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

15th International Planetary Probe Workshop

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Asteroid Redirect Mission (ARM)

High Efficiency, High Power Solar Arrays

High Power, High Throughput Electric Propulsion

Deep-Space Rendezvous Sensors & Docking Capabilities

Exploration EVA Capabilities

“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

15th IPPW - Key Challenges in Capturing a Boulder for the Asteroid Redirect Robotic Mission
Capture Module – Capabilities and Key Challenges

Built from capabilities under development for robotic satellite servicing and on-orbit assembly

Characterize surface of asteroid at 10 cm resolution

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

Autonomously grasp and anchor to natural rock surface

Autonomously extract the boulder breaking attachment / cohesion to surface

Autonomously depart asteroid

Defend the planet
Reference Target 2008 EV$_5$

Boulders identified from radar images
Significant uncertainty in understanding of C-type asteroid properties, including the quantity, accessibility, strength, and surface cohesion of boulders.

Evolution in mission objectives from original capability-driven 2-3 m boulder estimate, to a Level-1 requirement for returning a 6 m boulder.

Key forces and moments during extraction:

\[
F_{\text{cohesion for 6m boulder}} = A_{\text{worst case surface in contact}} \times P_{\text{worst case cohesion}} \\
\approx 6000 \text{ N}
\]

\[
F_{\text{extraction}} = 2F_{\text{cohesion}} = 12000 \text{ N}
\]

Classical calculation of required extraction capability given 6 m requirement.
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*.

\[
P_{\text{success}} = P(\text{Returnable}|\text{Selectable}) \times P_{\text{one selectable}}
\]

where
\[
P_{\text{one selectable}} = [1-(1-P_{\text{selectable}})^{\text{number of boulders}}]
\]

Probability of success formulation.
## Mission Performance Scorecard

<table>
<thead>
<tr>
<th>Boulder Size</th>
<th>100 N</th>
<th>200 N</th>
<th>500 N</th>
<th>1500 N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CI</td>
<td>CM</td>
<td>CK</td>
<td>CR</td>
</tr>
<tr>
<td>1 m +0.5 m</td>
<td>Robust</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 m +/- 0.5 m</td>
<td>Some</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 m +/- 0.5 m</td>
<td>No Capability</td>
<td>Some</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 m +/- 0.5 m</td>
<td>No Capability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 m +/- 0.5 m</td>
<td>No Capability*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 m - 0.5 m</td>
<td>No Capability*</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</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

- 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

An extraction force level of 1500 N provides 4 m nominal and 2 m off-nominal capability.
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 3-4 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.
Supplementary Material
ARRM Reference Target 2008 EV5
Capture Module Mockup
Reference ARV

**MegaFlex Reference Array:**
~20 m wing tip to base

**Capture Module:** (GSFC provided)
Robotics to support landing and capture Boulder

**Solar Electric Power/Propulsion Module:** (SePPM), S/C from Industry provider TBD
Hosts core spacecraft housekeeping functions, GN&C, and Ion Propulsion System

**Electric Propulsion Engines and Power Processors:** (Aerojet Corp provided, thru GRC)
Four 13 kW engines using 5 t of Xe propellant

**ROSA Reference Array:**
~25 m wing tip to base
Augmentation Trade Space

Fixed/Passive Anchor
- Grasping/Active Anchor
  - "Free" Boulder
    - Encapsulated
    - Pinned

Boulder attachment

CAPM Attachment

Extracting Force Generation & Reaction

Thrust-generated
- S/C thrust-reacted
- Asteroid/CRS-reacted
- CRS-generated

RA-generated
- High-force articulated system

Landing/Ascent System
- Multi-point wind/winch system
- Alternate H/W Asteroid-reacted

AJCR: Improve Extraction Robustness
Example

N = 1000
N(R) = 500
N(S) = 100
N(SR) = 1

Psel = 100/1000 = 10%
Psr = 1/1000 = 0.1 %

P1sel = 1-(1-Psel)^1000
P1sel = 0.999999
P(R|SEL) = 1/100 = 1%
Ps = P1sel*P(R|SEL) = 1%

Note, this would be wrong:

Ps = 1-(1-Psr)^1000
Ps = 63.23%