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Optimal Architecture for an Asteroid Mining Mission: Equipment Details and Integration

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Abstract. Near-Earth asteroids (NEAs) are of increasing interest as we learn more about their number, attributes, potential risks to Earth, and enormous wealth of resources. With the civilian space movement underway, driven by economic engines, it is feasible to formulate profit-making ventures in space that require little-to-no governmental funding. The profit potential and technical aspects of mining NEAs has been explored in numerous articles. This paper presents a detailed, optimal return-on-investment plan for mining NEAs, outlining the necessary engineering components and interaction between system components. The proposal emphasizes flexibility, cost-efficiencies, and fail-safes to maximize the probability of success. The on-site equipment utilizes only robotic components, with telecontrol by humans from Earth. Such a system minimizes human risk and cost. The primary targets are to maximize flexibility, redundancy and capacity for self-correction in all components of the equipment payload. Redundancy of key components is addressed, as this is critical to success and investor profit. Systems including propulsion, power supply, regolith detection-acquisition-and-mining units, processing equipment for platinum-group metals (PGMs), ore and volatiles including water, and propellant manufacture and storage are all described. The necessary artificially-intelligent, distributed control-communication-and-navigation programs permitting component adaptability to varying surface conditions on NEAs are detailed. A sample mission to a representative NEA is outlined, to demonstrate (a) the interaction of all system components, (B) fail-safes for several potential problems that could be encountered, and (c) final configuration of payload and sample return. The system components include: a command/control/communication (CCC) unit that remains next to the NEA and communicates with Earth operators and the landers; four small lander-miner (LM) units capable of acquiring and processing regolith (two specialized for volatiles, two for PGMs and ore); a solar-powered hydrolysis unit for processing water into O2 and H2; systems for storing LOX and LH2; storage units to return PGMs, ore and water; and a return launcher utilizing LOX and LH2 fuel that carries these storage units back to LEO. The CCC unit, LMs, solar-powered hydrolysis unit, and one set of storage containers for LOX and LH2, PGMs and ore remain on the NEA to allow continued processing of regolith, in preparation for their return by future launchers from LEO. The proposal assumes the NEA has already been evaluated by a scouting unit for resource mapping, and the mission delta-V and propellant requirements are estimated based upon launch of the initial mission from LEO. NEA mining for water, ore and PGMs can serve as an economical backbone for catalyzing lunar, Martian and other space exploration. An efficient, flexible and cost-effective mission utilizing adaptable and resilient robotic components is essential to accomplishing this goal.

I. Introduction

The analysis of technical and economic issues involved in mining asteroids has reached a considerable level of sophistication[1-4]. A recent thorough review describes a plausible business plan for a prospecting and mining venture with a five-year timeline, for $100 to $150 million[1]. Considerable time and money has been invested in international efforts to build a comprehensive catalog of near-Earth objects (NEOs) and their orbits: Spacewatch, Near-Earth Asteroid Tracking (NEAT), Lincoln Laboratory's Near-Earth Asteroid Research (LINEAR) and Lowell Near-Earth Object Survey (LONEOS). To date, over 4100 NEOs have been catalogued, including nearly 800 larger than 1 kilometer in diameter. A prime motivator has been to identify NEOs capable of impacting the Earth and causing significant damage. NEAs with the lowest departure energy present the higher danger of Earth impact, making them prime candidates for the lowest-cost supply of materials into the growing Earth orbital market[5].

NEAs are defined as Earth-crossing or Earth-approaching asteroids with perihelion distances $\leq$ 1.3 AU and aphelion distances $\geq$ .983 AU. They are divided into four groups: Amors, Atens, Apollos, and Arjunas based upon orbital parameters[3]. The Amors NEAs orbit in close to but do not cross Earth's orbit, whereas the Apollos asteroids do cross Earth's orbit. The Atens NEAs have average semi-major axes less than one AU (see Figure 1).

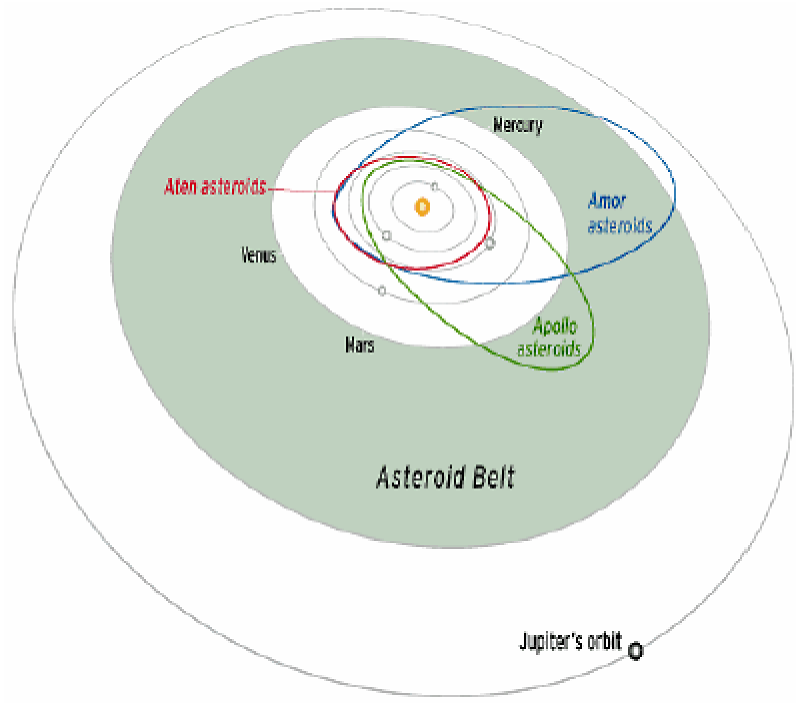

Figure 1. Depiction of orbits of Amors, Atens, and Apollos NEAs[1]. Approximately 10% of NEAs may be more accessible than the Moon, having a minimum outbound delta-v from LEO for rendezvous of less than 6 km/s[3,4], the most accessible being those with low eccentricity and inclination[4].

Transfer	Delta-V (km/s)
Earth surface to low-Earth orbit (LEO)	8.5
Earth surface to escape velocity	11.2
Earth surface to geosynchronous orbit (GEO)	11.8
LEO to escape velocity	3.2
LEO to Mars transfer orbit	3.7
LEO to GEO	3.5
LEO to highly-elliptical Earth orbit (HEEO)	2.5
LEO to Moon landing	6.3
LEO to near-Earth asteroid[a]	4.0
Lunar surface to LEO (aerobraking)	2.4
Near-Earth object (NEO) to Earth transfer orbit	1.0
Phobos/Deimos to LEO	8.0

Table I. Delta-V requirements to and between various off-Earth destinations[1]. Delta-V is provided by the thrust of a rocket engine. A delta-V estimate between two points in space permits calculation of the propellant mass necessary to transport a cargo of a given mass between them.

a. Typical near-Earth asteroid; actual delta-V varies by individual asteroid, and depends also on where in the NEA's orbit rendezvous occurs.

Asteroids vary greatly in composition, and have been classified into a number of categories, including three major subtypes. C-type (carbonaceous) asteroids are water-bearing with very high contents of opaque, carbonaceous material. S-type (stony) asteroids are anhydrous and rocky, consisting of silicates, sulphides, and metals. M-type (metallic) asteroids exhibit high radar reflectivity characteristic of metals such as iron, nickel and cobalt[1,3,5]. About half of the NEAs are believed to be C-type, with most of the remainder S-type, and a small percentage M-type[7]. Based upon spectroscopic studies of NEAs and on mineral analysis of meteorites ("ground truth" in that meteorites are believed to come from asteroid fragments)[1,4,], NEAs are likely to bear high content of platinum group metals (PGMs). All common classes of meteorites contain higher concentration of PGMs than the richest ore bodies in Earth's crust[3]. On Earth, the best mines contain 4-6 ppb (parts per billion), whereas based on meteorite content, 30-60 ppb is guessed in many asteroids, possibly much higher[5].

	Mineral	C2-Type	C1-Type	S-Type	M-Type	Lunar Regolith
Free Metals	Fe	10.7%	0.1%	6-19%	88%	0.1%
	Ni	1.4%	—	1-2%	10%	—
	Co	0.11%	—	0.1%	0.5%	—
Volatiles	C	1.4%	1.9-3.0%	3%	—	0.014%
	H2O	5.7%	12%	0.15%	—	0.045%6
	S	1.3%	2%	1.5%	—	0.12%
Mineral Oxides	FeO	15.4%	22%	10%	—	15.8%
	SiO2	33.8%	28%	38%	—	42.5%
	MgO	23.8%	20%	24%	—	8.2%
	Al2O3	2.4%	2.1%	2.1%	—	13.8%
	Na2O	0.55%	0.3%	0.9%	—	0.44%
	K2O	0.04%	0.04%	0.1%	—	0.15%
	P2O5	0.28%	0.23%	0.28%	—	0.12%
	CaO	—	—	—	—	12.1%
	TiO2	—	—	—	—	7.7%
Physical	Density (g/cm^3)	3.3	2.0-2.8	3.5-3.8	7.0-7.8	1.5-1.9

Table II. Mineral Composition of Meteorite Types. This table depicts four representative asteroids based on four different meteorite types. Individual meteorites vary dramatically in composition, and only four categories are presented here[6].

Technologies have advanced rapidly in recent years which make the execution of a robotic mining mission to an NEA far more viable. Asteroid flyby's beginning in 1991 culminated in the NEAR spacecraft (see Figure 2) encounter, orbiting, and landing on 433 Eros, the second-largest NEA[8,9]. In 2005, the MUSES-C spacecraft landed on 25143 Itokawa, and may have successfully brought back a surface sample[10]. The Deep Space-1 craft successfully utilized autonomous navigation and highly autonomous mission execution. The Mars Rovers have performed far beyond initial expectations and have demonstrated successfully the combination of autonomous decision-making, coupled with human telecontrol from Earth. The mining industry has turned some of its best efforts in recent years to automation of complex mining equipment[11].

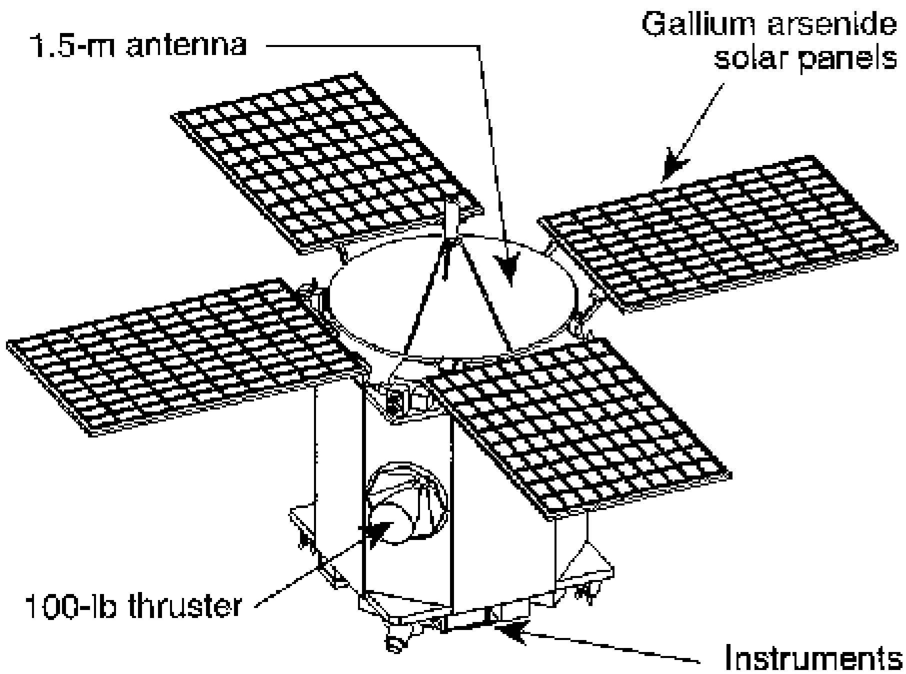

Fig. 2. Schematic of the NEAR spacecraft showing its basic components, including the solar panels, the 1.5-m antenna which transmits data to Earth, one of four rocket thrusters used to maneuver the spacecraft, and the instrument platform[12]. The lander-miner units proposed in this article will utilize a similar solar array and octagonal configuration, with six thrusters.

II. Mission Priorities and Principles

An optimized plan for a mining expedition to an NEA should emphasize the following goals:

1) NEAs should be targeted that promise maximum potential resource return, and minimal delta-V and orbital transfer demands, to hold down fuel costs and trip duration.

2) Mining equipment should be flexible, adaptable, and reusable to handle a variety of NEA conditions and problems. It should utilize high levels of autonomous robotics for fluid on-site response to conditions, with telecontrol by human operators from Earth to permit overall direction and trouble-shooting of the project.

3) ISRU should be used whenever possible for necessary elements such as propellant and power.

4) "Mission Enhancing technologies" (METs) should be tested, such as solar-powered hydrolysis, on-site development of propellant, and solar-thermal steam propulsion, to provide additional profit potential if successful.

5) A "minimal product return" design should permit profit potential even if only partial product return is successful (emphasizing first PGMs, then water, then Ni-Fe ore).

6) The use of distributed robotics technology should be advanced with this as well, including:

- communication and time-sharing between CCC and LMs
- high-level autonomy for terrain-mapping, mobility, and tool-manipulation
- capacities for human telecontrollers to override operations at many levels, as needed.

III. In-Flight Operations

To optimize chances of success, preliminary steps must include: selection of an accessible and profitable NEA and choice of an ideal launch window; payload components emphasizing versatile response capacities depending on conditions at the NEA and yet minimizing payload mass as much as possible; and propellant from LEO and returning to LEO that allows for reasonable mission duration.

A. Asteroid Selection

A number of studies have addressed selection of NEAs for rendezvous and sample collection based upon such factors as accessibility (delta-V, orbital parameters such as eccentricity, inclination, sidereal and synodic period), mineral types, and others[2,4,8,13-16]. Target accessibility plays a major role in attracting venture capital to the project, and the delta-V for sample return is the most relevant variable, since this affects the amount of profitable product that can be returned to LEO[4].

Much more mineralogic information needs to be acquired for those NEAs that are most easily accessible, before finalizing the optimal choices for this mission. However, for the purpose of recovering PGMs – and possibly water – two asteroids are suggested for the present proposal: 25143 Itokawa, a stony of about 500 meters length[10]; and 433 Eros, the second largest NEA also found to be S type but having somewhat variable composition[9]. The stony NEAs possess enriched amounts of PGMs[4], and Itokawa has an orbit of a mere 1.5 years duration, permitting multiple opportunities for approach from Earth. It is small enough to easily encompass with cables (see anchoring strategies below). Eros has both hard surfaces which allow cable attachments and smoother "ponds" between for regolith collection. Both have been explored through rendezvous and even landing attempts. Although water is likely to be more plentiful on C-type asteroids, PGMs are the first priority for this mission design. That ranking could change given a very active orbital and/or lunar infrastructure at the time the mission launches, since water and Ni-Fe ore would have a much greater profit value in supporting that infrastructure[19].

B. Computation on payload:

Using prior estimates for components of the payload, particularly the mining units[1,4], and adding a return launcher unit and solar-powered hydrolysis unit, an estimated payload of 8000 kg is used for this project, not counting the primary launcher from LEO. This includes 1500 kg for the two water-harvesting lander-miners, 2200 kg for the two ore-PGM-harvesting lander-miners, 500 kg for the orbiter (CCC), 1200 kg for the return solar-thermal steam launcher, 600 kg for the solar-powered hydrolysis unit, 1200 kg for the LH2 storage tanks, and 800 kg for remaining items, such as the solar reflector mirror. Table III summarizes the components, mass estimate, and functional role of the major components.

C. Type of Propellant

The most widely-used propellant with greatest thrust remains LH2/LOX, used for example to launch the space shuttle. This is the propellant of choice for launching this payload from LEO (Isp = 450 sec.), augmented en route by solar-electric propulsion (Isp = 900 sec.). The launcher should have adequate return fuel to operate a lean return mission bringing PGMs to LEO, whether or not the water extraction and hydrolysis units fail. However, if these systems operate properly, the prospect is opened up for returning more PGMs or adding substantial water and ore return. An alternative to LOX/LH2 has been described in detail using in-situ water resources: the use of solar (or nuclear) thermal steam or H2 propulsion[17]. The mission will include this as an MET which could expand versatility of mission (going to a second asteroid, for example) and/or permit the return of more processed materials. Some asteroids may have as high as 30% water content[18], and harvesting this for use in space will be of great value.

IV. On-site Operations

The following architecture is laid out to meet the project goals of flexibility to varying NEA conditions, adaptability to unforeseen problems, redundancy of units and systems in case of breakdown, and cost-effectiveness. This last condition is crucial to attract venture capitalists, and will require the use of miniaturization to reduce payload and therefore propellant requirements, as well as the use of in-situ resource utilization (ISRU) METs appropriate to this project to expand its profit potential.

Table III. Mission Hardware Components, mass, and function

Component	Mass (kg)	Function
CCC orbiter	500	Orbits NEA, providing uninterrupted linkage with LM units Maps surface of NEA and conveys map to LM units Updates map as LMs obtain more surface information Coordinates/directs LMs to optimal sites for mining
Solar mirror	200	To direct reflected solar energy to solar panels of LM units
Water-harvesting Lander-miner (LM)	750 (X 2)	Maneuvers in milli-G environment with 6 hydrazine thrusters Deploys cables and anchors these Moves along cables through ring hooks Analyzes, acquires and processes regolith by solar oven to produce $H_2 0$ Handles tools (e.g., jackhammer drill, cables, anchors, etc.)
Ore-PGM harvesting Lander-miner (LM)	1100 (X 2)	Maneuvers in milli-G environment with 6 hydrazine thrusters Deploys cables and anchors these Moves along cables through ring hooks Analyzes regolith, acquires and processes ore to obtain Ni-Fe ore and PGMs Handles tools (e.g., jackhammer drill, cables, anchors, etc.)
Solar hydrolysis unit	600	Hydrolyzes mined water to H2 and O2, providing LH2 and LOX fuel
Solar-thermal Propulsion Unit	1200	Provides additional launch platform to return additional harvested PGMs, Ni-Fe ore, or water to LEO, using either LH2 (Isp of 800 sec.) or water (Isp of 200 sec.)
Cables, winches, Pitons, drills, etc.	400	For LM units to maneuver, and to break up regolith
Containers for PGMs, ore, water	200	For return of product to LEO
LH2 storage tank	1200	Provides storage of LH2 obtained from solar hydrolysis unit to either add to primary launcher propellant, permitting more product mass return to LEO, or to launch the solar-thermal propulsion unit and cargo back to LEO.
Subtotal	8000	
Primary launcher From and to LEO	7000	Transports payload to NEA from LEO; returns mined product (PGMs, +/- Ni-Fe ore, water) to LEO
Total	15000	

A. The Command-Control-Communication Unit (CCC)

This unit will orbit the asteroid in a plane perpendicular to the line from the Earth to the NEA, and provide the necessary uninterrupted high-bandwidth communications with Earth. All the landers will have periods of time when their communication with Earth would be interrupted due to asteroidal rotation. The CCC will be positioned so that it can provide an angle of access to the side of the NEA, providing unbroken access to each lander (See Figure 3). Additionally, the CCC will provide the initial digital terrain map – obtained from orbit – that it will transfer to the AI of each lander-miner unit to provide each an initial crude map of boulders, surface irregularities, and textures to improve their maneuvering decisions. The CCC will provide ongoing monitoring of prospecting by the landers in infrared, UV and visible light ranges, and ongoing spectroscopic analysis of surface materials. It will coordinate the deployment of landers toward the optimal sections of the asteroid for prospecting. As a back-up system, in the case that the CCC malfunctions, the landers will each have the capacity to communicate with each other and with the Earth as well. This system would be less efficient of lander AI resources, but will still permit the mission to continue.

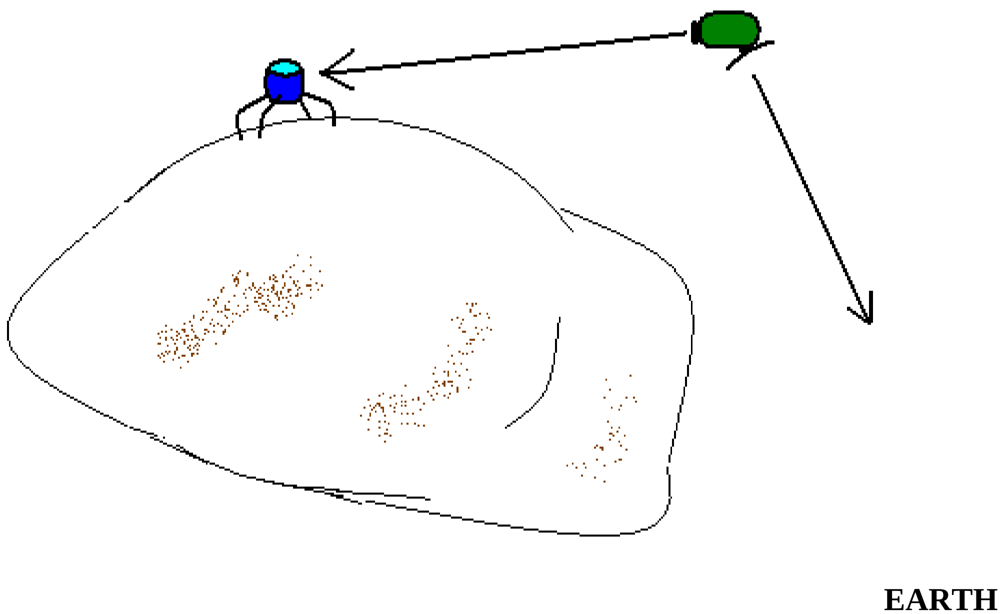

Figure 3. The CCC (in green) orbits the asteroid, providing uninterrupted access to the LM unit (in blue). Likewise, an orbiting mirror would provide access to solar radiation for LMs in shadow.

To provide additional "daylight" hours to the LM's solar panels, one MET will be the deployment of an expandable parabolic mirror that will capture and slightly focus sunlight, reflecting this to each of the LM's solar power units when they are out of the Sun's direct radiation as the asteroid rotates. The IN-STEP inflatable mirror experiment orbited by the Shuttle in 1996 was a 14-meter diameter reflector with a mass of about 100 kg[4], and could be adapted for this project.

B. Four Lander-Miner (LM) units:

An excellent NEO mining mission architecture has been proposed for harvesting PGMs, featuring an orbiter and four lander-miner units to provide redundancy in case of unit failure[1]. The current proposal takes the position that PGMs (a) may not be as plentiful as anticipated even with careful prospecting, since current techniques only permit study of the surface layer of regolith and a prospector will only analyze a small patch of regolith at depth; and (b) the return of water and secondarily Ni-Fe ore may approach the value of PGMs in the second decade of this century for a growing LEO and lunar space pathway[19]. Therefore, this proposal utilizes two LMs specialized for Ni-Fe ore and PGM extraction, and two for water extraction. Water not only provides staples for in-space colonization (water, propellant, shielding, and oxygen) but will be used for enhancing the proposed mission through additional fuel. The second LM in each category serves not only as a back-up unit should one fail, but expands the profitability potential of the mission substantially – doubling the potential harvest. All four LMs will be capable of operating in a fully autonomous manner. They will be operating in milli-G conditions, and will have to overcome the key challenges of anchoring to and moving on the asteroid surface, one that is often covered with loose regolith. A variety of means for addressing such problems have been proposed[4, 20].

A specific set of approaches will be implemented by these LM units for this proposal. Miniaturization will be used extensively to decrease their mass, reducing payload requirements. They will be able to navigate in the milli-G environment using a bank of six small hydrazine jets to maneuver in three dimensions (one for each face of the LM). They will each possess four articulated robotic legs (if one or even two legs fail, they can still operate to a limited extent utilizing the procedures below). These legs will each have three degrees of freedom, as the LM moves along the surface in a type of crab-walk[21, 22]. Each LM will possess two robotic arms for performing a large variety of tasks, including for example: the manipulation of cables along which the LMs will move; setting expandable anchors in drilled holes; moving containers of PGMs, Ni-Fe ore, or water; and cleaning off the LM's solar panels from accrued dust.

Clearly, the LMs will require the most complex and autonomous AI programs of all mission components. They will utilize sophisticated digital terrain mapping and maneuvering programs, currently under development[21-25], by which they can move along relatively uneven and variegated terrain without requiring human telecontrol. In addition, they will be capable of a number of tool-handling routines involving the arms, which will be fitted with a grasping unit with a prehensile type of grip. The advanced AI required for this is already undergoing testing in a number of applications[26-28].

The end of each of the four "legs" will be fitted with a four-fingered robotic "clawed foot" capable of gripping objects as large as 30 cm across, to permit "perching" or bracing against small outcroppings while moving. At the center of the "foot" will be a small diamond-headed drill that permits drilling to a depth of 10 cm for purposes of securing the foot and therefore the LM's leg to the surface for operations that demand substantial anchoring (Figure 4). This will be a smaller version of a diamond-headed drill proposed for asteroid mining[29].

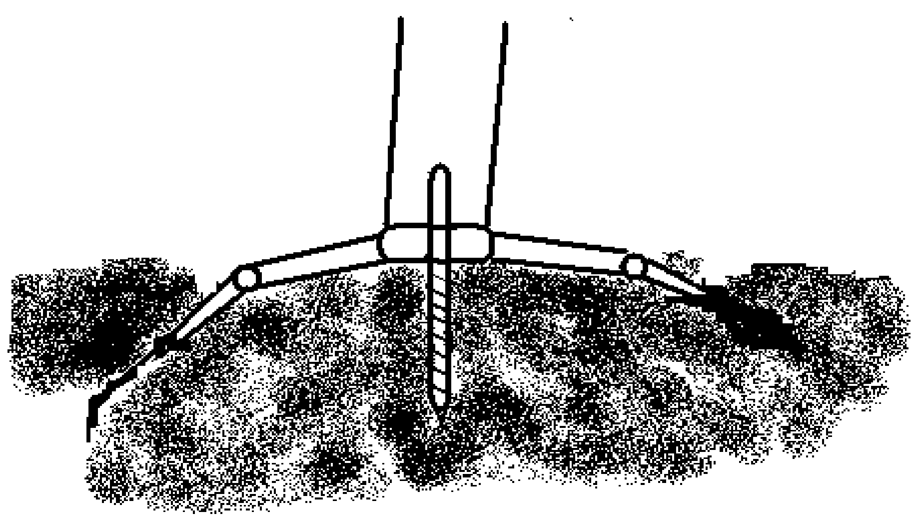

Figure 4. The "claw" at the end of the LM's leg grips the regolith while a diamond-tipped drill anchors it into hard substratum.

Initially, the four LMs will be deployed to four corners of a quadrilateral (Figure 5), each carrying the end of a cable, each of the two LMs at opposite corners of the quadrilateral sharing a cable between them, so that two cables cross each other in the center of the quadrilateral. The location for this crossed-cable configuration will be based upon initial mineralogic mapping by the CCC. Once positioned, the LMs will drill into the asteroidal surface at stony, rigid sections of the surface using diamond-headed drills and will insert pitons with expandable anchors into the drill holes (Figure 5). The cables will be tightened using small winches by each lander, and form a cross that will serve as the backbone of movement across the loose regolith, securing the LMs to the surface. Ideally, the distance between LMs carrying the two ends of each cable would approach half a kilometer (to both reduce the number of times pitons need to be re-set, and to take advantage of some degree of curvature or "wrapping" effect around the NEA to better secure the cable against the surface). To keep mass of the payload as small as possible, the cables will need to be very thin and made of tough, flexible material. These cables will serve as anchoring stabilizers, each LM being equipped with two hook-rings on their undersurface through which the cable slides. This allows them to move along the cables, securing them to the surface as they move.

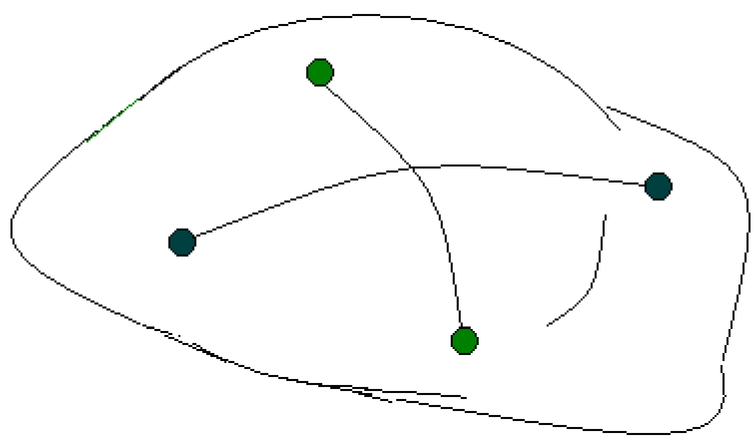

Figure 5. Lander-Miners (in green) deploy cables to four corners of a quadrilateral on surface of the NEA. There, pitons anchor the cables, and winches tighten them. LMs then use these cables to stabilize their motion along the NEA surface.

Alternatively, the LMs could entirely circle the NEA with the cables (e.g., with Itokawa). Once this system has been laid out, the LMs will deploy to those surface areas along the cables that the CCC mapping has indicated to be best for their specialized capacities, and begin regolith acquisition and processing. They will utilize a crab walk system for movement.

In the case of drilling into hard surfaces, the LM's four robotic legs will be secured with their central diamond-headed drill first[29], and a small expansion anchor will be inserted into each drilled hole, securing the legs firmly. Then, a jackhammer drill, which has the best capacity for breaking up hard regolith without placing back-pressure on the LM[2] will be inserted beneath the LM to break up the regolith, a chute lowered around this to prevent material from escaping into space. Each LM will be fitted with a clamshell-grab system for taking in the loose regolith.

There have been extensive discussions of mining platforms and systems for NEAs[1,2,4]. The current mission will utilize simplified mining units within each lander. For processing, each LM will have a pulverizer system using ultrasonic grinders to further break up the regolith. These ultrasonic grinding mills impart the fragmentation energy to feed-stream particles through a ceramic transducer operating at high frequency, rapid oscillations being used to crush feed material to the desired size. This appears to be a good choice, as they require significantly less energy than conventional grinding techniques, no fluids are used, and vacuum operations appear to pose no problem[1]. The material will then be advanced into an inner processing unit that will be unique for each of the two types of LMs.

C. Two Water-Harvesting LM Units:

Each of these LMs will contain an internal oven powered by photovoltaic panels that will heat the ground regolith to 700 degrees K., as heating to 673 degrees K. is necessary to boil out volatiles from phylosilicates[2]. Next, a cooler that rotates to provide centrifugal force will extract the water (the first of the volatiles to condense), and pipe it through small tubes to a collection sac. A separate solar oven unit could be utilized for more complex volatile extraction, but would add considerable payload cost and technical development costs to the project. Water is likely to be the single most valuable volatile, and the first to condense upon cooling from gas form. It will be the focus of the MET for this mission.

D. Two Ni-Fe Ore/PGM LM Units:

The "NEO Miner" described by Gerlach and associates[1] is a complex unit, and like the present LMs possesses anchoring screws and robotic legs, although in a different configuration. For processing of regolith the NEO Miner utilizes magnetic rakes, a movable auger extraction feed system, ultrasonic grinding mill, electrostatic beneficiation system, chemical processing unit, and platinum deposition and return containers. The three last components are relevant to the specialized Ni-Fe/PGM LMs herein described. Milled material will be fed into an internal electrostatic separation unit, to draw out the ferrous material and remove the remainder. Electrostatic beneficiation should work even better in the anhydrous, milli-G, vacuum environment of the NEA[1]. A portion of this ferrous material will be retained as Ni-Fe ore and stored in a receptacle for return to Earth.

For the final steps in producing PGMs, chemical refining will utilize either the carbonyl extraction process[1,30] or a chemical vapor metal refining (CVMR) process for extraction and separation of PGMs[31]. The carbonyl process requires CO which can be extracted as a volatile on-site but can also be recycled within a closed-loop system. The residue from this process using ferrous metal alloys is rich in cobalt and PGMs[1]. Another advantage of this process is that considerable development work has already gone into such a unit[32]. The CVMR process has the advantage of operating at low pressures and temperatures (80 to 100 degrees C.), thus making it more economical, but it is uncertain whether it can be miniaturized and automated[1]. Finally, PGM deposition will occur into an enclosed container for Earth return.

E. Solar-powered hydrolysis unit (SHU):

This MET would provide additional propellant with high thrust capacity, using the primary launch unit. It can also provide H2 and O2 for on-site fuel cells if needed. Development of this technology should emphasize miniaturization, automation, and particularly the management of LH2. Utilizing a solar-cell array to generate the necessary voltage (1.3 V) and standard platinum electrodes to hydrolyze water, the hydrolytic unit would convert liquid water provided by the water-harvesting LMs into H2 and O2 gas; these would be siphoned through separate pipes in which temperatures would plummet to the range needed for liquid H2 (-259 to -253 degrees C) and liquid O2 (-219 to -183 degrees C)[19]. Much of the temperature drop necessary would be provided by simply directing the pipes into shadow, while providing selective degrees of thermal conductance. Imparting motion or flow may require the use of centrifugal motion to elements of the apparatus along the pipes. The LH2 and LOX would then be collected in separate propellant units in the launchers until the units were adequately filled. The cooling and storage of liquid oxygen will be far simpler than that of LH2. LOX temperatures span a range of 36 degrees C., while LH2 must remain within a narrow 6 degree C. range, very close to absolute zero. In addition, the LH2 requires a tank that can hold 20 psi pressure at 20 degrees K[33]. Recently, Hydrogen Solar has developed a solar hydrolysis unit with 8% conversion rate using nanocrystalline metal oxide film, which produces hydrogen from water[34]. This could produce H2 for the solar-thermal propulsion unit described below, or additional LH2 and LOX for the return launcher, expanding the mission propellant capabilities to include another asteroid.

F. Solar-thermal Propulsion Unit (STPU)

This novel method of propulsion, using either H2 or water, and a nuclear or solar thermal power source, has been quite extensively investigated[17]. The advantages are that either H2 from hydrolysis of asteroidal water or just water itself can be used with a solar power source to provide high thrust alternatives to LH2/LOX, using entirely space-based resources. If the hydrolysis unit functions, the STPU offers the ability to extend the project to deliver more PGMs, water, or Ni-Fe ore to LEO with a separate launcher, or to allow the exploitation of an additional asteroid. If the unit does not function, unhydrolyzed water extracted from the NEA can be utilized to supply steam propulsion. Although LH2 provides a higher degree of thrust than water (Isp of 800-900 sec versus 200 sec), it also requires much heavier containment, as well as a refrigeration system[17]. In making final decisions with regard to which system to invest in, this proposal favors the use of water-to-steam propulsion, solar-powered. It is far simpler, less expensive, and removes the necessity of heavy tanks required for LH2 storage[33]. The application will be an MET to either (a) bring back additional PGMs, ore and water with the steam-powered launcher; or (b) launch two of the LMs to a second NEA if the initial NEA is disappointing in its resources. The two additional landers could both be the PGM LMs, or could be one of each type of lander, depending upon mission parameters dictated from Earth. Since delta-V to depart from the NEA is so small, it is feasible to use this MET to deliver additional supplies to HEEO or LEO[4]. Extensive work has been performed on STPUs by the U.S. air Force Rocket Propulsion Laboratory with support from Rocketdyne, L'Garde, and Spectra Research[35]. Their goal was to produce light-weight, efficient concentrators and simple, reliable thrusters for a solar rocket. Rocketdyne performed research and development on the engine using hydrogen as propellant, but modifying it to use water would not be very difficult[35].

G. Return launchers

The return launchers therefore include:

a) the primary launch unit that brought the mining platform to the asteroid. This will be equipped with LH2 and LOX propellant chambers, and provide maximum thrust for transporting PGMs, water and/or nickel-iron ore back to LEO. Sufficient LH2/LOX will remain after reaching the NEA to return to LEO for "minimum-return" of PGMs, and at least small amounts of water and Ni-Fe ore as a demonstration of those METs, if possible.

b) a back-up launcher that can utilize solar-thermal steam propulsion. If the ISRU equipment for producing LH2/LOX malfunctions, then this system can utilize water itself from the asteroid to return the PGMs, and smaller samples of water and nickel-iron ore if desired. This could provide mass payback ratios as high as 1000:1[17].

Transport of water may be managed through thin collapsible polybenzoxazole membranes[36], ore and PGMs through vectran-kevlar composite inflatable bags such as are being currently tested for orbiting space hotels by Bigelow Aerospace[37].

V. Artificial Intelligence for Intercomponent Operations

The use of an advanced level of artificial intelligence to provide autonomous operation for the on-site project components will enhance likelihood of mission success. The following capacities will be of key importance:

Decision-making based upon:

spectroscopic data indicating surface composition and terrain to guide mining location on the NEA

position of the component (whether LM or CCC) relative to the terrain and to all the other units

For LMs: Complex movement in three dimensions using thrusters and legs; manipulation of objects

Capacity by the LMs to choose drilling based upon direct analysis of regolith texture and content

LM capacity to sense temperatures and ore-grade and content within internal processors, as well as volume and mass of the regolith that is being taken into the unit.

In this architecture, the CCC will provide a "big picture" view of the surface features and spectroscopic data to assess mineral content. This will allow it to deploy the LMs first to optimal points for placing pitons for the cables, and second to points with the highest likely content of interest, whether PGMs, Ni-Fe ore, or water. It will provide the LMs with ongoing analysis and input from human teleoperators when mission parameters need to be changed.

The LMs will have built-in autonomous navigation permitting them to assess terrain features, guide their legs in movement along the terrain, control the placement of the clawed "feet" and drilling anchors, as well as govern the automated processing units in the LMs for refining regolith into PGMs, Ni-Fe ore, or water. In addition, their robotic arms will permit manipulation of objects such as collection sacs to place onto the return launcher, of cables to hook onto, of pitons, of additional drilling or analytic tools, etc. The water-harvesting LMs will be capable of transferring water containers to the hydrolysis unit and to the solar-thermal propulsion unit, via use of these arms. Therefore, the LMs will require the highest degree of AI, borrowing on: advanced robotics technologies being developed for various applications[21-28], extensive experience with the Mars Rovers[38]; and the increasingly complex robotic mining tools being developed for Earth-based mining[11], some capable of digital terrain mapping, various types of sensor-guided movement, and self-monitoring of various ore processing steps.

VI. Outline of Sample Mission to Eros

The following outlines a potential sequence of events for a mission with 433 Eros chosen as the NEA target:

A. Launch of payload, including primary launcher, and fuel, to LEO via Russan Proton booster.
Launcher is fueled in LEO and launch initiated from LEO; or alternatively,
single launch of entire payload from Earth surface directly to Eros (probable cost savings).

B. Upon rendezvous with Eros

As the craft orbits Eros, the following components detach and deploy:

1. The inflatable mirror deploys to orbit Eros in a plane perpendicular to the axis from the Sun to Eros.

2. The CCC orbits in a plane perpendicular to the axis from the Earth to Eros.

3. The LMs disengage from the payload and two move the STPU and SHU to the surface, anchoring them to hard surface regions via short tethers. Two others anchor launcher, pitons and cables.

4. While the LMs are in operation, the CCC orbits and forms a detailed map (updating earlier maps from the NEAR spacecraft mission with specific detailed mineralogic/terrain analyses), downloaded to LMs.

C. Mining Operations

1. Based on this data, teleoperators from Earth choose optimal sites for the initial crossed-cable placement; this should secure adequate anchoring cites for cable ends via pitons as well as optimize the terrain and ore grade for PGMs along the path of the cables.

2. LMs begin moving and extracting regolith, whether hard (via drilling) or soft. As they go, they form their own detailed terrain maps, adding details of their on-site mineralogic analyses, and send these updates to the CCC and thereby back to Earth.

3. Based upon initial run along these cables, decision may be made from Earth to set cables in a new configuration.

D. Deployment of Mission-Enhancing Technologies (e.g., solar hydrolysis, solar-thermal propulsion, etc)

1. The solar-hydrolysis unit (SHU) begins operation using its initial water supply; LMs bring more water - if harvestable - to provide greater amount of LH2 and LOX for primary launcher as well as STPU.

2. The solar-thermal propulsion LH2 tank is filled by the LMs bringing LH2 from the SHU. If SHU does not function, water itself can be brought and the STPU will use steam propulsion instead.

F. Return to Earth

1. The LMs load the return primary launcher with PGMs, and/or Ni-Fe ore, and water

2. The LMs remain behind as the primary launcher returns with its payload to LEO

3. LMs continue their mining, and load the STPU.

4. Depending upon the results from the mission, one or two LMs may be attached to the STPU and go to a second NEA for a much longer, steam- or LH2- driven flight and more harvesting attempts. More likely use of STPU will be to return additional product directly to LEO.

VII. Addressing Potential Problems

The mission design emphasizes back-up processes to troubleshoot a variety of potential problems that could arise in this project. It is crucial that adequate flexibility and adaptability be built into the plans, because even with considerable preliminary analysis of an NEA by a prospector unit, many unknowns will remain. Profitability will be enhanced if the design is robust enough to handle anticipated problems and still return profitable product.

A. Failure of individual components

The redundancy of the landers provides a single back-up to each type of LM. If the CCC fails, the four LMs each have a smaller bandwidth means of communicating with Earth depending upon whether the NEA is blocking the signal or not. Their capacity to work as a group may require some of the AI being developed for autonomous group-robotic behaviors for undersea mapping[39,40].

Whether or not the solar mirror MET deployed by the CCC fails, the LMs will be equipped with solar-powered fuel cells similar to those designed for the NASA HELIOS wing system[41], although their activity will have to be further conserved due to the decreased solar energy exposure. Failure of the solar-powered hydrolysis unit has already been addressed above: the system can work with the remaining fuel from the initial launch to return to LEO in the minimal-return case, and water can itself be used for the solar-thermal steam propulsion unit to bring back some additional material.

B. Varying surface conditions and regolith content

The LMs - including the cable transport system - are designed to deploy over a variety of surface conditions, from hard to dusty/soft, and the robotic legs permit anchoring for jackhammer drilling. In conjunction with the CCC overarching analysis-and-deployment system, they provide a tremendously flexible, adaptive approach to harvesting because they are prepared to yield profitable PGMs, Ni-Fe ore, and/or water and can be deployed to the best locations on the asteroid being mined. They can also alter their priorities via human telecontrol, in response to real-time feedback from initial mining processes on the surface and new spectroscopic analyses of overturned regolith.

C. Variable solar exposure and temperature variation:

As already discussed, the MET of a reflective mirror (already deployed on a Space Shuttle mission)[4] to concentrate solar energy and direct it to the solar cells of each LM can improve the power performance for the entire mining operation, despite asteroid rotation. All equipment will be built to withstand temperature extremes. For example, on Eros these can range from –150 degrees C. to 100 degrees C[8].

The use of regenerative fuel cells which can be “recharged” through hydrolysis powered by solar arrays is being actively developed[41], and should be used for the CCC, LMs and SHU if available.

D. Drilling in null-G conditions

This most challenging condition is managed by the "layered" sequence of: (1) fastening pitons at hard surface points at a distance, in two directions, crossing at a central location, then (2) having the LM units fasten ringed rods to these cables to secure them as they move, and (3) using the drills in the center of each robotic "claw" to further secure the four "walker" legs as much as possible to the harder surfaces before using jackhammer drilling. For softer surfaces, this will not be needed, as a simple clamshell or corkscrew system will be able to bring regolith into the LM, using the cables to anchor.

E. Dust

This could be a major impediment, as noted by the Apollo astronauts with regard to lunar dust during the manned Moon missions. Currently, NASA has launched a four year Project Dust to investigate ways to deal with dust impacts on equipment. The Mars Rovers solar panels worked effectively long past their predicted lifespan, without the use of small wipers to clean off the solar panels**.** Problems for the use of PV solar cells on asteroidal surfaces will resemble the challenges on Mars in some respects: lower solar intensity due to greater distance from the Sun; dust which may well possess an electrostatic charge from solar radiation; low operating temperatures[38]. Electrostatic charge reversals may be needed for the removal of Ni-Fe dust from key parts of the machinery. The use of vaporized water or steam ejected from a small "cleaning unit" may be a cheap source of cleaning, manipulated by the robotic arms of each LM if water can be harvested in sufficient quantities. Dust brushes will otherwise be used to permit cleaning of solar panels and other surfaces.

F. Handling liquid H2

Because it has such a narrow temperature range (6 degrees celsius) and needs to be pressurized, this may be the most challenging MET to address. The use of LOX/LH2 storage in LEO has been addressed in a preliminary way[42]. The thick casing needed for additional storage tanks (beyond that of the initial LEO-to-NEA launcher which will be used to return the "minimal-return" products), would add to payload and thus propellant requirements[17]. Therefore, this MET will be reassessed for cost-benefit considerations before final selection.

G. Paucity of Harvestable Water

Since the mission priority is focused on the most currently profitable products – PGMs – the choice of NEAs has therefore been suggested as S-type asteroids. However, our knowledge of how variegated the mineral composition of a given NEA is remains minimal. It is possible that more carbonaceous silicates may be found on a stony asteroid, in which case the two water-harvesting LMs will be highly productive, and additional material can be returned to Earth via the solar-thermal launcher. Depending upon the launch window and existing orbital or lunar markets at the time of the mission, a C-type NEA may be included in the mission design as a primary or secondary mining target.

VII. Conclusion

The time is ripe for providing a specific paradigm for a profitable asteroid mining project. Relevant technologies have matured, and analyses of NEA types and details of mining techniques, equipment and costs have advanced to a tremendous extent in the last decade. The profitability of a mining mission that permits flexibility, adaptability to varying NEA conditions, and multiple return scenarios depending upon the use of mission-enhancing technologies is increasingly likely. The specific details of the proposed mission are designed to optimize the likelihood of success and permit testing of those enhancing technologies that can further accelerate the expansion of NEA mining.

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