Robotic Mining System for Rapid Return of Asteroid Resources

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ABSTRACT

The development of Earth orbit for large-scale human tourism, habitation, and manufacturing is hampered by the high cost of launching materials into low Earth orbit (LEO) by existing launch vehicles ($10M per ton), and even on the next generation of launch vehicles from SpaceX, Boeing, and Sierra Nevada (about $5M per ton). At that cost, putting a pioneer family of 4 into orbit with a ton of supplies would cost more than $7 million, orders of magnitude more than the pioneers to the American West paid two centuries ago. This is 3 orders of magnitude higher than the present cost of shipping air cargo across the world. Furthermore, all current space vehicle designs must meet the exacting requirements of rocket-launching.

The Cornucopia Mission will bring back multi-tons of raw regolith ore to LEO, which will enable the manufacturing of space habitats and deep-space manned vehicles designed in space for space, built using space-provided materials, all built safely in LEO, inside the protection of the Van Allen belt and within close-support of Earth-based resources, free from the Earth’s gravity well and of the rocket-launching restrictions.

To address this problem, we present the system architecture and proposed hardware components for a complete robotic mining system dubbed “Cornucopia,” which is designed to return large amounts of marketable materials from near-Earth asteroids into LEO as quickly as possible. Cornucopia missions are to be built using mostly available components and operated with simple and robust technologies. The goal is to have our first return vehicle back to Earth before the end of the decade, to energize Earth orbit development with large amounts of building materials, propellants, radiation shielding, and valuable minerals.

The Cornucopia mission can be launched as a 20-ton payload on a single Atlas 5, Delta IV, or Falcon 9 launch vehicle, and rendezvous and dock with a suitable near-Earth asteroid using advanced ion rockets. After landing and attachment to the surface, a solar-powered auger system is used to extract regolith and load it into four return vehicles. Within this decade, return vehicles can bring multiple tons of material each back to Earth orbit for use in space manufacturing, as propellant and for space habitat shielding. One of the first return vehicles will be equipped with a heat shield and re-entry system to return it to Earth for analysis and extraction of high-value platinum-group metals. This will enable future missions to be designed to bring back only the more valuable asteroid resources. A continuing stream of Cornucopia return vehicles will provide large amounts of extraterrestrial material to substantially advance space development, making possible the large-scale human habitation of space.

1. Introduction

The development of Earth orbit for large-scale human tourism, habitation, and manufacturing is hampered by the high cost of launching materials into low Earth orbit (LEO) by existing launch vehicles ($10M per ton) and the next generation of launch vehicles from SpaceX, Boeing, and Sierra Nevada (about $5M per ton). This is 3 orders of magnitude higher than the present cost of shipping air cargo across the world, which is below $3000 per ton (UPS Air Cargo Reserved International).

During the 1970s, NASA supported many studies on space colonies, and organizations such as the L5 Society (a precursor to the National Space Society) developed plans for large space colonies at the Earth-Moon L5 Lagrangian point, the origin of the name. But building colonies for 10,000 people using Earth and lunar materials was very expensive, and the methods for utilizing those materials were not as
advanced as they are now, with advanced composites and additive manufacturing (3D printing). Using advanced propulsion, solar power, miniaturized and highly reliable electronics, and simple mining techniques, we believe that it is now possible to retrieve asteroid materials at a low enough net cost to make possible the large-scale industrialization of Earth orbit.

To address this problem, we present the system architecture and proposed hardware components for a complete robotic asteroid mining system dubbed “Cornucopia,” which is designed to return large amounts of marketable materials from near-Earth asteroids into LEO as quickly as possible. Cornucopia missions are to be built using mostly available components and operated with simple and robust technologies. The goal is to have our first return vehicle back to Earth before the end of the decade, to energize Earth orbit development with large amounts of building materials, propellants, radiation shielding, and valuable minerals. And the small amount of valuable platinum-group metals, gold, and silver in some asteroids could provide a significant revenue stream to support the entire enterprise3.

Several technology developments in several fields have all come together to make it possible now to begin the development of asteroid resources for space development. The Japanese Hayabusa spacecraft mission4 to the Apollo asteroid Itokawa demonstrated the basic capability for asteroid mining. The NASA Dawn mission demonstrated long-term space operation of advanced ion rockets. Advances in solar cells driven by terrestrial applications have greatly increased the efficiency of using solar power. And asteroid regolith has been transformed into useful forms needed for space manufacturing, using solar power and additive manufacturing.

Recent 3D printing experiments have already demonstrated the capability of generating structural material directly from unrefined regolith5. Therefore it may not even be necessary to refine the raw regolith material to create the basic building blocks of space structures in space. A simple interlocking building block design may be all we need to create a massive basic habitat radiation protective shell, made of raw regolith in orbit6 as shown in Figure 1.

![3D-Printed Tubes Directly from Raw Lunar Regolith Simulant and Example of Concrete Interlocking Building Blocks](image)

Figure 1. 3D-Printed Tubes Directly from Raw Lunar Regolith Simulant and Example of Concrete Interlocking Building Blocks

The Cornucopia mission plan has the goal of returning several tons of marketable asteroid regolith by the end of the decade, at a projected cost of less than $450M. An unexpected potential application is that the in-orbit ore-processing system can also be used to recycle the thousand tons of high-grade aluminum in upper stage debris in LEO Using current launch cost of $5000 per kg, this material is worth at least $5 billion.
2. AMS System Architecture

The proposed mission architecture for the asteroid mining system (AMS) is shown in Figure 2. It is based on a single launch of a large vehicle, such as a Delta IV, Atlas 5, or Falcon 9, totaling about 20 tons. The launch vehicle will provide at a minimum a boost into a LEO parking orbit, and at best Earth escape velocity. At that point, the AMS propulsion system, consisting of multiple high-Isp ion rockets, takes over for the orbit transfer to the target asteroid. The AMS consists of the mining module, power module, and 4 return vehicles. Solar arrays power the 4 ion rockets on each return vehicle, and all 16 thrusters are available for the transfer to the asteroid.
As shown in Figure 2, the AMS approaches the target asteroid, deploys the power module, and lands on a suitable spot for mining using auxiliary chemical rockets. It fills the four return vehicles with regolith, and each one lifts off after it is full, using its 4 ion rockets. The surface gravity of even as large an asteroid as Itokawa (500 by 300 by 200 m) is only about $10^{-4}$ m/s$^2$, so a 10-ton return vehicle will require only 1 newton of thrust to lift off the surface. However, the separation mechanism can also be used to give the initial impetus.

The return vehicles use their ion rockets to return to Earth, perhaps using lunar gravity assist or even Earth gravity assist to minimize the total delta-V. Excess velocity is bled off by aerodynamic or electrodynamic braking, and the return payload is placed in LEO to match orbits with a space processing facility. The first return vehicle may be used for direct Earth entry, using a suitable heat shield such as the NASA inflatable HEART (Figure 3) that has successfully been tested at Wallops Island and will be tested at full scale sometime next year. This would provide immediate revenues from the sale of the regolith, commercial items made from regolith, and from the precious metals separated from the regolith. The succeeding return vehicles can be processed in LEO for the production of structural materials, radiation shielding, and propellant for various applications.

Figure 3. NASA Inflatable Heat Shield (Currently under development)

3. Target Asteroid Selection

We are interested in the most rapid return of asteroid resources, in order to jump-start space development in LEO. This leads us to find suitable target asteroids that are accessible (low delta-V), with adequate sunlight, reasonable size, composition, and rotation rate. The most accessible targets belong to the near-Earth objects such as the Apollo, Aten, and Amor groups with Earth-orbit crossing or near-Earth orbits. The best bets are small Apollo types, Earth orbit crossers with semi-major axis greater than 1 AU, such as Itokawa. We use the S-type asteroid Itokawa as a prototype in the AMS mission planning, because the Japanese Hayabusa mission demonstrated almost all of the operations required of the AMS except for the actual regolith mining.

Asteroid mineralogy varies among the asteroid types, which fall into the following three categories:

- **C-type** (carbonaceous): Includes more than 75 percent of known asteroids. Very dark with an albedo of 0.03-0.09. Composition is mainly silicates, olivine (manganese/nickel/iron) and serpentine (chromium, manganese, cobalt, iron photosillicate, nickel) minerals, oxides and...
sulfides, an estimated 2-to-4% carbon, depleted in hydrogen, helium, and other volatiles. C-type asteroids inhabit the main belt's outer regions. The largest definite example is 10 Hygiea

- **S-type** (stony): Composition is mainly iron and magnesium silicates. Accounts for about 17 percent of known asteroids. Relatively bright with an albedo of 0.10-0.22. S-type asteroids dominate the inner asteroid belt. Examples are the largest, 15 Eunomia, and also 3 Juno.

- **M-type** (metallic): Includes many of the rest of the known asteroids. Relatively bright with an albedo of 0.10-0.18. Composition is apparently dominated by metallic iron. M-type asteroids inhabit the main belt's middle region. The largest example is 16 Psyche.

The Hayabusa mission returned a few particles from Itokawa for further analysis (Figures 4 and 5).

These particles showed that Itokawa is an LL-Chondrite, S-type asteroid. Further analysis shows that approximately 70% of Itokoawa’s mass could potentially be refined into usable materials for manufacturing purposes, and the remaining 30% could be used for radiation and meteorite shielding.

The potentially more valuable S- and M-Class asteroids will be targeted for this project. The actual target selection for the AMS mission will proceed based upon the composition and the orbital characteristics for minimum delta-V, synodic period, semi-major axis, eccentricity, and inclination. The accessibility of asteroid material can be estimated by analyzing the volume of orbital element space from which Earth can be reached under a certain energy threshold and then by mapping this analysis onto an existing statistical near Earth objects (NEO) model. This method is used by NASA/JPL’s near-Earth object human space-
flight-accessible targets study (NHATS) project\textsuperscript{10}, and can be utilized to make a NEA resource map for raw resources exploitation.

The LINEAR and NHATS programs from NASA Goddard and JPL are producing new candidate targets on a regular basis, and it seems reasonable that we can select an accessible target from their discoveries. It may be possible to select an M-type asteroid with higher concentrations of platinum-group metals, so as to increase the potential monetary return of the first return vehicle. This would improve the return on investment, making it more likely to find backing for the AMS program.

4. Asteroid Mining System

The asteroid mining system consists of several components: the mining module, the four return vehicles, with solar arrays and ion rockets, and the power module. In cruise mode, shown in Figure 6, the mining module is surrounded by the four return vehicles, and the solar arrays of the return vehicles and the power module are extended for maximum power to the ion rockets, which are used both for propulsion of the entire system to the asteroid and for propulsion of the return vehicles to take the regolith payloads back to Earth.

![Figure 6. Asteroid Mining System in Cruise Mode](image)

The primary function of the mining module is to excavate regolith from the surface of the asteroid and load it into the return vehicles. The AMS will carry it to the asteroid rendezvous, select the landing spot and anchor the mining module to the surface, and provide command and control, instruments, and vision systems to perform the mining operations. It consists of the following sub-systems:

- Guidance and navigation
- Attitude control
- Scientific instrumentation package
- NEXT ion propulsion system
For visual control of the mining operations, the AMS will include several vision systems. The primary vision system will be mounted on two articulated motorized arms designed to cover each mining head and the entire AMS lander. Each mining head will be equipped with a set of stereoscopic vision cameras for redundancy and additional mining head monitoring and control capability.

The main camera will be positioned on a mobile arm located on the top of the mining module, where it will be able to pan/tilt/zoom to view any part of the AMS lander and the mining head as well as provide views of the asteroid surface around the AMS lander. It will be a full-color- stereo-vision camera which will give the operator a 3-D view of the entire AMS lander and its nearby surroundings. An independent backup camera system will be on the top of the AMS lander. The secondary system can be controlled by the sponsors of the project and can also serve as a mission control backup if necessary.

The first job of the AMS lander is to anchor itself to the surface. The almost complete lack of gravity on tiny asteroids means that the AMS lander must fasten itself firmly to the surface before it can begin mining. A versatile fastening system must be capable of penetrating and attaching to the surface material under a wide range of potential surface conditions.

The anchoring techniques that will be considered and studied are an impact-driven progressive bi-directional auger and a pyrotechnic counterweighted deep-penetration harpoon using the JPL model.
developed for comet landing. Each of these techniques as well as others yet to be identified will be thoroughly tested independently, and then tested together as a system (Figure 8).

Using Earth-mining technologies in near-zero-g conditions on remote locations such as an asteroid will require a high degree of automation. The on-board computer must have a high degree of automated fault-sensing and fault-recovery capabilities. The systems must be able to adapt to unexpected conditions detected by the on-board sensors. The systems must also provide for mission operator override control and for very significant time-delays of up to half an hour or more between send/receive sequences.

In order to effectively extract and package the desired asteroid regolith any device intended to mine asteroids must be versatile enough to adapt to the specific consistency of the potential mining area. A number of potentially applicable mining technologies derived from Earth-based mining are good candidates. The best candidate is the simple, robust, and proven “post-hole-digger” approach for the asteroid mining heads. This vertical auger system is shown in Figure 9.

Figure 8. Auger/Harpoon AMS Anchoring Concept
The AMS will have sufficient basic on-board solar cells to run all basic house-maintenance, telemetry and data communication functions, as well as the continuous mining operations. The auger screw transport system will be used to move the ore up into the main body of the AMS, as shown in Figure 10. From there, it will be moved into the return vehicle and compacted, as shown in Figure 11.

*Figure 9 - AMS Vertical Auger Drilling*

*Figure 10. Ore Transport via Archimedes/Worm-gear Screws*
5. Payload Return Vehicles

The function of the return vehicles is to receive the packed regolith and store it for return to Earth. To that end each return vehicle (RV) consists of a regolith packing and storage system, an ion propulsion system, a control computer and guidance system, and on some of them an Earth atmosphere re-entry system, as indicated in Figure 12. On the first AMS mission, at least one of the RVs will be designed to re-enter Earth atmosphere where the regolith will be analyzed. The results will be used to build an automated ore processing system in Earth orbit and to develop a more efficient mining system for succeeding missions. After that, only high-value products will be returned to Earth from LEO.

The RV control systems perform the same basic functions as the mining module, and can be used as backup control systems for the mining module, providing quadruple redundancy as a safety margin upon landing. The solar panels, communications, guidance and attitude control systems will also be identical for each RV module and will be cross-linked with the main AMS mining module and can be used as backups. After the RVs are ready to return, the primary systems will be used for the payload return journey and orbital insertion and atmospheric re-entry if being brought back to the surface of Earth. The RVs will typically be delivered to rendezvous with a space processing facility in LEO, or to a LEO parking orbit until a facility is available.
The RV propulsion system consists of 4 proven ion rockets, the NASA NEXT ion thrusters that were used on the Dawn spacecraft. The NEXT engines have a specific impulse (Isp) of 3100 s and a thrust of 90 mN. In line with the general AMS design philosophy of using off-the-shelf or high technology readiness level components, these engines have been proven with thousands of hours of thrusting in deep space. A photograph of one of these ion engines in operation is shown in Figure 13.
6. Power System, Communication, and Auxiliary Functions

The AMS power system consists of arrays of high-efficiency, radiation-resistant solar cells. The system can accompany the mining module to the surface if it is well placed, such as at the sunward pole of rotation. An alternative is to place the power system in a matching orbit with the asteroid so that it is visible to both the mining module and the sun, to provide continuous power for mining. This will not require much station-keeping thrust\textsuperscript{15}. This action is essentially identical to the one performed by the Dawn mission, in which the module was able to successfully place itself in orbit around the asteroid Vesta. The problem then is to provide efficient power beaming, possibly laser or microwave\textsuperscript{16}.

The power system will contain a communications relay that is designed to provide a continuous communications link between the AMS and the mission control on Earth if it is stationed in orbit about the asteroid. If it accompanies the mining module down to the surface, a separate relay may be used to provide continuous communication.

The AMS main guidance system will be very similar to and modeled on the Dawn, Hayabusa, and other previous successful deep space missions. This will provide a high TRL, and the only modification needed will be to adapt the existing components to the AMS mission.
7. Cornucopia Missions Expected Results

Cornucopia Mission 1 will demonstrate the capabilities of the AMS design and pave the way for the Mission 2. The objective of Mission 1 is to return a sizable amount of asteroid regolith, in the order of several metric tons. Most of this material will be delivered to LEO for space development uses, including space manufacturing of large structures, providing propellant for upper stages, and radiation shielding for human habitats. At least one return vehicle will deliver regolith to the surface of the Earth for analysis, extraction of platinum-group metals, and design of improved mining modules.

Cornucopia Mission 2 will build on the lessons learned from Mission 1, and will aim to return many more tons of raw asteroid regolith to Earth orbit for efficient production of space structures. Current 3D printing experiments have already demonstrated that the technology has the capability to generate structural material directly from unrefined regolith; therefore it may not even be necessary to refine the regolith tailings after valuable mineral removal to create the building blocks. It is expected the building blocks can be of any size or shape and will provide adequate shielding for permanent human settlements in orbit and in deep space.

In summary, these two initial Cornucopia missions aim to be the first of a continuing for-profit endeavor, designed specifically to provide significant ROI to investors as well as providing the first step to true space exploration and exploitation via future manned missions. All efforts will be made to launch as soon as possible, using proven technologies with as many fail-safe as possible to minimize risks and ensure a successful, profitable return on investment within this decade.

8. Conclusions

Rapid retrieval of asteroid resources using simplified mining techniques seems quite possible. With low-cost mining processes and proven spacecraft technology, we may be able to provide all the raw material needed for extensive space development at lower overall costs than launching from Earth. The small percentage of precious metals found in suitable asteroid targets may be sufficient to pay for the asteroid mining enterprise, as well as augmenting declining terrestrial resources. This added value could help us overcome the cost barrier that has prevented large-scale space development since the Apollo program ended in the 1970s. It appears that our current technology development status argues for beginning this enterprise immediately.

Glossary

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