Asteroid Mining Methods

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Overview

• What is **Mining**?
• Who is the **Customer**?
• How to **Mine Asteroids**?
• Preliminary **Requirements and Constraints** (mining vs. civil engineering of space objects)
• **Mining** and **Planetary Defense** – natural allies
• **Conclusions**
Mining Defined

• Definition of **mining**
  – The extraction of *valuable minerals*, other geological materials, or any non-renewable resource

• Definition of **ore**
  – Any material that can be mined for a *net benefit*

• Mining is an **economic activity**
Asteroid Customer Profiles

• Classified by commodity type (and limited by asteroid classification)
  – PGMs for terrestrial markets
  – Volatiles for propellant, life support
  – Metals for tanks, structures, construction, etc.
  – Silicates for ceramic composites
  – Hydrocarbons for plastics, propellant, food, etc.

• Classified by consumer type
  – Planetary defense apps (a.k.a. Civil Engineering)
  – Human space exploration & military uses of asteroid materials
  – Construction materials for G.K. O’Neil space colonies
  – Feedstock for Orbiting Shipyards
  – Settlement needs: fuel, food, water, housing, entertainment, etc.

sustainable space settlement duplicates most terrestrial activities
Preliminary Requirements Analysis

- Mining
  - Fragmentation
  - Moving / hauling
  - Separation
  - Melting
  - Containment
  - Processing

- Planetary Defense
  - Fragmentation
  - Moving / hauling
  - Containment
  - Separation

*Note level of commonality between mining and planetary defense*

*Also note that this list is notional - more work is needed to capture a complete set of systems requirements and constraints*
First-order Constraints

• Astrodynamics
  – Manifolds vs. Hohmann transfers
  – Earth-Moon vs. Earth-Sun Lagrange points destination

• Environmental conditions
  – Very low gravity, variable gravity vector
  – High vacuum
  – Hard radiation
  – Thermal cycling
  – Available sunlight & diurnal cycle

• Launch systems (payload mass & volume)
• Available energy (power sources)
• Maintenance & Repair (service life)
• Communication delays
• Other system constraints will likely be identified as asteroid exploration and development advances…
Asteroid Mining Process Steps

• Mine development and site preparation
  – Anchor to the NEO and attach tether
  – NEO motion control
    • partial or complete de-spin and de-wobble
  – Emplace body/fragment restraint system
  – Construct operations platform system
  – Emplace processing system
  – Emplace auxiliary and support equipment

• Extraction/modification operations
  – Mining
  – Beneficiation and Processing
  – Transport

• Orbit modification (transport)
  – Main body
  – Fragments
Process steps, cont’d

- Principles of terrestrial mining include
  - Max productivity + revenues
  - Min costs + need for reclamation
  - Actions that lower risk are typical
  - Low maintenance / complexity technology is often preferred over higher productivity (perception of longer service life)

- Mine design process
  - Planning and sequencing of unit operations in time and 3D space
  - Extract the mineral of interest at the maximum net benefit (total benefits minus costs)
  - The capabilities required to make the mining method work are the first-order determinants
  - Mining methods are refined to the second and third orders by the constraints imposed by the technology choices made
Developing Mining Methods for Asteroids

- Types of mining methods:
  - Classified by fragmentation energy storage
    - Self-supporting
    - Artificially supported
    - Caving
  - Classified by access
    - Surface
    - Underground
  - Classified otherwise
    - Spin-assisted
    - Others?

- Mining method selection
  - Market (output) controls
    - Demand rate
    - Location
  - Geologic (input) controls

What to produce? Who’s buying it?

The answers determine the mining method
Asteroid mining methods

- Notional asteroid mining methods proposed in the literature can be abstracted into various categories:
  - Bag & Boil => volatile extraction
  - Magnetic Rake => collect high grade ore
  - Divide & Deliver => take a smaller piece home
  - New Moon => put into earth orbit
  - Hot Knife => cut up a comet core with nuclear heat
  - Inside-out => remake it in your own image
  - Mosquito => remove the good stuff from under the shell
  - Laser torch => divide & conquer
  - Etc.

- Operational experience will determine which methods work (all of the above are theoretical at best)

- Note: There is a strong dependence between mining method and ore type / geomechanical properties…
Unit Operations

• The concept of “unit operations” is used in the mining industry to describe elements in the process that connects a pristine mineral occurrence to a deliverable commodity.

• Elements of mining Unit Operations include:
  – Resource Assessment – Determines what is available, where it is, what form it is in, and how it can best be extracted.
  – Resource Extraction – Provides raw materials from the local environment by removing them, concentrating them, and preparing them for further processing, manufacturing, or direct use.
  – Resource Acquisition – Separates and removes the target raw material -- gas, liquid, and/or solid -- from its original location to Resource Beneficiation.
  – Resource Beneficiation – Converts the raw material into a form suitable for direct use, manufacturing, or further processing.
  – Site Management – Comprises supplemental capabilities needed for...
Capability analysis

• Several technologies usually can be applied to achieve the same capability

• Drilling example (all create access to rock at depth)
  – mechanical excavation
    • down-the-hole hammer drilling
    • top-hammer drilling
  – chemical drilling
  – laser drilling
  – nuclear drilling
  – gnomes with picks and shovels…
Current Mining Capabilities

• Some **in-space capabilities** have already been demonstrated:
  – Scooping of regolith samples on the Moon and Mars.
  – Coring & drilling of regolith samples on the Moon.
  – Grinding and analysis of rock samples on the Moon and Mars.
  – Mars atmosphere capture and separation
  – Cryo-coolers demonstrated on satellites for long duration (Mars conditions).

• Present capabilities of **terrestrial resource extraction** include:
  – Semi-automated drilling/boring, fragmentation, excavation, and transportation of rock, both underground and on the surface.
  – Semi-automated pre-processing of gases, liquids, and solids into forms suitable for further processing, manufacturing, or direct use.
  – Production rates from a few liters/day to 200,000+ tonnes/day.
  – Successful operations:
    • from 4,600 m elevation to 3,800 m depth in the crust, and on the sea bottom;
    • in locations accessible only when the ground freezes, when it thaws, or
Required Asteroid Mining Capabilities

- Resource Assessment
  - Prospecting
  - Delineation
  - Development
- Resource Acquisition
  - Underground Liquids and Gases
  - Regolith
  - Rock
  - Mixed Materials
  - Excavated Openings as Product
  - Waste Materials
- Resource Beneficiation
  - Change of Phase
  - Particle Size Change
  - Separation
  - Internal Materials Handling
- Site Management
  - Site Planning
  - Dust Control
  - Anchoring
  - Ground Stability Control
  - Transportation and Storage
  - Monitoring
  - Auxiliary Operations
  - Waste Management
  - Site Reclamation
Asteroid Mining Gaps and Risks

• Gaps:
  – Products and target materials – better definition required
  – Extraction method depends on detailed resource information
  – Extraction and beneficiation also depend on detailed product specifications
  – Current data useful only for prospecting – better resolution required
  – Unknown mass/mission constraints – precise architecture required
  – Lunar and martian granular materials behavior poorly understood
  – Effects of lunar and martian environments on equipment technologies
  – Required capabilities are common to all environments
  – Only the technologies needed to achieve these capabilities vary

• Risks:
  – Prospecting uncertainty
  – Economic uncertainty (no current customers exist)
  – Systems reliability and costs
  – Effects asteroidal environmental conditions
  – Political and legal uncertain (e.g., property rights)
  – Terrestrial experience in resource extraction is broad and deep, but translating
Planetary Defense Synergies

• Flood control analogy
  – Dams are built by USACE to avert floods
  – Power-generation and recreational facilities created by the impoundments provide benefits
  – Example of converting a hazard into a resource

• Asteroid mining could simultaneously de-threaten a PHA orbit while providing resources for space exploration
  – Public / private partnerships could leverage government resources with private capital
  – Partnership could extend limited liability to the private party and return valuable civil engineering data (dynamics of moving an asteroid)
  – Could help initiate a ‘space gold rush’
Mining for Planetary Defense

- Example asteroids classified:

<table>
<thead>
<tr>
<th>Group 0</th>
<th>Class 2</th>
<th>Class 3</th>
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<tbody>
<tr>
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<td><em>Wild2</em></td>
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<td>Group 1</td>
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<td><em>Itokawa</em></td>
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<td>Group 2</td>
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<td><em>Eros</em></td>
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<td>Group 3a</td>
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<td>1986 DA</td>
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<td>Group 3b</td>
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- Controlled fragmentation process →
  - explosives emplacement needs R&D
  - resource extraction possible concurrently but is not the main focus
Physical Classification of Asteroids for Mining & Planetary Defense

• Size Axis:
  – Class 1. Requires only one blast of a few to several hundred charges. A single human-robotic team is needed for blast design and construction.
  – Class 2. Requires between two and 20 simply layered blasts. One to several teams are needed, depending on the mitigation speed required.
  – Class 3. Requires more than 20 blasts, with significant complexity, including multiple layers of blasts. Many human-robotic teams needed.

• Composition Axis:
  – Group 0. Ice composites – very weak, containing ices with or without organic compounds.
  – Group 1. Friable rock – similar to Group 0, but with no volatile components. Also weak.
  – Group 2. Hard rock – strong and brittle, the most similar to materials encountered in terrestrial mining and excavation practice.
  – Group 3. Metallic:
    • 3a. Massive metal – may be ductile.
    • 3b. Rock-metal composites – would fracture mainly at rock-metal interfaces.
Conclusions

• Partner planetary defense with asteroid ISRU
  – Begin a comprehensive, ongoing missions program to characterize PHAs:
    • Measure properties pertinent to mining and defense
      – destruction and deflection can be designed for simultaneously
    • Return samples for detailed analysis
    • Build and maintain robust database of PHA traits
      – follow and improve on the USGS model with modern information technology

• A partnership between planetary defense and asteroid mining would be enabling for both
  – Certain PHAs may be excellent resource choices
  – Many common knowledge requirements exist
  – Many common technologies and capabilities apply
  – Detailed engineering analysis and design is warranted
    • Knowledge should include mining, aerospace and astrodynamics
    • Trade studies should include detailed analysis of technical requirements and constraints as well as economic forecasting
Backup Charts
References Cited


Technology Concepts for Some Asteroid Mining Capabilities

• Fragmentation
  – Nuclear explosives
  – Cycling fatigue
  – Impact

• Drilling and excavation
  – Mechanical systems
    • Heat build up on cutting tools is limiting factor
    • Reaction mass is a major issue
  – Lasers
  – Kinetic drilling
  – Chemical drilling

• Beneficiation and processing
  – Synthetic biology
  – Electrostatic / electrodynamic separation systems

Note: for more detail see 1997 paper “Near-Earth Resources” in reference list
The lists that follow are derived from lunar ISRU technology roadmapping and needs modification to incorporate unique asteroid environmental effects – see Sanders et. al. reference.
# Technologies Needed

<table>
<thead>
<tr>
<th>Technology</th>
<th>Capability Applications</th>
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<tr>
<td><strong>Mapping Technologies</strong></td>
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<tr>
<td>Remote Geophysical Survey Technologies</td>
<td>Prospecting and Delineation, Site Planning, Monitoring</td>
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<tr>
<td><strong>Human &amp; Robotic Transportation Technologies</strong></td>
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<tr>
<td>Pit and Trench Excavation Technologies</td>
<td>all Resource Assessment capabilities; Transportation and Storage</td>
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<tr>
<td>Drilling Technologies</td>
<td>all Resource Assessment capabilities; Waste Management, Site Reclamation</td>
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<tr>
<td><em>In Situ</em> Geophysical Survey Technologies</td>
<td>all Resource Assessment capabilities; Underground Liquids and Gases, Regolith, and Rock Resource Acquisition; Monitoring and Site Reclamation</td>
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<tr>
<td>Field Sampling Technologies</td>
<td>Prospecting, Delineation, Site Planning, Monitoring</td>
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<tr>
<td>Sample Analysis Technologies</td>
<td>Prospecting and Delineation, all Resource Beneficiation capabilities, Site Planning and Monitoring</td>
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<tr>
<td>Dust Mitigation/ Control Technologies</td>
<td>Development, all Resource Acquisition capabilities, all Beneficiation capabilities, and Dust Control</td>
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<td>Atmospheric Extraction Methods</td>
<td>Development, Atmospheric Gases Resource Acquisition</td>
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<td>Borehole Liquid &amp; Gas Extraction Methods</td>
<td>Development; Underground Liquids and Gases Resource Acquisition</td>
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<td>Underground Extraction (Mining) Methods</td>
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<td><em>In Situ</em> Extraction Methods</td>
<td>Development, Regolith and Rock Resource Acquisition</td>
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<td>Tunnel/Shaft Excavation Technologies</td>
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<td>Gas Collection Technologies</td>
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<td>Granular materials performance models</td>
<td>Development; Regolith and Rock Resource Acquisition, and Excavated Openings as Product; Beneficiation Separation and Internal Materials Handling; Site Management, Anchoring, Ground Stability Control, Site Reclamation</td>
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<td>Continuous Materials Handling Technologies</td>
<td>all Resource Acquisition capabilities, and Beneficiation Internal Materials Handling</td>
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<td>Liquid and Gas Containment Technologies</td>
<td>Atmospheric Gases, Underground Liquids and Gases Resource Acquisition, Internal Materials Handling</td>
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