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Comprehensive Report on Extraterrestrial Resource Extraction

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Abstract

The prospect of asteroid mining provides a plethora of riches that include metals and water. As the number of discovered asteroids continues to grow, opportunities arise to commercialize these resources within Near-Earth Asteroids (NEAs). With urgent applications on Earth and in space, NEAs allow for a surge in sales. Planning forward, Astroider Aerospace Systems follows a mission split into four phases. Phase 1 develops a series of spacecraft using existing technologies, titled as Near-Earth Asteroid Miners and Near-Earth Asteroid Surveyors. Phase 2 first launches the surveyors to candidate NEAs, prospecting them for ores. To identify potential celestial bodies for this phase, astronomical tools are employed: Precovery Database, Photometry, and Radar Data. Phase 3 then proceeds to launch the miners as soon as targeted NEAs are determined to have ample mining zones. The miners commence extraction and once finished, deliver the payloads back to Earth. Phase 4 finally commercializes these transported NEA material payloads, where they are sold under Astroider Aerospace Systems for profit. Findings showcase the constituents of each phase working in synergy to promote the start of an NEA mining program.

Keywords: Asteroid Mining, metals, water, Near-Earth Asteroids, Asteroid Miners, Asteroid Surveyors, NEA mining program

The Mining of Cosmic Treasures from Near-Earth Asteroids

Asteroid mining provides an advantageous platform in which harvested materials can be applicable for all of humanity. As the human population increases, a growing demand exists for natural resources such as phosphorus, silver, copper, gold, etc (Hessel et al., 2020). That said, views have been expressed about asteroid mining and its overall viability. To elaborate, a prevailing opinion suggests no concern for the current capacity of metals, as technical progress extends current mineral reserves, and recyclable products add to the supply of ores (Bignami & Sommariva, 2016). On the other hand, arguments advocating for asteroid mining stem from the critically of minerals, which refers to minerals whose supply is constrained, demand is high, and market is global (Bignami & Sommariva, 2016). Because of this, tensions can arise in how countries wish to accumulate and distribute their resources. Bignami and Sommariva (2016) detail that South Africa accounts for the largest deposits of PGMs (Platinum-Group Metals), whereas the Democratic Republic of Congo constitutes 50% of cobalt mined. Due to their political instability and labor unrests, the authors exclaim highly volatile prices exist for both, which are present in glass, electronics, non-transport emission-control equipment, and industrial manufacturing on Earth. Given the proximity of Near-Earth Asteroids, expeditions can allow for the commercialization of different types of materials available, to gradually combat the high demand in our growing population.

Commercialization of Near-Earth Asteroid Types

The four types of NEAs (Apollos, Atens, Amors, and Arjunas) are classified based on orbital trajectories, which allow for different mining timeframes highlighted in **Table 1**. Alongside each type of NEA, they can comprise of different compositions denoted by a letter system. Loder (2018) explains, type C asteroids contain mostly water, metal, and organic compounds. Type S asteroids hold platinum-group metals (platinum, osmium, iridium, rhodium, ruthenium, and palladium) and Type M asteroids consists of common metals (iron, nickel, magnesium, etc.). Heavily applying to the field of space exploration, water can be used for life support in space to sustain organisms, rocket fuel via electrolysis (splitting water into hydrogen and oxygen with electricity), and filling tanks onboard spacecrafts to provide radiation shielding (Loder, 2018). Regarding the myriad of metals available on NEAs, applications in manufacturing and electronics utilize their differing properties in conductivity, melting points, malleability, etc. Evident in how much wealth they can bring, an asteroid more than 200 meters in diameter could supply >~ 500 tons of platinum-group metals worth more than $5 billion (O'Leary, 1988). Accounting for inflation, this would equate to around $11 billion in today's economy (Alioth Finance, n.d.). The opportunistic value of Near-Earth Asteroid Mining paves the way for space commercialization.

Previous Work Done

Although asteroid mining is still new and barely explored, it has ignited various ventures in the past. The Planetary Resources Incorporation had plans to conduct ultra-low-cost robotic space exploration beginning with the Arkyd 100 Series of space telescope missions to identify commercially attractive near-Earth asteroids (Lewicki et al., 2013). Likewise, the Deep Space Industries had an objective to fly Prospector-1 to a Near-Earth Asteroid and investigate the value its resources could bring (Business Review USA, 2016). Failure to acquire proper funding, prevented the progression of either projects. However, with Astroider Aerospace System's financial allocation, we can jumpstart the field of asteroid mining once again with our mission plan.

Mission Overview

Within our four-phase mission, they first include Asteroid Surveyors in identifying rich ore deposits. After deposits are identified, our Asteroid Miners excavate these sites and transport the collected supplies back to Earth. With assistance from SpaceX's Falcon Heavy Rocket, each phase capitalizes on the introduction of commercial space mining operations. That said, we will mine Near-Earth Asteroids to generate profits on Earth.

Phase One: Development

At Astroider Aerospace facilities, a set of spacecrafts are to be developed in preparation for Near-Earth Asteroids expeditions. We examine their core components to highlight their purpose and contribution toward the success of any mining mission.

Near-Earth Asteroid Miners

Starting with the miners, it is advisable to adapt different methods to break up an asteroid surface, which can be metallic, rocky, and icy. Using techniques similar on Earth, this can include numerous rotary drills, cutters, and crushers. Additionally, Andrews et al. (2015) notes the development of helical boring tools which can utilize microwaves to break up frozen ores. Ensuring stability for this mining process, a culmination of anchors should also be in place to mitigate any slight movements. As the OSRIRS-Rex mission traveled to asteroid Bennu, Bierhaus et al. (2018) details that landing on a small body required the spacecraft to maintain contact and orientation with the surface using thrusters or anchors. As miners extract the surface, constituents from its ores will require separation to yield pure asteroidal materials absent of any valueless particulates. Used in the nickel purification industry for over a century, Aghamiri and Ghobeity (2020) note, the MOND Carbonyl process refines metals by a reaction between its ore and heated carbon monoxide. Operating around 50–60 °C from the flowing heated carbon monoxide gas, this temperature raises between 200–280 °C as the process is complete (Morrison et al., 2018). The result includes high purity products, minimal energy consumption, and a non-polluting effluent waste (Aghamiri & Ghobeity, 2020). Similarly, a heated distillation system can be implemented for the collection of water. Andrews et al. (2015) identifies a temperature of 700 °C to extract water from small particles on an asteroid. Both metals and water should be separated by distinguishable parameters that include but are not limited to density, magnetism, and conductivity. This step mitigates any cross-contamination while allowing for a method to organize consumer goods. For each miner, they are estimated to weigh around 5,000 kg to allow flexibility for its multiple sub-components, to capitalize on the collection of asteroidal supplies.

Payload Return Capsules

Aboard each miner, the Payload Return Capsule contains the supplies taken from Near-Earth Asteroids. Split into two compartments, one will hold metals and the other water. Ensuring ample profits and supplies are met, each capsule should have around a 1-3 metric ton capacity. **Table 2** shows the current prices for various NEA resources at 1 kilogram on Earth, advocating for this design. As capsules reentry Earth's atmosphere, few elements need to be in place to ensure the safety of the products onboard. Utilizing a similar heatshield on the Stardust Return Capsule, it uses a graphite-epoxy material covered with a PICA (Phenolic-Impregnated Carbon Ablator) based thermal protection system (Sandford et al., 2020). PICA is a lightweight material developed to withstand high temperatures up to 2800 °C (Tran et al., 1996). Following this, parachutes serve to increase the payload's drag force, lowering its descent velocity. Moreover, this parachute system can be used to control the reentry trajectory to lower risks against populations or facilitate an easier retrieval (Bogdan et al., 2017). Optimizing this step further, incorporation of GPS can provide the positional coordinates a reentry capsule follows to establish rendezvous zones for pickup.

Power & Propulsion

A Plutonium-238 RTG (Radioisotope Thermoelectric Generators) powers our miners as its applicability focus on space exploration and terrestrial equipment (Gusev et al., 2011). **Table 3** lists previous applications of RTG's which include missions to the Moon (Apollo), Mars (Viking-1,2), and deep space (Pioneer-10,11, Voyager-1,2). Notably these authors emphasize pluntonium-238 RTGs are completely self-contained electric power sources that have long proven service lifetime (>15 years) and high reliability. In addition, pluntonium-238 has a half-life of 87.74 years and a specific power of 0.56757 Watts per gram (Rinehart, 2001). To avoid radiation exposures within Earth's atmosphere, Gusev (2011) explains, adapting an iridium plated carbon-carbonic leak-tight pressure capsule tested to not exceed 300 ℃, is probable during emergencies that can arise during launch or entry. This is important as missions can vary in how much radioactive material is carried. On a SNAP-27 RTG for Apollo 12, this apparatus utilized 8.36 pounds of Plutonium-238, which accounted for all travel and experiments respective to the Moon (International Atomic Energy Agency, n.d.). Given the total distance to an NEA being significantly greater, each spacecraft would require a higher amount of Plutonium-238. However, Caponiti (2015) states by 2022, the remaining inventory of Pu-238 will be around 21 kg (46.297 pounds) in the United States. Priced at $1,968 per gram (Werner et al., 2016), a pound of Pu-238 nearly costs $893,000. Obtaining a couple to few pounds at most due to the scarce limit, Astroider Aerospace Systems would have to wait on more Pu-238 production or consult other nations for additional amounts. Despite these delays, this extra time can help secure other modules that play a part in our Near-Earth Asteroid mission plan.

Alongside this power source, a monopropellant of hydrazine will be used for propulsion. Known as the most used monopropellant, its quick response in thrusters have allowed for sufficient attitude control system (Adami et al., 2015) which is responsible for a spacecraft's orientation. Composing of hydrogen and nitrogen, hydrazine has a performance of about 20% higher than hydrogen peroxide as a monopropellant (Adami et al., 2015). Present in deep missions such as Voyager 1 and OSIRIS REx, applications of this propellant can serve to cover the distances between NEAs and Earth.

Near-Earth Asteroid Surveyors

Powered and propelled identically, the Near-Earth Asteroid Surveyors will examine and determine optimal mining locations on NEAs for miners to land at. Going about this process, the NEAR Laser Rangefinder (NLR) that was a part of The Near-Earth Asteroid Rendezvous (NEAR) mission to 433 Eros will be implemented. Consisting of a direct-detection, time-of-flight laser altimeter, it determines the range of a spacecraft from an asteroid by measuring the laser pulses round-trip travel time (Cheng, 2000). This individual also clarifies, as these laser pulses are pointed at an asteroid, observations yield topographic data which can assist in determining the shape, mass, and density to help understand its internal structure. **Table 5** reports the specifications for the NLR alongside other LIDAR instruments. To that end, the potential of autonomous navigation arises as an urgent alternative in which an NLR supports. As said by Weeks (2002), the accuracy of autonomous navigation is critically dependent on the development of an accurate shape model. Given the laser altimetry data from NLR, it gives us the opportunity to negate human ground-based navigation when dealing with multiple deep space missions.

Aiding in locations for optimal mining, an X-ray/gamma-ray spectrometer (XGRS) is employed onboard. Apart of the same mission to Near-Earth Asteroid, 433 Eros, this device measures X-ray, and gamma-ray emissions to map the surface elemental composition (Goldsten et al., 1997). The team describe the configuration of this apparatus weighing 27 kg and using 31 Watts of power. Operating in two modes, the first includes X-rays fluorescence measurements in the 1-10 keV range to indicate surface abundances of Mg, Al, Si, Ca, Ti, and Fe. The second mode involves Gamma-ray quantifications between 0.1 to 10 MeV to highlight cosmic-ray excited elements (O, Si, Fe, H) and naturally radioactive elements (K, Th, U). Assisting space mining further, X-ray florescence can calculate PGM ratios (Plantium Group Metals) (Suggs et al., 2014). While Gamma Rays can help evaluate the presence of possible ice deposits (Mitrofanov et al., 2021). Totaling around 200 kg per surveyor, Andrews et al. (2015) emphasizes this value for similar apparatuses to help launch as shared payloads to save time and costs. Working in numerous units plays a key in maximizing the allocation of resources from NEAs.

Launch System

Astroider Aerospace System's Near-Earth Asteroid mining missions launch with the Falcon Heavy Rocket and its associated stages. As described by SpaceX (2021), the Falcon Heavy Rocket stands at 70 m high and 12.2 m wide. Classified as the world's most powerful rocket, its 27 Merlin engines use RP-1 and liquid oxygen to generate more than 5 million pounds of thrust at liftoff. Having a total of 7 landings, 4 rockets have reflown, capitalize on this launch's system reusability for repeated missions. With payload limits differing with respect to an orbital destination, a journey to Mars involves a 16,800 kg max capacity. Tied with a height of 13.1 m and 5.2 m diameter, this offers mission flexibility in how big/small we wish to design our miners and surveyors as payloads. Although the orbital distance to Near-Earth Asteroids varies, we know they cannot dwell near or past the orbit of Mars (~2.5 AU). Hence, providing leniency to launch multiple units of both spacecraft types. Going forward, it is ideal to use the Falcon Heavy repeatability to carry Asteroid Miners separate from the Asteroid Surveyors. Mainly, to have surveyors relay the prospecting data back before deciding where to launch the miners. That said, SpaceX (2021) explains the individual components for this space vehicle. Starting with Stage One, it comprises of 3 center core engines and 12 landing legs made of state-of-the-art carbon fiber with aluminum honeycomb. Moving on, Interstage, a composite structure connects the center core on the first stage and second stages. As well as holds both release and separation system. Finally, Stage 2 draws upon Falcon 9's design of one Merlin Vacuum Engine, to deliver the rocket's payload into high LEO, to be nuclear safe and above 99% of the space debris (Andrews et al., 2015). After the main engines cut off, Stage 2 restarts and aligns the payload to follow an orbital trajectory to a desired NEA. Once aligned, the payload module separates and makes it voyage. Acting as an ideal carrier, the Falcon Heavy rocket strengthens the start of space mining.

Phase Two: Surveying

Astroider Aerospace Systems will initially launch 5 Asteroid Surveyors via the Falcon Heavy Rocket for every Near-Earth Asteroid candidate. Once at their destinations, their NLR and XGRS devices begin relaying data back on Earth to prep miners for departure. Success of this program depends on the long-term commercialization for accessible NEAs. Given this, we analyze the orbital paths Near-Earth Asteroids can take and methods to help select viable ones.

Orbital Trajectories and Assistance

Detailing the orbital parameters of known NEA types (Atens, Apollos, Amors, and Arjunas), Ross (2001) details their semi major axis and perihelion distance available in **Table 4**. While optimal mining periods yield varying parameters, a lower value for all missions would be more favorable, despite shorter mining timeframes. Being measured in astronomical units (1 AU = 1.496×10^8 km), the semi major axis is half the total of a celestial object's nearest (perihelion) and furthest point (aphelion) from the Sun. This estimates the total distance a spacecraft would have to travel, which ultimately affect how often an NEA can be visited. To further assist in our selection process, few astronomical applications prove use: PRECOVERY, Photometry, and Radar Data.

PRECOVERY

Through the EURONEAR (European Near Earth Asteroids Research) network, this database uses two types of formatted observing logs (Vaduvescu et al., 2009). According to these researchers, the first format contains the data: RA & Dec at epoch J2000, Instrument Field of View, Julian Date, exposure time, and IAU observatory code (Vaduvescu et al., 2009. Otherwise, the second uses a WFPDB format, available in hundreds of old wide field plate archives around the globe that have insufficiently been explored. Combining recent and past astronomical information allows for the recovery/discovery/improvement of asteroid orbits (Vaduvescu et al., 2009). Evident already, the team mention assigning the Bucharest Observatory old plate archive onto PRECOVERY, where 100 NEAs observed were either precovered or recovered. Likewise, the Canada-France-Hawaii Legacy Survey used PRECOVERY to discover NEAs being present in over 200 images. Applying this to Astroider Aerospace Systems heightens our knowledge for orbital accuracy and pinpointing.

Photometry

Previous brightness measurements of NEAs, indicate its rotation and motion around the Sun (Badescu, 2013). Moreover, applying different filters at various wavelengths on these measurements, can allow the construction of color maps to indicate surface composition (Badescu, 2013). This can be useful for Astroider Aerospace Systems to find abundant deposits of specific resources to accommodate changing consumer needs on Earth.

Radar Data

Ideal for Near-Earth Asteroids due to its limited signal, range-Doppler radar samples an asteroid surface in bins (Badescu, 2013). With a bin representing one pixel in a range-Doppler plot, the shape and rotation of an NEA can be modelled from a set of plots at different geometries (Badescu, 2013). Astroider Aerospace System can combine this information with data from the Asteroid Surveyors to supplement additional perspectives for NEAs.

Phase Three: Extraction

Once sufficient data is obtained from the Asteroid Surveyors, Astroider Aerospace System will launch 3 Asteroid Miners via The Falcon Heavy for every Near-Earth Asteroid target. Arriving, the miners will land at locations predetermined by the surveyors. Shifting from one marker to another on-site, the miners begin to fill up the payload return capsules. When filled, the Asteroid Miners begin their journey back to Earth. Two situations arise at this point depending on the NEA target. One, if all mining operations are complete, the Asteroid Surveyors follow the miners back to Earth. However, if multiple expeditions are to be made the surveyors remain on-site continually looking for additional sites to mine.

Phase Four: Commercialization

Venturing back, Asteroid Miners will transport the payload return capsules to the surface of Earth. Astroider Aerospace Systems will then retrieve the space goods and bring it back to the facility. Products are gathered and undergone through a quality and inspection check by a ground team. Displayed on the market, money generated goes back into Astroider Aerospace Systems to promote future missions.

Near-Earth Mining Mission Analysis

Among any asteroid mining mission, it is evident numerous steps need to be in place. Although we are just limited to NEAs, there contributions can provide the assets other space exploration mission need to progress humanity. Brian O'Leary (1988) emphasizes that space exploration can improve East-West relations, industrial growth, spiritual awareness, and perhaps the first signs of extraterrestrial life. Despite numerous advantages, these other space missions can also cause a delay for Near-Earth mining missions. On top of asteroid mining still being a new field, many other projects have been in development for a while and are currently being prioritized. Such include the 2024 Artemis program to return astronauts back to the Moon, JWST 2021 December launch, missions to Mars, and uprise of commercial space travel. As a result, this can put delays in Astroider Aerospace's System mission phases.

Near-Earth Mining Mission Conclusion

Altogether, an asteroid near Earth will be mined to generate profits for Astroider Aerospace System. Utilizing existing technologies form a step-by-step process to prioritize objectives that contribute toward space commercialization. With various resources on different types of NEAs, this mission plan format can be customizable in how many Asteroid Miners & Surveyors wish to be sent, promoting feasibility and adaptability. Given that a multitude of NEA available resources play fundamental roles in society, without them life would be much scarcer and more primitive. While humanity's population continues to ascend, methods must be in place to extend our current reserves to promote future advancements in all fields around the world.

Near-Earth Mining Mission Recommendations

Regarding the scope of a mining mission plan to Near-Earth Asteroids, there are two recommendations that can optimize this endeavor to aid Astroider Aerospace Systems.

Partnerships

Establishing partnerships with other space organizations/industries can increase the frequency of Near-Earth Asteroid mining missions. Additionally, it opens the opportunity to promote awareness and invite teams to help contribute. Space mining has the potential to benefit day-to-day living for everyone, by providing resources than can advance all societies.

Warehouses

As Astroider Aerospace Systems acquire supplies from NEAs, a larger amount of space on Earth will be required to accommodate them. Investing in warehouses act as storage hubs, to keep track of these materials that will be sold to consumers.

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Table 1

Mining Timeframes

Mining Period	**Near-Earth Asteroids**
x ≤ 3 Months	Apollos & High eccentric Amors
1.0 Years ≤ x ≤ 1.5 Years	High eccentric Atens
3 Months < x < 1.0 Years	Arjunas & Low eccentric Atens

Note. Eccentricity plays a major role in the accessibility of NEAs, as it determines their orbital shape being circular or elliptical. From *The technical and economic feasibility of mining the near-earth asteroids*, by M. Sonter, 1997, (https://doi.org/10.1016/s0094-5765(98)00087-3).

Table 2

Prices for various Near-Earth Asteroid Resources (2021)

Near-Earth Asteroid Resource	Weight (kg)	Price ($USD)
Iridium (Ir)	1	$138,248.21
Platinum (Pt)	1	$30,661.52
Rhodium (Rh)	1	$440,465.23
Ruthenium (Ru)	1	$18,968.94
Nickel	1	$20.07
Iron	1	$0.09444
Cobalt	1	$63.155

Note. Prices for the listed metals per kg were based on November 26, 2021. From *Daily Metal Spot Prices*, by showtheplanet inc, (2021), (https://www.dailymetalprice.com/contact.php).

Table 3

RTGs Flown on U.S. Spacecraft

RTG ID (# of RTGs)	Spacecraft	Mission Type	Launch Date
SNAP-3B (1)	Transit 4A	Navigational	June 29, 1961
SNAP-9A (1)	Transit 5BN-1	Navigational	September 28, 1963
SNAP-9A (1)	Transit 5BN-3	Navigational	April 21, 1964
SNAP-27 (1)	Apollo 12	Lunar	November 14, 1969
SNAP-27 (1)	Apollo 13	Lunar	April 11, 1970
SNAP-27 (1)	Apollo 14	Lunar	January 31, 1971
SNAP-27 (1)	Apollo 15	Lunar	July 26, 1971
SNAP- 19 (4)	Pioneer I0	Planetary	March 2, 1972
SNAP-27 (1)	Apollo 16	Lunar	April 16, 1972
SNAP-27 (1)	Apollo 17	Lunar	December 7, 1972
SNAP-19 (4)	Pioneer 11	Planetary	April 5, 1973
SNAP-19 (2)	Viking 1	Mars	August 20, 1975
SNAP-19 (2)	Viking 2	Mars	September 9, 1975
MHW-RTG (3)	Voyager 2	Planetary	August 20, 1977
MHW-RTG (3)	Voyager 1	Planetary	September 5, 1977

Note. List of various RTGs launched by the U.S. using Plutonium-238 Isotope. From *Design characteristics and fabrication of radioisotope heat sources for space missions*, by G. H. Rinehart, 2001, (https://doi.org/10.1016/s0149-1970(01)00005-1).

Table 4

Instrument	Target	Range (km)	Accuracy (cm)	Resolution (cm)
MOLA	Mars	200 - 787	100	37.5
MLA	Mercury	< 1500	100	6
LOLA	Moon	< 150	10	~1
NLR	Eros	0.1 - 300	32	32
Hayabusa	Itokawa	≤ 50	< 1000	50
Hayabusa 2	Ryugu	0.03 - 25	< 550	50
OLA	Bennu	0.01 - 7	6 (L), 31 (H)	0.1 (bit), 1.1 (L), 2.5 (H)

Note. Highlighted in green represents the observational specifications for the NLR instrument. From *The OSIRIS-REx Laser Altimeter (OLA) Investigation and Instrument*, by Daly et al., 2017, (https://doi.org/10.1007/s11214-017-0375-3).

Table 5

Orbital Parameters

Atens	Apollos	Amors	Arjunas
a < 1.0 AU	a > 1.0 AU	a > 1.0 AU	a ~ 1.0 AU
q < 0.984 AU	q < 1.017 AU	1.017 < q < 1.3 AU	q ~ 0.9832

Note. The semi-major axis (a) and perihelion distance (q) for each NEA type are listed. From *Near-Earth asteroid mining*, by S. D. Ross, 2001, (https://space.nss.org/wp-content/uploads/Near-Earth-Asteroid-Mining-Ross-2001.pdf).