National Aeronautics and Space Administration

Asteroid Redirect Mission
Asteroid Operations Phase

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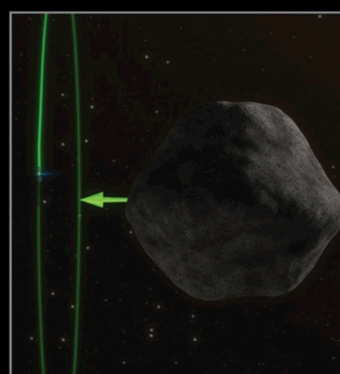
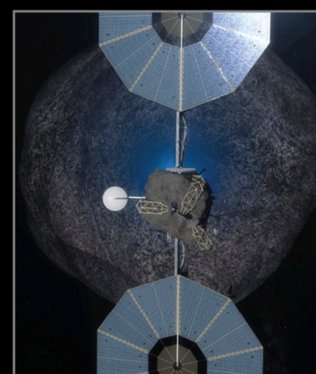
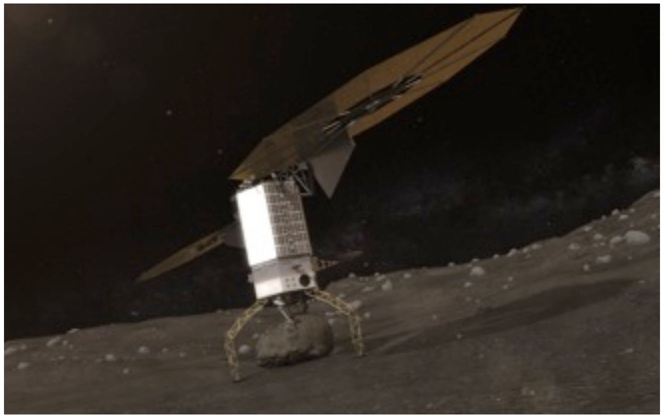
13th Meeting of the NASA Small Bodies Assessment Group

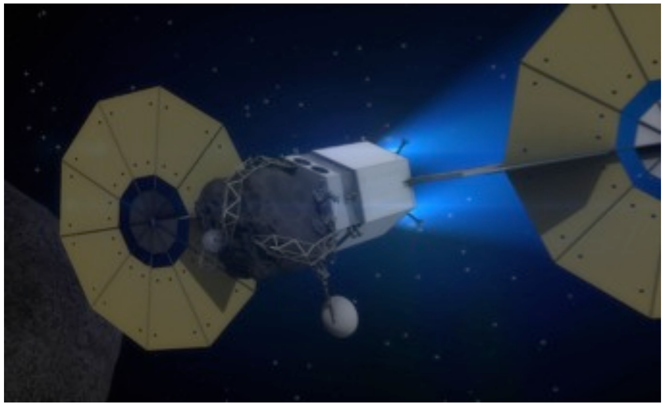
June 29, 2015

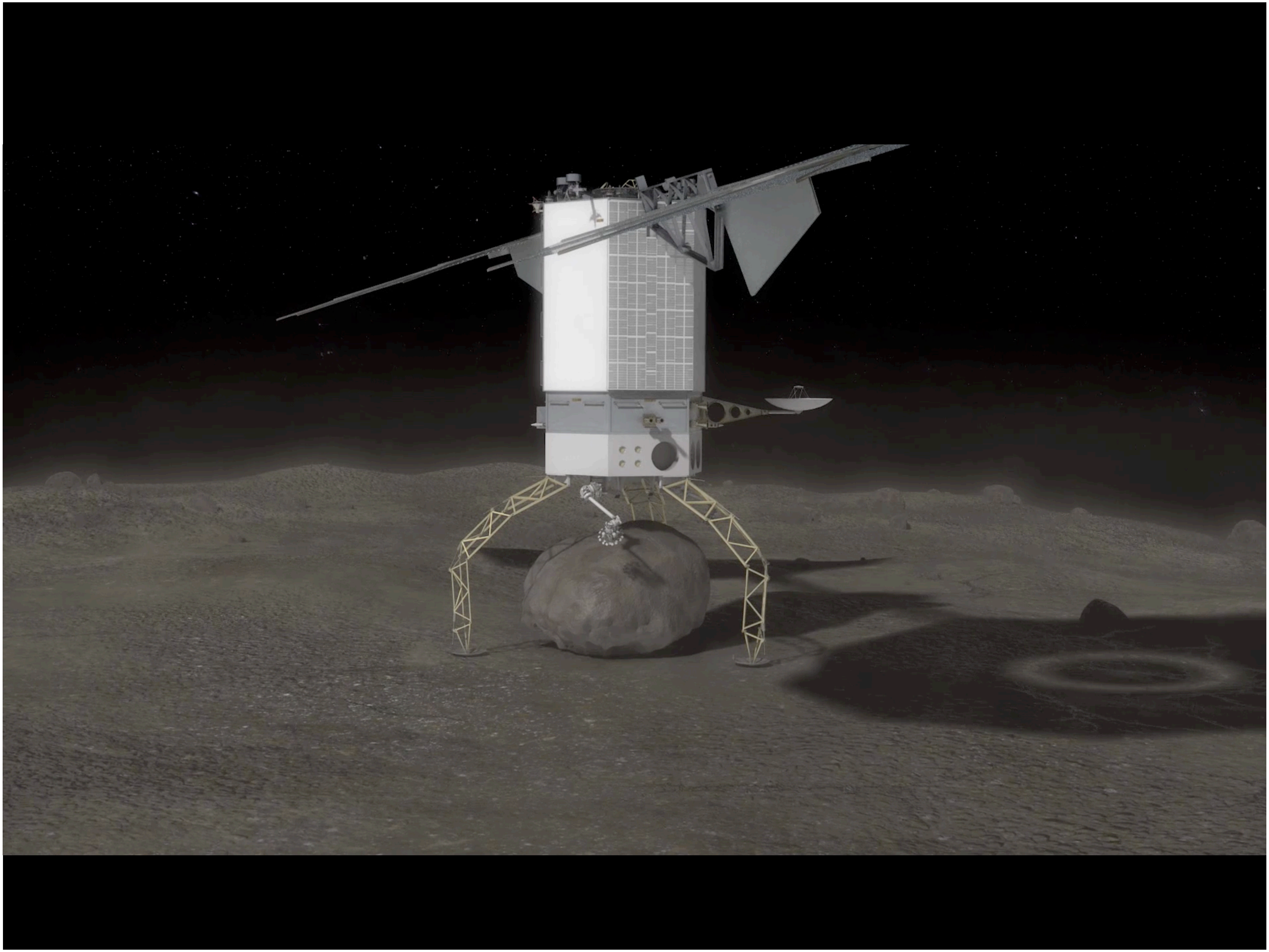

Introduction

- ARRM completed MCR February 2015
- Option to capture a boulder from a PHA-sized target asteroid selected to proceed into Phase A
- Key mission dates
  - Launch December 2020
  - Available for crewed mission 2025



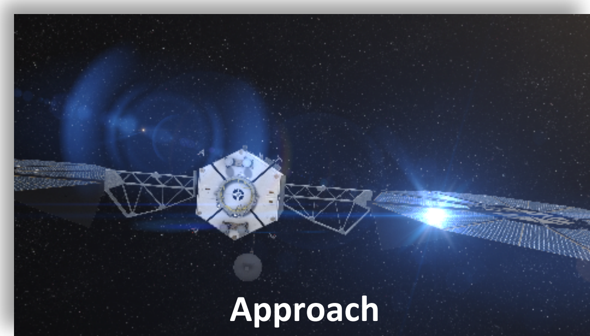


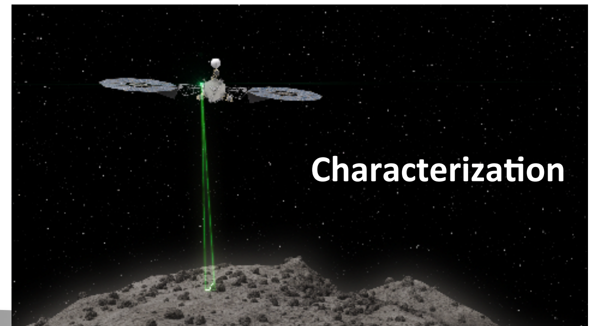
- **Outline of Briefing**
  - Asteroid Operations Phase overview and animation
  - Capture Module overview
  - Summary of significant capture system risks, uncertainties, sensitivities
  - Technology development status



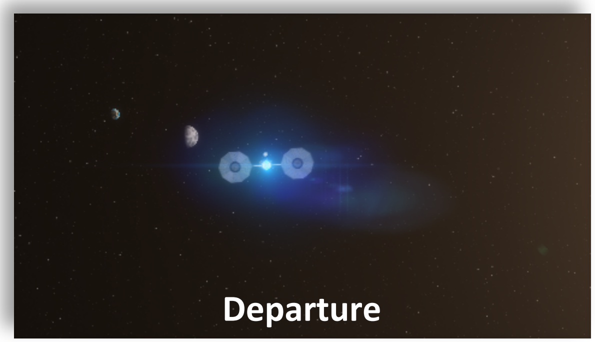
Asteroid Operations Phase Overview

Approach	Characterization	Boulder Collection	Planetary Defense Demo
2 weeks	2 months	2.5 months (allocated)	5 months



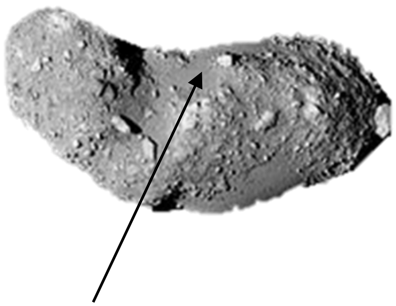


Note: Asteroid operations timeline varies depending on target asteroid. Times shown are for 2008 EV_5: total stay time of 305 days with an additional 95 days of margin.



Candidate Parent Asteroids

ITOKAWA

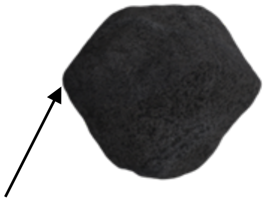


Muses C –
Hayabusa landing

BENNU

Radar –
OSIRIS-REx target

2008 EV5



Radar – boulders and extremely pronounced bulge at equator suggests movement of loose material

1999 JU3

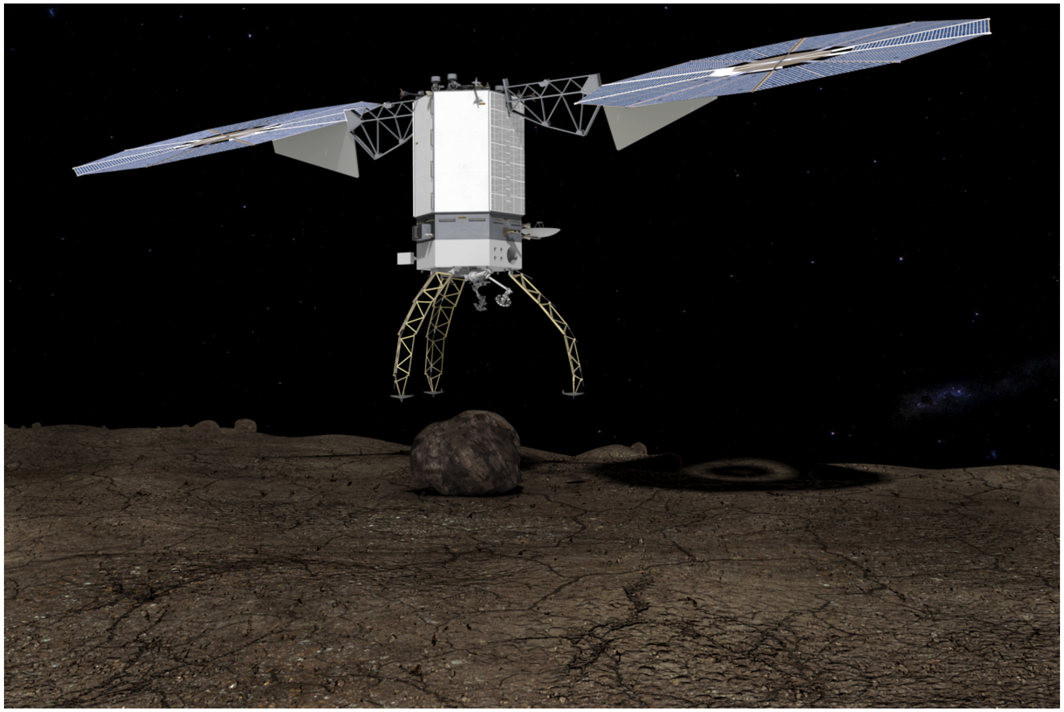
Expected valid target.
Low resolution radar –
Hayabusa 2 target

Asteroids not to scale

Comparison of reference parent asteroids

	Itokawa	Bennu	2008 EV_5	1999 JU_3
Size	535 x 294 x 209 m	492 x 508 x 546 m	420 x 410 x 390 m	870 m diameter
V_∞	5.68 km/s	6.36 km/s	4.41 km/s	5.08 km/s
Aphelion	1.70 AU	1.36 AU	1.04 AU	1.42 AU
Spin Period	12.13 hr	4.297 hr	3.725 hr	7.627 hr
Type	S	B (C-grp volatile rich)	C (volatile rich)	C (volatile rich)
Precursor	Hayabusa (2005)	OSIRIS-REx (9/2016 launch, 8/2018 arrival)	None currently planned (boulders implied from 2008 radar imaging)	Hayabusa 2 (launched 12/4/2014, 7/2018 arrival)

Approach, Descent, and Landing



Asteroid Redirect Vehicle (ARV) landing on the asteroid surface

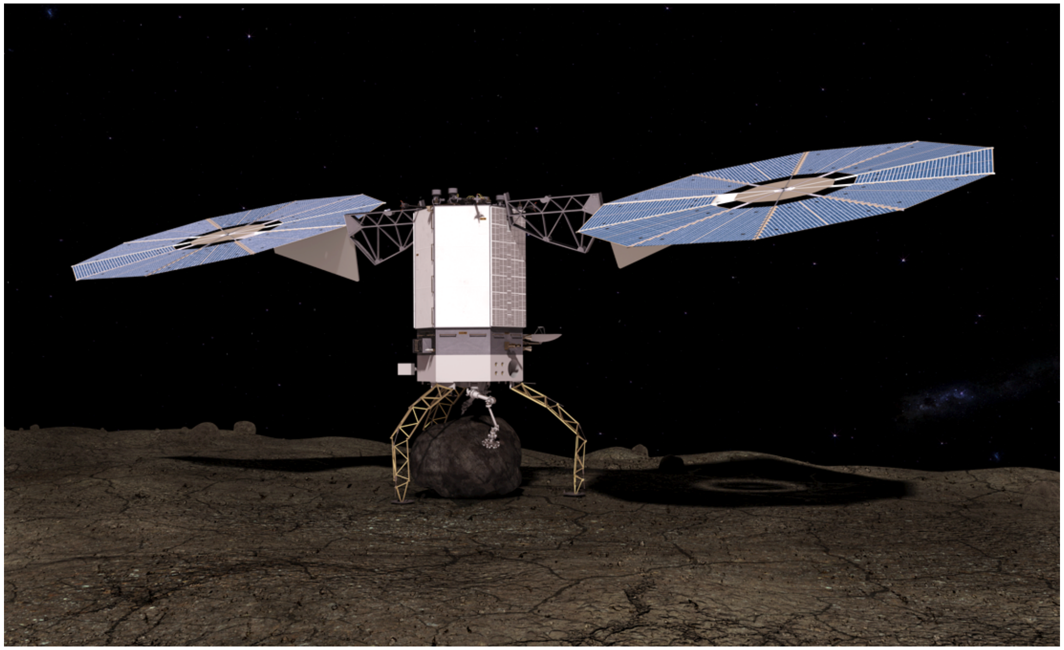
Approach and Characterization

- *Approach*
  - 1,000 to 100 km at ~45 degree sun angles
  - Refine initial shape and gravity models
- *Characterization*
  - Six fly-bys at 1 km close approach
  - 1 cm resolution imagery and detailed gravity model
  - Characterize parent asteroid and select 3 candidate boulders

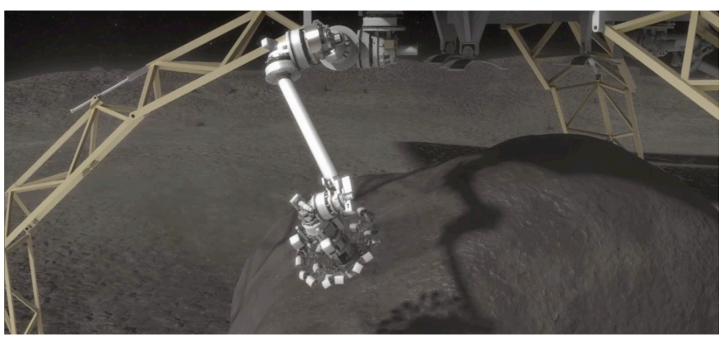
Descent and Landing

- Closed-loop autonomous descent and landing with 2 “dry runs” within 50 m of surface
- Descent over boulder using Terrain Relative Navigation (TRN) based on wide field of view camera images and LIDAR measurements
- Contact and Restraint Subsystem (legs) attenuates touchdown loads
  - Max touchdown velocity: 11 cm/s
  - Touchdown accuracy: 50 cm

Surface Operations



Asteroid Return Vehicle (ARV) on surface with deployed robot arm

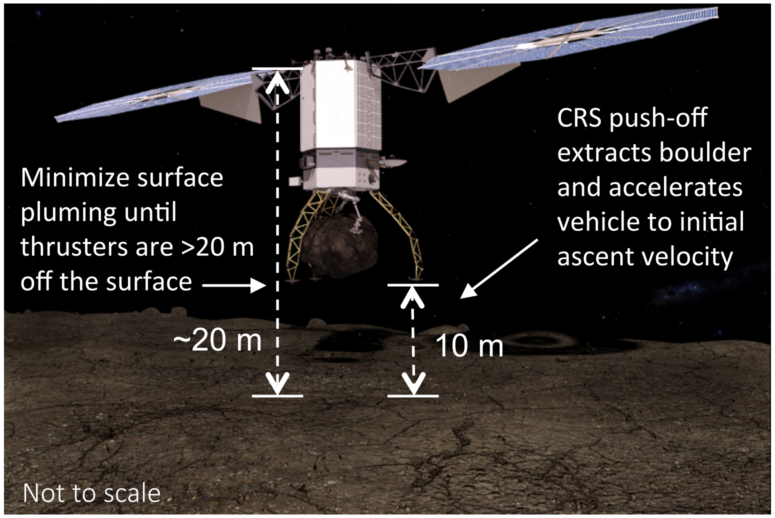


Boulder capture with Microspine tool

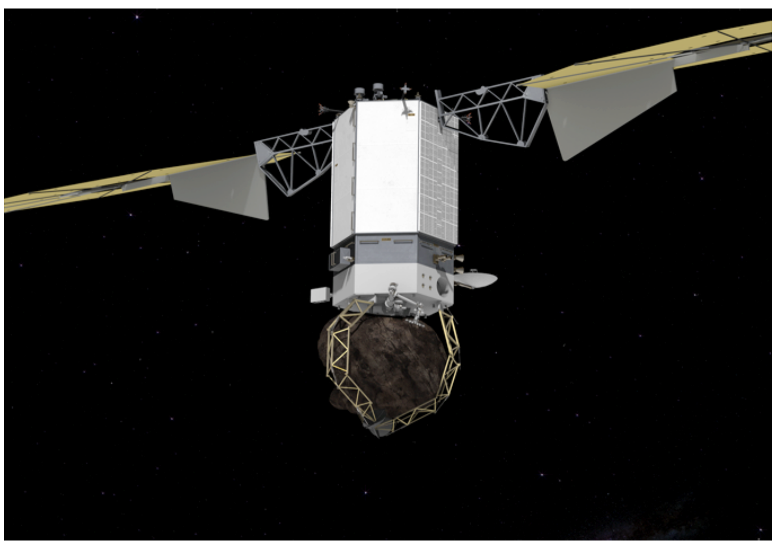
Surface Operations

- Capture multi-ton boulder from the surface
- After landing, vehicle thrusts into surface to maintain contact and increase stability
- Robotic arms are moved one at a time until contact with a maximum contact speed of 1 cm/s
- Contact points are approximately 180 degrees apart with the height of contact depending on the size and shape of the boulder
- After each contact, Microspine grippers engage and anchor boulder – process takes less than five minutes
- Once a successful grip and anchoring is detected, the system engages the brakes on the arm joints, and prepares for ascent

Ascent and Restraint



Boulder ascent from surface of the asteroid



Boulder restrained for return cruise

Ascent

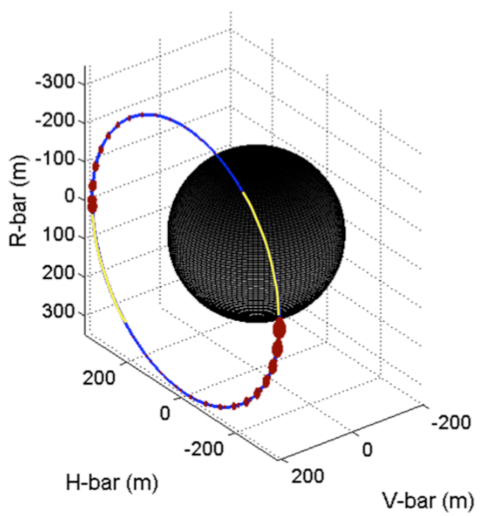
- CRS provides push-off of at least 6 cm/s
- CRS push-off breaks cohesion and provides ascent ΔV in single motion
- Attitude control in rate damping mode
- Minimal surface pluming until a minimum of 10 m off the surface (thrusters are 20 m off surface)
- At 50 m altitude closed loop attitude control is activated and reaction control system provides additional ΔV to achieve escape velocity (ΔV up to 20 cm/s)

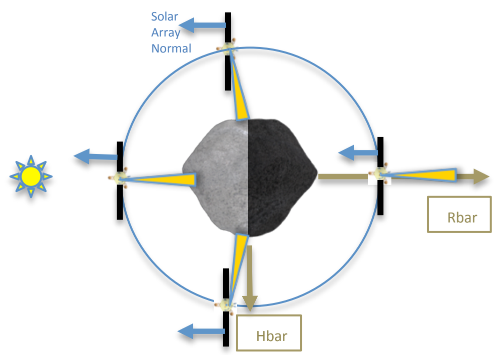
Restraint

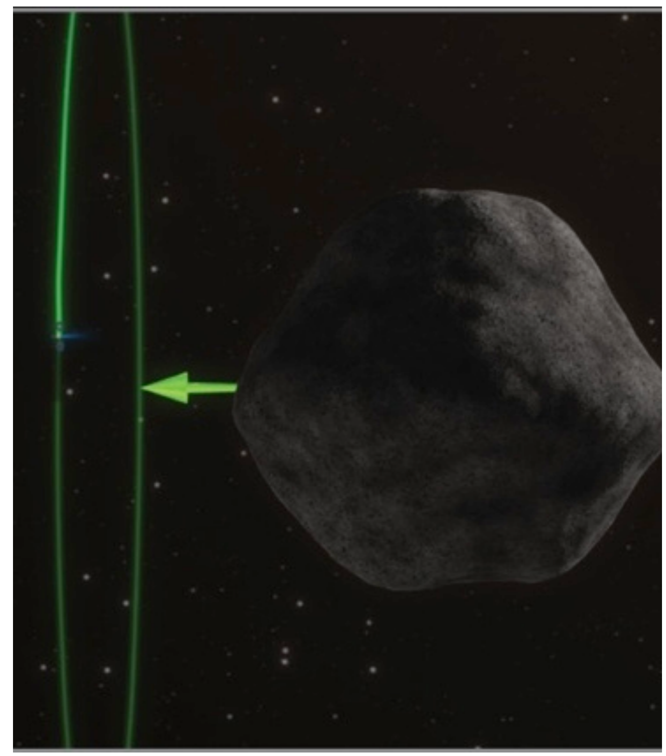
- Over 3 days allowed for ground to analyze collection data and restraint process
- Each step of the restraint process is ground commanded
- One joint of one leg is moved at a time
- Each joint is cycled until contact with all planned segments is achieved
- All joints are tightened to provide small pre-load to finalize a secure restraint
- Full process takes ~30 minutes (operations time only)

Planetary Defense Demonstration

- **Enhanced Gravity Tractor (EGT)**
  - Performed post-boulder collection, boulder provides the “enhanced” mass
  - ARV establishes and maintains halo orbit and/or asteroid-velocity-direction standoff
  - Demonstrates challenging extended duration operations in close proximity
  - Induces a measureable deflection of the parent asteroid
  - Deflection verification can be performed locally with ARV, or potentially with Earth-based radar after the mission

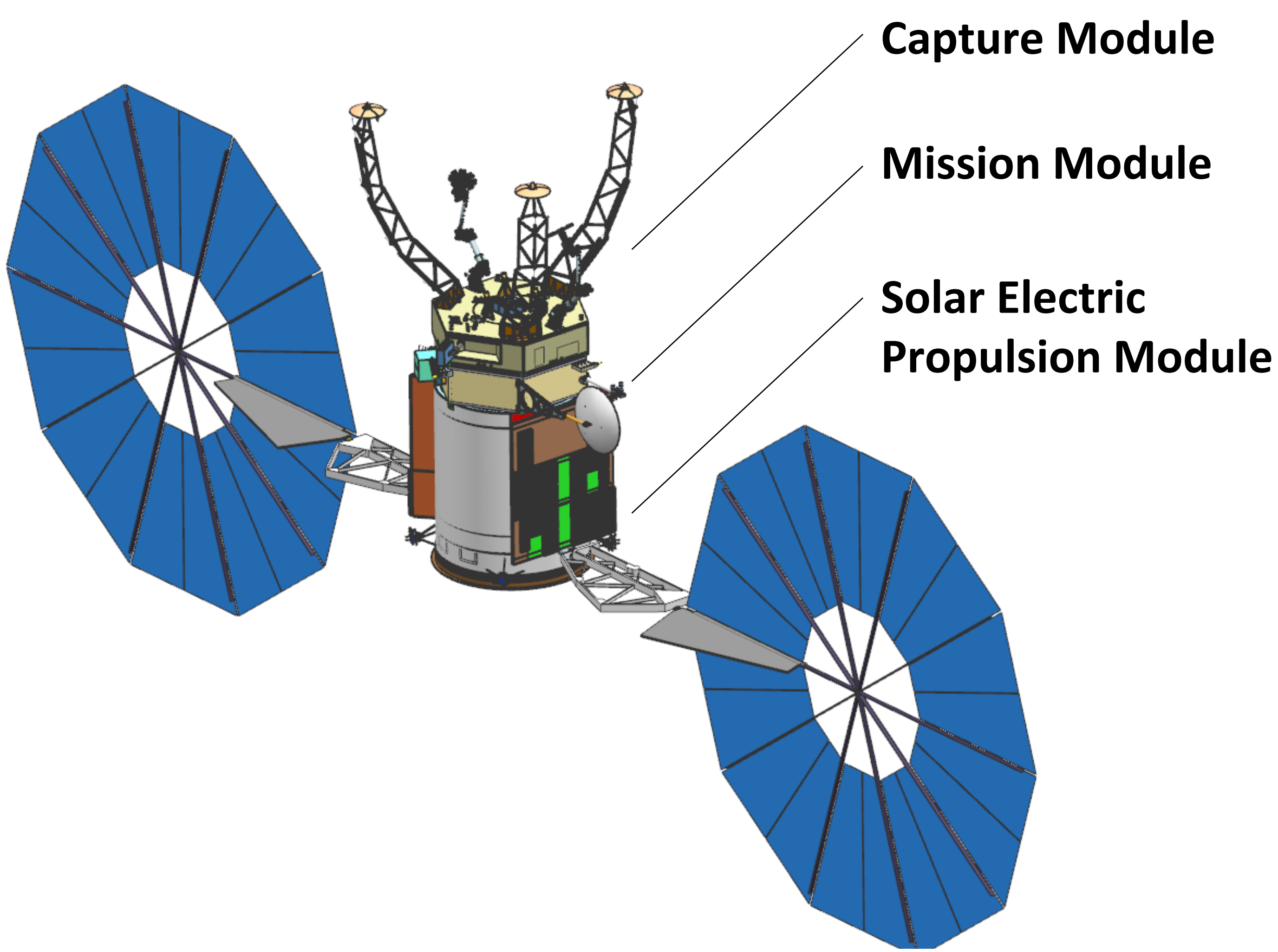




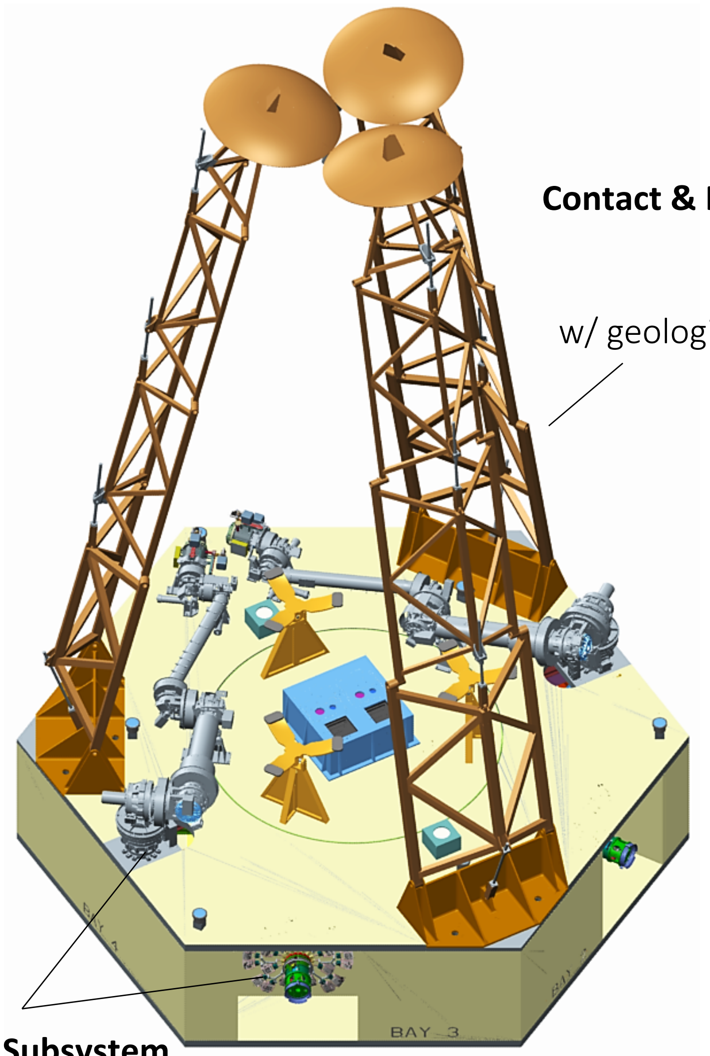


Enhanced Gravity Tractor (EGT)

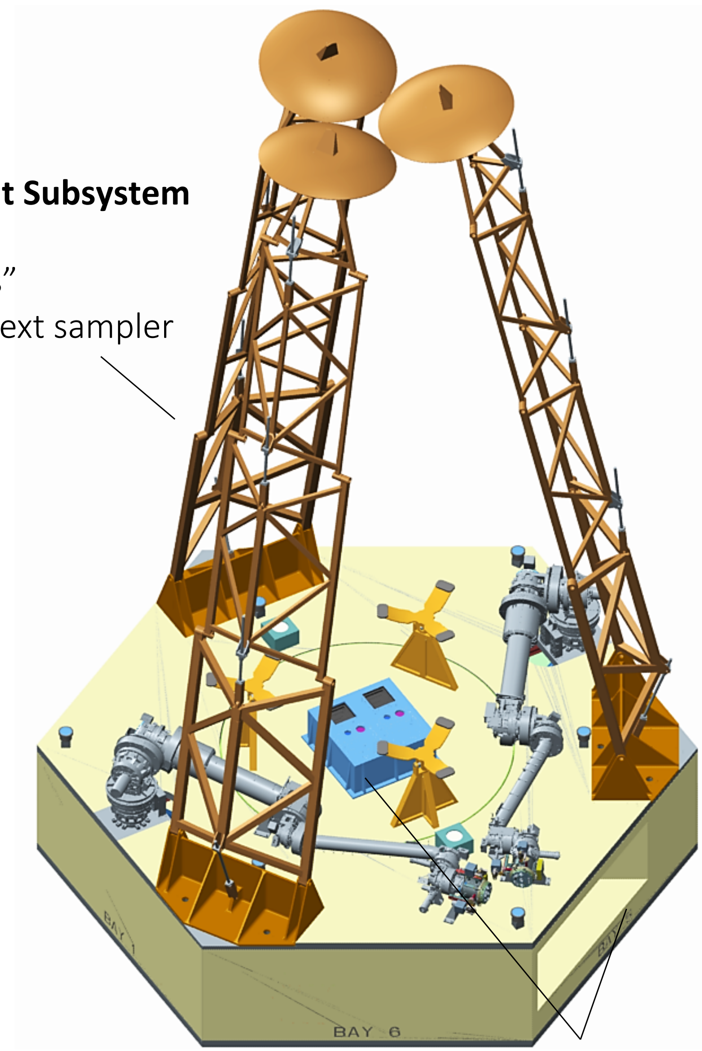
ARRM Concept Vehicle



Capture Module Overview



Contact & Restraint Subsystem (CRS)
3X "legs"
w/ geological context sampler



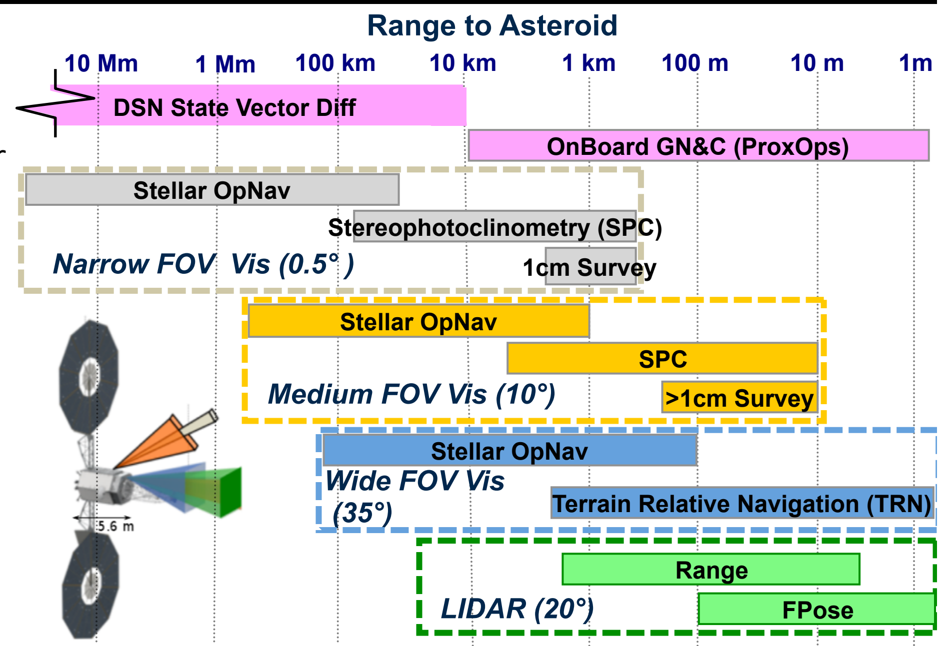
Robot Subsystem
Capture arms (2X)
and tool stowage (2X)

Relative Navigation Subsystem (RNS)
Deck sensor assembly and
gimbal sensor suite (shown stowed)

Relative Navigation Subsystem (RNS)

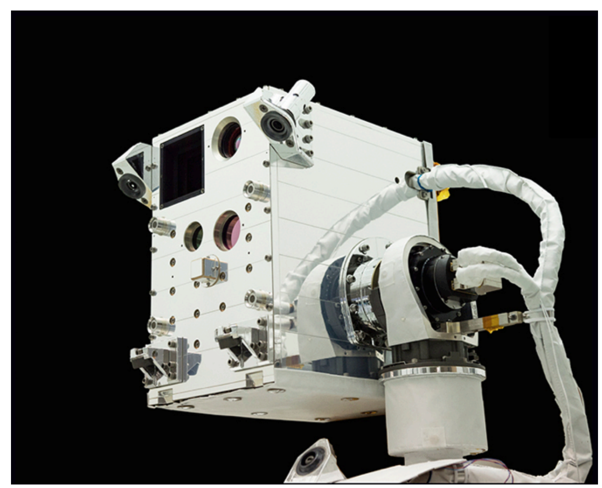
Subsystem overview

- Ground processing: ~1cm res. map of boulder site
- Onboard processing: precision landing over boulder
- Fault tolerant sensors: Narrow (NFOV), Medium (MFOV), and Wide (WFOV) cameras, LIDAR system
- 6-DOF navigation algorithms hosted on hybrid HW/SW compute platform
  - Flash Pose (FPOSE) for use with the 3D LIDAR
  - Terrain Relative Navigation (TRN) for use with optical images
- Two estimation algorithms functionally redundant, providing independent estimates of vehicle state



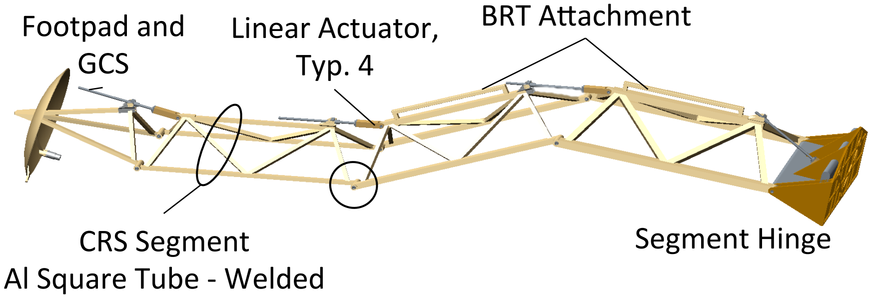
Heritage/technology assessment

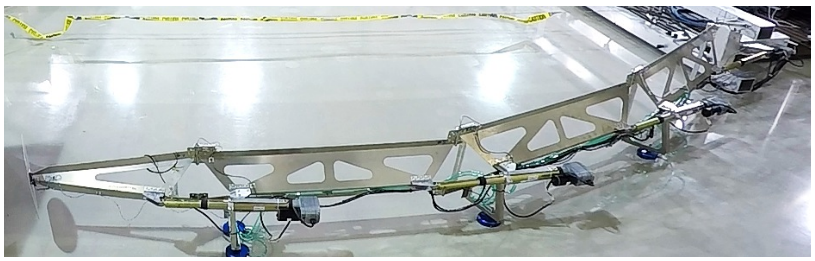
- Sensors will meet NASA Common AR&D Sensor spec
- High Speed Processor, relative navigation filter, FPOSE developed under satellite servicing Raven and Restore missions and directly applicable for ARRM
- Optical TRN derived from ground-based processing used on several missions, leverages Raven/Restore vehicle relative navigation algorithm (GNFIR)



Raven AR&D testbed (will launch to ISS in 2016)

Contact and Restraint Subsystem (CRS)





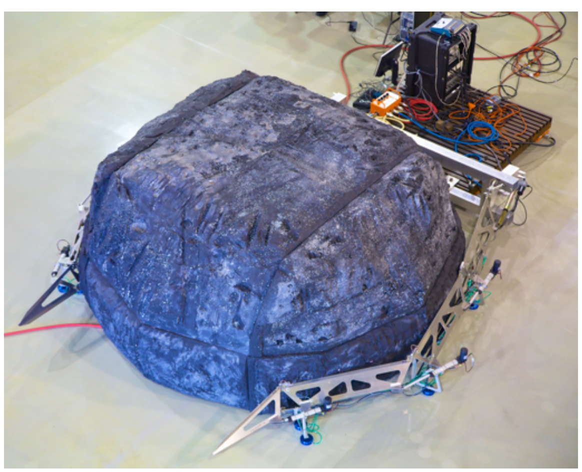
Prototype full-scale CRS limb

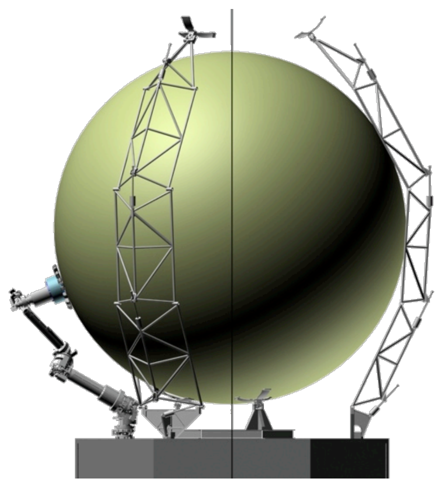
Subsystem overview

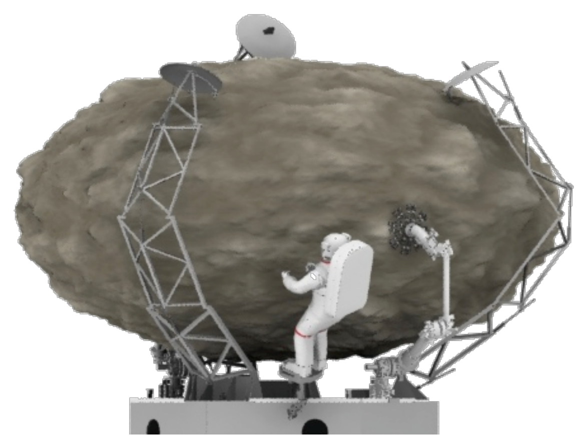
- Performs touchdown, ascent, and boulder restraint
- Three 4-DOF ~5 meter long truss legs with integrated linear actuators
- Footpads with accommodation for Geological Context Sampler (GCS)
- Designed to accommodate crew translation, including Body Restraint Tether (BRT) attachments

Heritage/technology assessment

- No new technologies required for implementation
- Design allows 1g engineering performance testing and validation







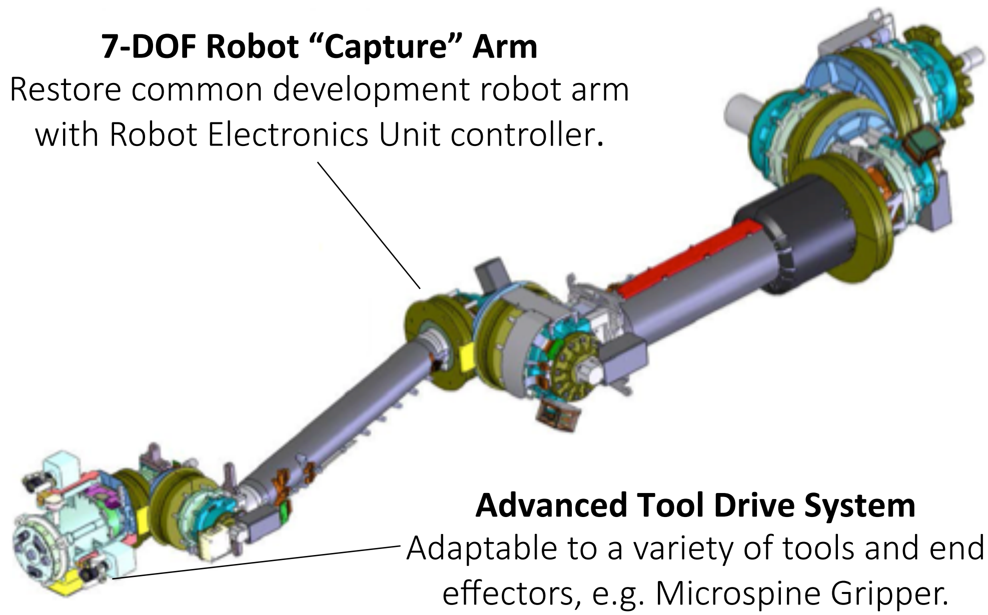
Robot Subsystem

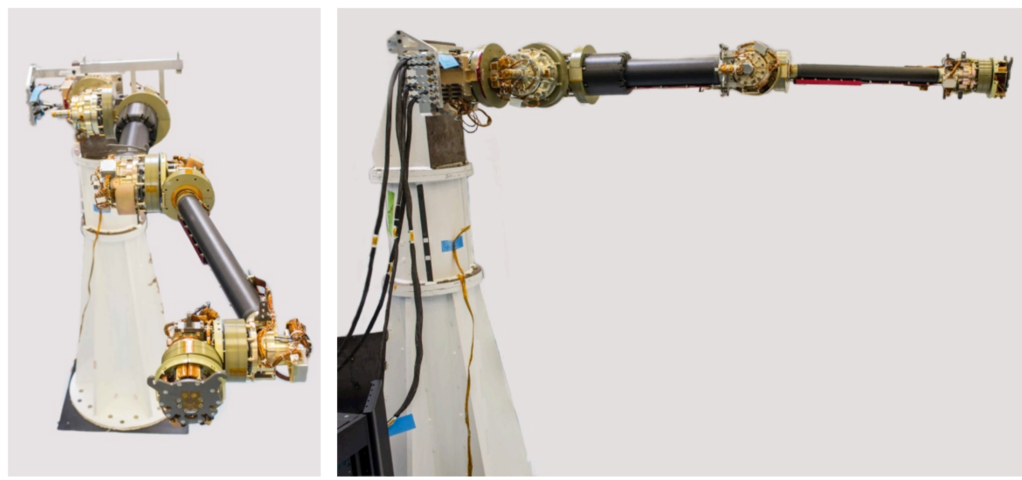
Subsystem overview

- 7-Degree-of-Freedom (DOF) robot arm with supporting electronics
- Advanced Tool Drive System (ATDS) at end of robot arm supports use and change out of multiple tools during the mission
- Common control electronics and software

Heritage/technology assessment

- Derived from DARPA/FREND arm
- Build-to-print common design with Restore
- Flight-proven design and implementation heritage from Mars Exploration Rovers, Mars Phoenix, and Mars Science Laboratory
- Leverages investment from DARPA/NASA
- Based on ARRM mission requirements, updated arm common spec to include accommodation for locking brakes to increase load capability
- Restore EDU delivered June 2015





Capture arm EDU – direct heritage from FREND, synergy with Restore-L

Robot Subsystem - Microspine Gripper

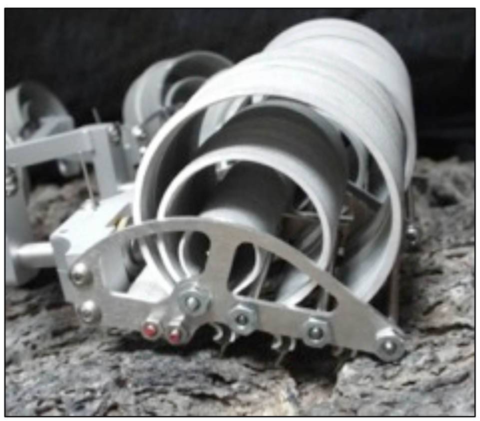
Microspine gripper

Tool overview

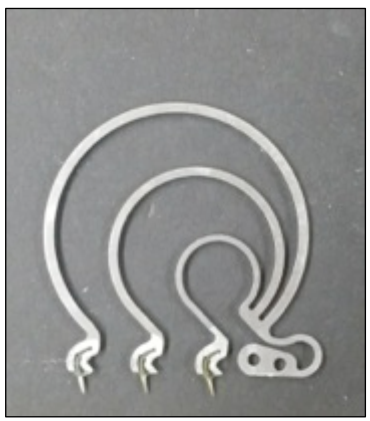
- Uses ~2000 independent hooks to opportunistically grip the surface
- Fast release capability
- Integrated rotary-percussive anchoring drill augments Microspine grip capability
  - Design update from risk reduction

Heritage/technology assessment

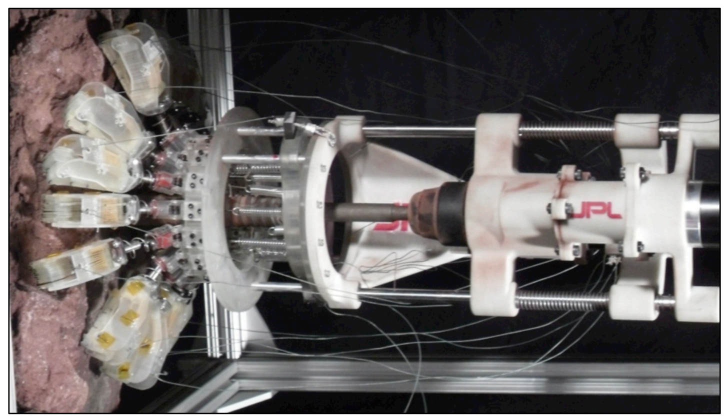
- TRL 5 gripper and TRL 5 anchoring drill
- Prototypes completed and characterized separately with industrial robot arms
- Initial integration feasibility demonstrated with Microspine "1.0" prototype and commercial drill



Carriage (1 of 24)



Microspine (1 of 652)



Microspine 1.0 and integrated drill

Capture System Risks, Uncertainties, Sensitivities

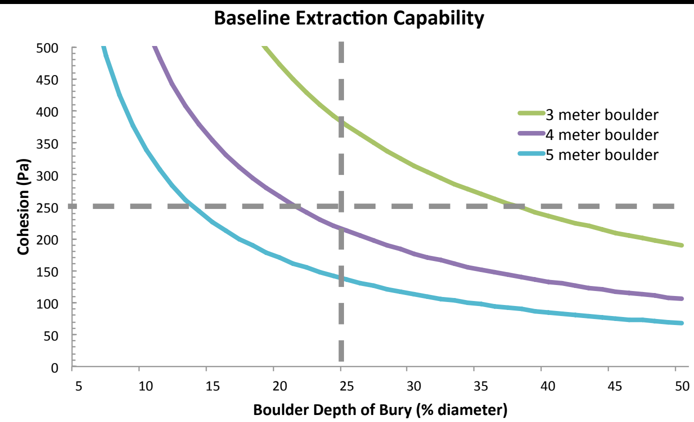
- Previous SBAG findings provided key assistance on formulating this concept, especially including:
  - Preferred asteroid type for ISRU and science relevance
  - Asteroid and boulder physical properties (composition, strength, etc)
  - Likelihood and diversity of boulders
  - Planetary defense and resource utilization recommendations

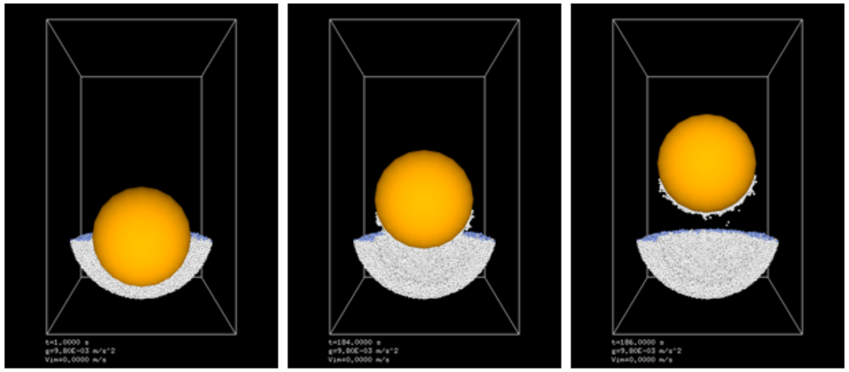
- Additional areas that SBAG can help with
  - Boulder-to-parent-body cohesion (details on next chart)
  - Boulder depth of bury
  - Additional input on likelihood of boulder fracturing, surface degradation
  - Dust environment

Extraction Force

Extracting the boulder from the parent asteroid

- The force required to extract boulder from asteroid drives design of Capture Module
- SBAG special action team: extraction force likely dominated by cohesive forces between the boulder and the parent asteroid
- Extraction force very sensitive to estimated cohesive force as boulder size and depth of bury increase
- Also sensitive to depth of bury
- Have engaged community to perform physics-based simulations of boulder extraction to characterize force required to break cohesion
- Plan to validate simulations using extraction testbeds with regolith and boulder simulants
- Both activities would benefit from further engagement with the community





Boulder extraction simulation

KSC Swamp Works full-scale testing of boulder extraction