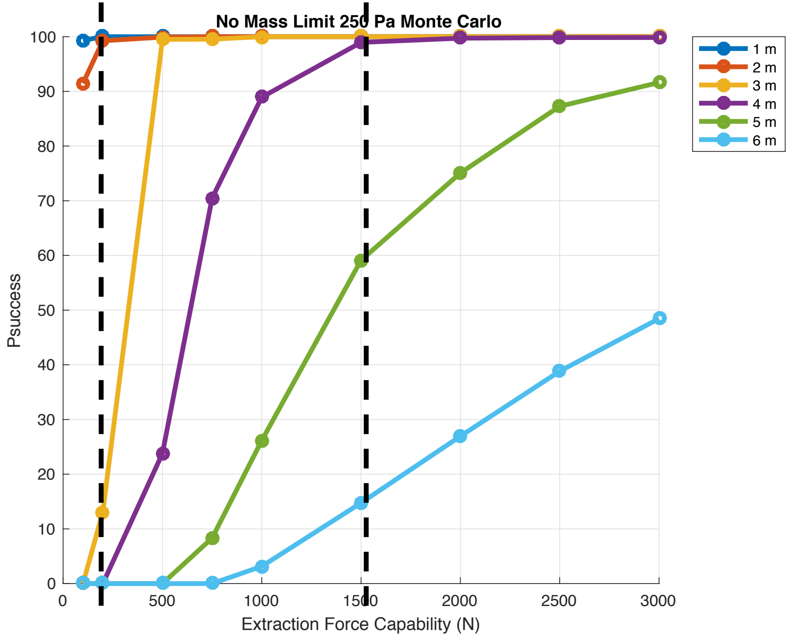
Maximum return mass of 20 t
Cohesion range 25-250 Pa
Depth-of-Bury range 5%-75%

Size estimation accuracy 2 cm length/width 3 cm height for DOB < 25%
95% estimate of P(success) required for selection

Able to determine spectral type and select boulder after arrival at asteroid
Results categorized based on density range for C-type sub-types: CI, CM, CK, CR

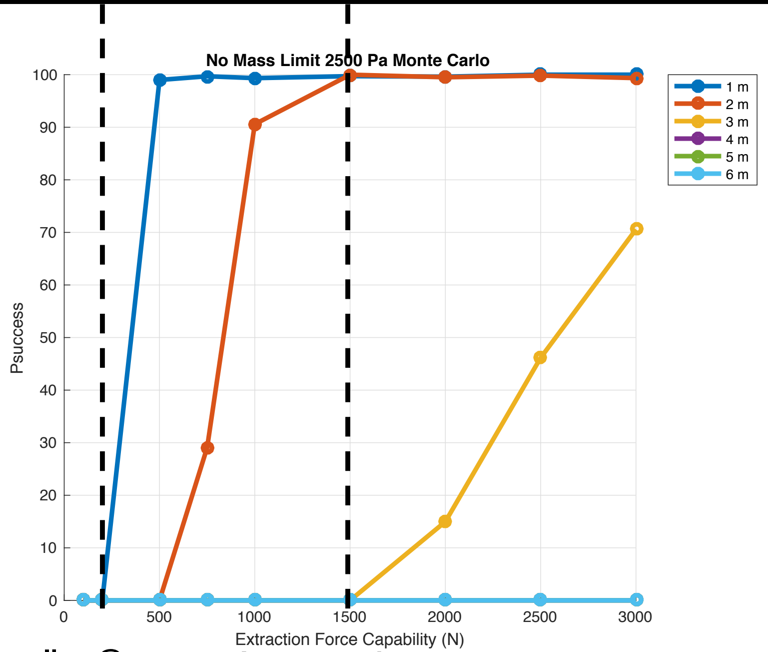
Robust capability, P(s) > 95%
Some capability, P(s) ~50-95%
Marginal capability, P(s) ~10-50%
No capability, P(s) < 10%
* Limited by return mass

Sensitivity Analyses to Establish Robustness



Baseline @ 200 N = 2 m

Augmentation @ 1500 N = 4 m

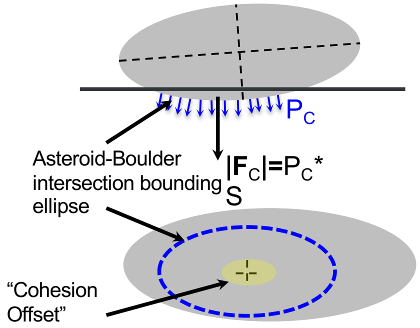


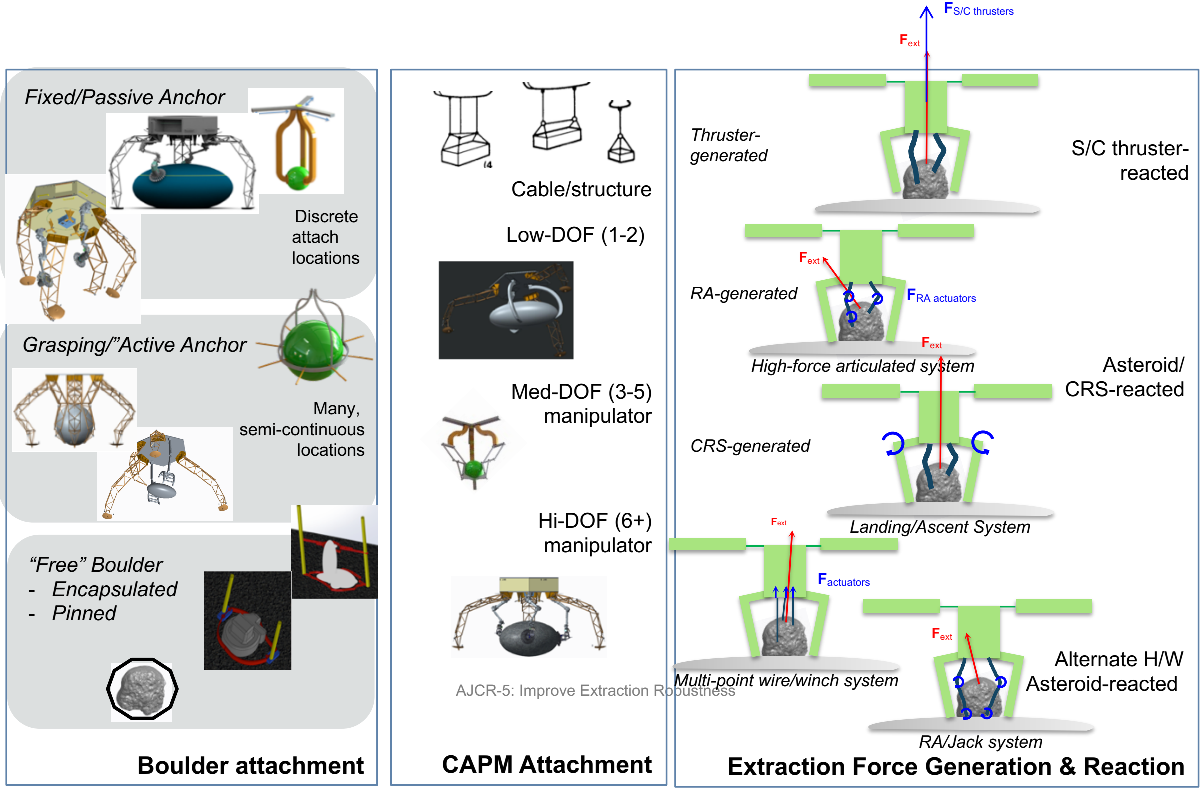
Baseline @ 200 N = no

Augmentation @ 1500 N = 2 m

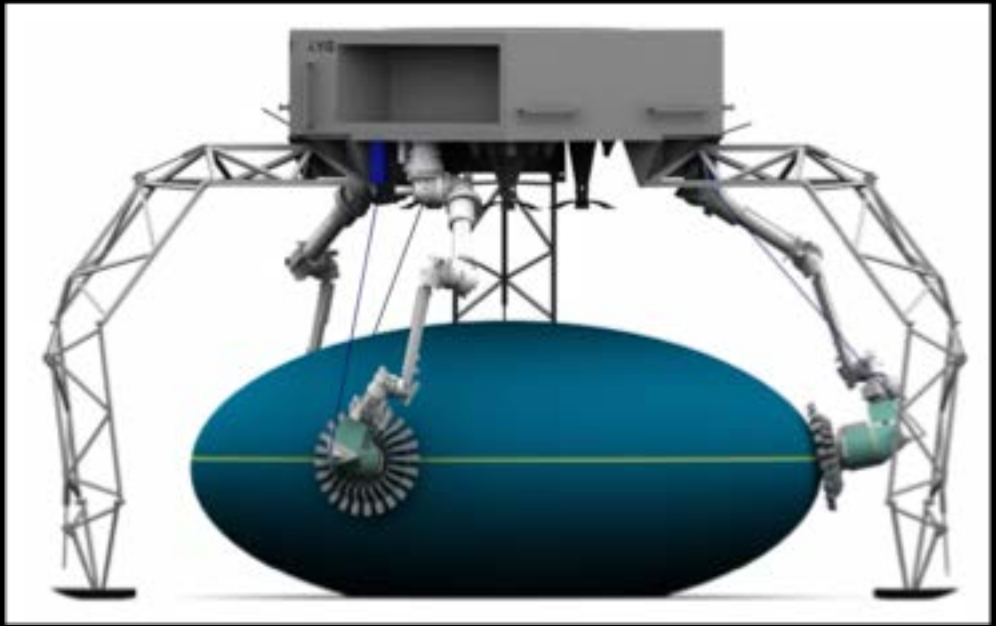
An extraction force level of 1500 N provides 4 m nominal and 2 m off-nominal capability

Augmentation Trade Space





Augmented Capture Module



CAPM PDR baseline with 3 arms and load bypass cables

Mission Performance analyses created a common language to discuss the expected size of boulder the mission could return given a capability level of the capture system

Stakeholders agreed to update requirements to reflect capability of 3 m boulder

Capture Module team in turn augmented Capture Module design with additional robot arm and load bypass cables in order to robustly meet 1500 N extraction force requirement

Updates to requirements and design retired major implementation risk, and put the team on a credible path towards PDR

Summary

ARRM had a number of technologies under development which could be useful for future small body and planetary mission concepts

The Autonomous Rendezvous and Docking and in space assembly communities are maturing technologies that can be very useful for planetary exploration

Be conservative in claims of heritage, wary of capability-driven missions with with evolving performance requirements, and open to starting over again from a blank sheet of paper

NASA