Robotic and Human Space Exploration of Near-Earth Objects

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NEO Missions – Why Send Humans?

- Near-Earth Objects (NEOs) have been identified as candidate destinations for future human missions beyond low-Earth orbit
  - NEOs provide an intermediate destination between the Moon and Mars that, among other benefits, can reduce the risks for all human deep space exploration
  - NEO missions can provide important scientific discoveries about the solar system, vital operational experience for Mars missions and beyond, assist in the development of planetary defense approaches, and foster the future utilization of space resources

- The total mission energy for some NEO trajectories can be less energetic than for lunar missions, while other trajectories can exceed that needed for Mars missions
  - Human mission durations are significantly longer than traveling to and from the Moon, but NEOs with reasonable energy requirements can have total mission durations of 6 months or even less, depending on the propulsion technologies utilized
  - Longer NEO mission durations of 1 year or more are commensurate with the in-space transit segments for sending humans to Mars

- If humans are ever needed to conduct a mission to neutralize an Earth impacting asteroid or comet in the future, gaining operational experience prior to that need is critical
NEO Missions – Why Send Robots before Humans?

- NEOs are the remnants from the earliest stages of solar system development, and represent a diverse group of airless planetary bodies whose population is poorly characterized
  
  - Approximately 1% of the currently known population has been characterized by remote sensing
  
  - Only two spacecraft have actually “landed” on the surface of a NEO
    - NEAR Shoemaker on Eros in 2001
    - Hayabusa on Itokawa in 2005

- NEOs are generally classified as comets or asteroids, based on whether or not active outgassing of volatiles or other frozen materials are known to be present
  
  - Approximately 5-10% of the NEO population may be dormant or inactive comets
  
  - NASA plans to send humans to asteroids, since the present of volatiles poses a significant mission risk

- It is anticipated that at least one robotic precursor will visit the specific Near-Earth Asteroid (NEA) targeted for a human mission approximately 3-5 years before sending the crew
  
  - Required to verify the asteroidal nature of the chosen target
  
  - Provide critical target reconnaissance for characterization to assist in operational planning and spacecraft development
Comet or Asteroid? Simple...

Comets contain volatiles in the form of ices and can produce visible atmospheres (coma)

Asteroids lack active ices and are essentially inert

All Images - Source: NASA
Small Body Diversity to Scale
NEA Human Mission Challenges

◆ NEAs are challenging targets as their minimum energy trajectories typically occur less often than Mars missions since many have long synodic periods
  • However, asteroids in Earth-like orbits can have continuous departure windows that can last many months and repeat for several years
  • Since there are many more smaller NEAs than larger ones, mission opportunities are constrained by the minimal NEA size deemed acceptable for a future human mission
  • Size estimates are based on observed visual brightness (absolute magnitude, H) and an assumed visual albedo range (typically 5-25%), which leads to large uncertainties
    - Infrared remote observations can greatly improve size estimates and radar can confirm (if target is close)
    - Robotic precursors may be required to confirm size

◆ Long-duration interplanetary space missions, including NEA missions, present unique challenges for the crew, spacecraft systems, and the mission control team
  • The cumulative experience and knowledgebase for human space missions beyond six months and an understanding of the risks to humans and human-rated vehicle systems outside of the Earth’s protective magnetosphere is severely limited at this time
  • A variety of challenges exist, including:
    - radiation exposure (cumulative dosage and episodic risks)
    - physiological effects, psychological and social-psychological concerns
    - habitability issues and consumables and trash management
    - system redundancy and life support systems reliability
    - missions contingencies and abort scenarios
    - communications light-time delays (crew autonomy, mission control operations, etc.)
NEA Destination Challenges

- Since NEAs have very low surface gravity, the mission will not require a surface lander in the traditional sense.

- A significant challenge will be to station-keep alongside the NEA or “dock” and anchor to the NEA’s surface.
  - May impact target selection and/or anchoring system design based on robotic precursor information obtained.
  - Need to be prepared to deploy the crew and delivered payloads to the surface without docking or anchoring.

- Asteroid spin rate and surface/internal structure are significant factors that influence this operational challenge and are significant factors in target qualification.
  - Small asteroids (~50-100 m or smaller) have a tendency to be fast rotators and are more likely to be monolithic with less surface regolith.
  - Large asteroids (~100 m or larger) tend to rotate more slowly and have a high probability of being rubble piles comprised of a variety of particle sizes.

- Anchoring to a rubble pile in a microgravity environment represents a critical challenge for NEAs and potentially for the future exploration of the Martian moons Phobos and Deimos.

- Uniqueness of targets could create unique design challenges for mission elements, operational approaches and scientific activities.

Source: NASA / AMA, Inc.
Example of Possible NEO Human Mission Elements & ConOps

- Total crew of 4 in the asteroid vicinity for 7-30 days
- Mothership consists of Deep Space Habitat (DSH) + Multi-Purpose Crew Vehicle (MPCV) + Solar Electric Propulsion (SEP) Module
- Space Exploration Vehicle (SEV) serves as a shuttle craft to provides access to the NEO capable of supporting 2 crew up to 14 days periods
- The Mothership maintains position at a safe distance from NEA and act as a communications relay between the SEV and Earth
- Extravehicular activity (EVA) with crew members exploring NEA via suitports and remaining physically connected to the anchored SEV (e.g., deployable platform, a robotic arm, exterior footholds on SEV)
Example Human NEA Mission Profile

NEA Exploration

Lunar/Earth Gravity Assist (C3=10) Utilized for Earth Departure

CPS 1 Expended

CTV SM Expended

CTV – A/E with Crew

Block 1 CPS 2

SEP 1 Expended

Kick Stage Expended

DSH

SEP 2 SM Derived

Block 2 CPS 1

Source: NASA
### Examples of Human Mission Activities

<table>
<thead>
<tr>
<th>Category</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Monitor and Maintain Crew Health</strong></td>
<td></td>
</tr>
</tbody>
</table>
- Monitor crew radiation doses on EVA  
- Intravehicular crew radiation monitoring  
- Monitor micro and artificial gravity effects on crew  
- Monitor and maintain physiological and psychological health  
- Practice in space medical care procedures Crew exercise |
| **Dock to NEA** |  
- Dock spacecraft to NEA  
- Attach EVA crew to NEA  
- Perform station keeping at NEA |
| **Deploy Element to Surface** |  
- Deploy ISRU element  
- Emplace Transponder for NEA tracking  
- Emplace seismic sensor network for long-term seismic investigation  
- Emplace charge for active seismometry  
- Emplace push/pull velocity change systems  
- Emplace science suite for long-term characterization (e.g., geophysical measurements or meteorologic/atmospheric monitoring)  
- Emplace radar or EM sounder (e.g., search for subsurface frozen water)  
- Deploy Radiation Shielding test systems |
| **ISRU** |  
- Extract ore (raw material)  
- Extract other resource (extract and process for use) |
| **Sample Collection and Processing** |  
- Core Sample  
- Deep Drill  
- Bulk Sample  
- Intravehicular Sample Analysis  
- Selective Sample  
- Curate samples |
| **Surface Measurements and Imaging** |  
- Hand-held compositional spectrometers  
- Measure fields and particles (dust, microbes, radiation, electrical)  
- Multi-spectral imaging  
- Visual photography  
- Panoramic photography |
| **Penetrate Surface** |  
- Penetrometer measurement  
- Emplace acoustic probe |
| **Operate Crew Systems** |  
- Operate Suitport  
- Perform EVA  
- Transmit data and voice from mother ship to NEA and Earth  
- Perform mobility on surface |
| **Operate Robotic Systems** |  
- Teleoperate to surface and acquire surface sample  
- Deploy autonomous robotic elements and/or crew assistants  
- Deploy autonomous long-lived satellites |
| **Participatory Exploration** |  
- Engage public in exploration activities |
Robotic Precursor Missions & Target Characterization

- Robotic precursor information obtained will influence target selection and the design of elements and systems and allow human mission activities to be planned and successfully completed.

- Some of the critical information from a sufficiently capable robotic mission includes:
  - Improvement of the orbital position of the object based on navigation data from the robotic spacecraft.
  - Target size and whether or not the NEO is a single object or part of a binary or ternary system - important particularly during an early mission to reduce mission complexity and increase mission success.
  - Accurate measurements of the spin rate and spin state of the NEO.
  - Assessment of any surface activity (some significant level of surface interaction is required).
  - Measurements of the near-surface structure and regolith mechanical properties.
  - Knowledge of the local gravity field and terrain.

- Engineering testing and evaluation of systems, such as those used to anchor to the NEO, will likely need to be tested using a robotic precursor before sending human to asteroids.

- A robotic precursor mission provides important data about the target NEO that has benefits for the scientific community, planetary defense, resource utilization (including commercial interests), as well as human missions.
Human NEA Exploration – Characterization for Safety/Success

<table>
<thead>
<tr>
<th>Maximize Crew Safety</th>
<th>Maximize Mission Success</th>
</tr>
</thead>
<tbody>
<tr>
<td>◆ Exact location</td>
<td>◆ Mineralogical/Chemical Composition</td>
</tr>
<tr>
<td>◆ System Type</td>
<td>◆ Regolith Mechanics/Geotechnical Properties</td>
</tr>
<tr>
<td>◆ Spin Mode</td>
<td>◆ Electrostatics/Plasma field</td>
</tr>
<tr>
<td>◆ Activity/Debris Field</td>
<td>◆ Local Radiation Assessment</td>
</tr>
<tr>
<td>◆ Mechanical Stability</td>
<td>◆ Thermal Properties</td>
</tr>
<tr>
<td>◆ Gravitational Field</td>
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Radar Study of Shape, Size, Motion & Mass of 1999 KW₄

~2 km primary body losing material to a ~0.5 km moonlet.
Rotation rate of primary body ~2.5 hours
Moonlet orbital period ~17.4 hours
Human-Robotic Synthesis During Human Mission

◆ Efficient exploration of a NEA will require use of several types of robotic “partners”
  - Tele-operated/supervised robots can expand exploration range, carry equipment, emplace devices, etc.
  - Free up EVA crew time for detailed examinations of optimal sites on the surface
  - Allow crew to avoid regions deemed to dangerous to explore and provide crew rescue assistance
  - The anthropomorphic attributes of Robonaut have the added benefit of capabilities that are human-like

◆ Human and Robotic Interaction
  - Efficiency/robustness improvement methods by having robot perform tasks prior to crew arrival or while awaiting human authority to proceed commands
  - Ground control of robotic EVA assistants and precursor/post-mission assets
  - In-situ intravehicular (IVA) crew controlling robotic EVA assistants (i.e., SEV and DSH)
  - EVA crew control of robotic EVA assistants where advantageous and safe

◆ Next-Generation Space Robotics
  - Develop, test and certify next-generation manipulators
  - Test and certify tele-operated and semi-autonomous robotic operations and multiple levels of tele-operations
Concluding Remarks

- **NEOs are not a well characterized population of objects**
  - The vast majority of the population has yet to be discovered
  - Only ~1% of the currently known population has been characterized by remote sensing
  - There are many “known unknowns” involved in the future exploration of NEOs, and there are likely a significant number of “unknown unknowns”

- **Remote characterization to the greatest extent possible (ground-based and space-based assets) should be performed and correlated prior to robotic precursor and human missions being initiated**
  - A space-based IR telescopic survey provides a valuable increase in the set of available human mission targets to select the best mission opportunities
  - Also allows a certain amount of critical remote sensing data to be gathered (light curves, spectroscopy, spin rate), and combined with other ground-based and space-based assets allows proper target selection for the robotic precursor mission and the human mission

- **Assuming that goal of a future human mission is to directly interact with the target NEO**
  - The uniqueness of each NEO and uncertainty of its physical characteristics requires a robotic precursor to the same human mission destination
  - Understanding the impact of those physical characteristics on the ability to anchor/attach to the NEO will likely determine the NEOs that can be visited
Thank you... Questions?

NEOs for Exploration
NEOs for Science
NEOs for Resources
NEOs for Planetary Defense

Source: NASA / AMA, Inc.
Backup
NEO Orbital Classifications

Near-Earth Asteroids (NEAs) q<1.3 AU & Near-Earth Comets (NECs) q<1.3 AU, P<200 years

- **Amors**
  Earth-approaching NEAs with orbits exterior to Earth's but interior to Mars'
  (named after asteroid 1221 Amor)

- **Apollos**
  Earth-crossing NEAs with semi-major axes larger than Earth's
  (named after asteroid 1862 Apollo)

- **Atens**
  Earth-crossing NEAs with semi-major axes smaller than Earth's
  (named after asteroid 2062 Aten)

- **Atiras**
  NEAs whose orbits are contained entirely with the orbit of the Earth
  (named after asteroid 163693 Atira)

$q = \text{perihelion distance}; \quad Q = \text{aphelion distance}; \quad a = \text{semi-major axis}$
Population and Cataloging Completeness to Date

◆ Population
  • 25,000+ with diameters ≥ 140 m
  • 300,000+ with diameters ≥ 50 m
  • Millions with diameters ≥ 15 m

◆ Cataloging
  • ~90% of 1 km NEOs are known
  • Only a few % of population down to 50 m are cataloged
  • Ground-based observations are biased towards the brightest targets (e.g., distance, size, albedo)
  • Current map of all the know asteroids in the inner solar system as of October 5, 2010 (right)
    - Green – objects that do not currently approach Earth
    - Yellow – Amors
    - Red – Apollos & Atens
    - Many, many unknown objects and incomplete knowledge of the size frequency distribution
  • Dynamically young NEO population - ejections and collisions from the main asteroid belt and comet reservoirs replenish and maintain the population
Diversity of NEOs

- NEOs represent a diverse group and every object is unique - these bits of jetsam and flotsam are the remnants of our solar system in that early stage of development and evolution (some are water rich - up to 30%)

- Asteroids have been divided into many taxonomic classes and an attempt has been made to relate these classes to similar-appearing classes of meteorites, but are only suggestive of composition
  - Color, albedo, and major spectral features
  - Many classes and variations within classes: A-G, I, K, M, P-V, X (100+ parent bodies)
  - Correlation to meteoritic samples may be biased based on what materials reach Earth
  - Chemical composition varies widely and may be difficult to predict remotely (observational biases) – ground truth is required to correlate targets with remote sensing data

- C-types (carbonaceous) ~75%
  - Blue colors, flat/feature spectra similar to carbonaceous chondrite meteorites
  - Lower albedos (0.03 – 0.09)

- S-types (silicaceous) ~17%
  - Red colors and spectra similar to stony-iron meteorites and consist mainly of iron- and magnesium-silicate
  - Higher albedos (0.10 – 0.22)

- M-types (metallic) ~7%
  - Reddish colors, flat spectra - composed of metallic iron, like the iron meteorites, and nickel
  - Moderate albedos (0.10 – 0.18)