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"Recent Technological Advancements in Asteroid Mining:

Expanding new frontiers of space."

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Abstract This research paper explores recent technological advancements in asteroid mining. It discusses improvements in asteroid prospecting through advanced remote sensing technologies and the integration of artificial intelligence. It also examines cutting-edge extraction techniques, including robotic mining and in-situ resource utilization (ISRU) methods. The paper explores refining processes such as electrostatic beneficiation and chemical processes for extracting valuable resources. Transportation advancements, including ion propulsion and asteroid redirect missions, are also analyzed. The study concludes by emphasizing the potential economic, scientific, and environmental benefits of asteroid mining and the need for international collaboration and ethical considerations in this emerging field.

Keywords: ***Asteroid mining, Asteroid prospecting, Extraction techniques, Remote sensing, Robotic mining, Technological advancements.***

I. INTRODUCTION

Asteroid mining, an evolving field with immense potential, has witnessed significant technological advancements in recent years. These breakthroughs have propelled the industry forward, enabling us to tap into the vast reservoirs of minerals and rare elements found within space. With Earth's resources depleting and the demand for essential materials rising, asteroid mining offers a promising solution for securing a sustainable future.

Asteroids, remnants from the early stages of the solar system, hold valuable metals, minerals, and resources. Technological progress has made asteroid mining increasingly feasible and economically viable.

Advances in spacecraft and robotic systems have played a pivotal role in asteroid mining. Innovative designs equipped with advanced propulsion systems, autonomous navigation, and precise landing capabilities enable us to reach asteroids with unprecedented accuracy and assess their mineral content.

Mining techniques tailored for the space environment have also seen significant development. From traditional excavation methods to novel approaches utilizing melting, vaporization, and chemical reactions, these techniques extract valuable elements from asteroid regolith. Advanced robotics and artificial intelligence ensure precise and efficient execution of mining operations.

Furthermore, in-situ resource utilization (ISRU) has revolutionized asteroid mining by enabling self-sustaining operations. ISRU utilizes on-site resources to generate propellants, life support systems, and construction materials, reducing dependence on Earth for supplies.

Current missions for asteroid mining consider spacecraft prospection as a first step before the extraction process.

Prospection itself usually falls into three different phases: discovery, remote characterization, local characterization. These last two characterization phases are endeavours are endeavours currently pursued by asteroid mining companies using small spacecraft. However, recent advances in the miniaturization of spacecraft components and mining equipment may allow for a more cost effective and reliable approach to mine NEAs overall.

II.REMOTE SENSING

Remote sensing assumes a pivotal role by offering invaluable insights into the composition, structure, and resource prospects of asteroids positioned millions of kilometers away from Earth.

By harnessing remote sensing techniques, essential data regarding mineral composition, surface characteristics, and potential resources can be obtained, facilitating informed decision-making and resource evaluation.

Various remote sensing techniques, including spectroscopy, thermal imaging, and radar mapping, empower scientists and engineers to collect critical data for evaluating the mineral composition, surface properties, and internal structures of asteroids. This wealth of information enables informed decision-making and resource assessment, thus paving the path towards a sustainable and efficient approach to asteroid mining.

A. Spectrophotometry

Spectrophotometry helps determine the mineral content, elemental composition, and physical properties of asteroids. By studying the unique spectral signatures displayed by different materials, scientists can identify the presence of valuable resources such as metals, minerals, and rare elements.

If the light reflected from an asteroid is measured at many wavelengths and subsequently compared with the colour of sunlight, this can grant valuable information on what material the surface of the asteroid is composed of, which in turn is a strong indication of what the asteroid is generally composed of. The result is compared with reflectance from known types of rocks and minerals. These are the basic principles of spectrophotometry.

The most recent technology is called Charge-Coupled Devices - more known as CCD cameras. These work through simultaneous comparison of the object of interest and several neighbouring field stars as reference in a two-dimensional image. Various filters can be applied for analyzing different spectra of interest.

B. Radiometry

Radiometry helps in determining the temperature, thermal inertia, and surface properties of asteroids. By measuring the radiation emitted by asteroids at different wavelengths, scientists can calculate their thermal characteristics, which provide insights into their internal structure and composition.

If the incident sunlight is known, comparing the emitted IR radiation with amount of sunlight reflected from the surface can give an estimation of the asteroid's albedo. When having determined the brightness, distance and albedo, and estimating the temperature distribution, the size of the asteroid might be computed.

When the Earth is struck by solar radiation, some is reflected and a larger portion is absorbed. The absorbed energy is emitted as long wave radiation which can be measured in the IR spectrum (see fig).

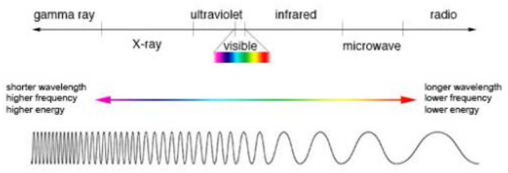

Fig: An image showing the different wavelengths of the electromagnetic spectrum. Radiometry is often measured in the infrared part of the spectrum. Credit: www.cyberphysics.co.uk

In order for this technique to be effective, it is necessary to make certain assumptions about the material composition of the asteroid beforehand. This is because the distribution of heat varies among different types of asteroids. For example, metals conduct heat more efficiently and experience a more uniform increase in temperature.

Hihara et al. (2015) suggest that by utilizing a combination of a thermal-IR imager and a near-IR spectrometer, it becomes feasible to observe and assess the geological characteristics and thermo-physical properties of an asteroid. Furthermore, this approach enables the detection of organic and hydrated materials present on the asteroid.

C. Thermal dynamics modelling

Thorough analysis of the heat signature emitted by an NEAs in space can provide valuable insights. By employing thermal imaging and measuring specific parameters, it becomes possible to extract significant information from the analysis process.

C.1. Spectral analysis: Thermal models can be developed based on the unique spectral signatures of different minerals. By comparing the thermal emission spectra obtained from thermal imaging with known mineral spectra, the presence of specific metals and minerals can be inferred.

C.2 Thermophysical modelling: Thermophysical models involve studying the thermal behaviour of materials based on their physical properties. By analyzing the heat distribution and thermal conductivity of different materials, it is possible to identify certain metals and minerals based on their distinct thermal characteristics.

C.3. Multi-sensor data fusion: This approach combines thermal data with other sensor data, such as spectroscopic or radar data, to improve the accuracy of mineral identification. By integrating multiple data sources, a more comprehensive and reliable assessment of the composition of asteroid materials can be achieved.

The most significant method for thermal analysing is NEATM. This NEA Thermal Model (NEATM) is based on spherical geometry and can produce the diameter and albedo of practically any atmosphere-less body from thermal-IR data [1]. In this model, a fitting parameter is utilized to consider thermal inertia, spin vector, and surface roughness simultaneously.

In the case of an asteroid with a rough surface, the subsolar temperature exceeds the expected temperature for a smooth surface. This phenomenon is attributed to the "beaming" effect, which involves the intensified re-emission of light from surface elements directly exposed to the Sun.

The utilization of alternative heat sources, such as electromagnetic induction and collisions, has been considered adequate primarily for basic feasibility calculations. Additionally, if a Near-Earth Asteroid (NEA) exhibits indications of heterogeneity, a combination of spectral reflectance data and the Near-Earth Asteroid Thermal Model (NEATM) can be employed to reasonably estimate whether the asteroid's resource richness is limited to its surface or extends to its core.

D. Spectropolarimetry

By definition Spectropolarimetry is a technique used to measure the polarization properties of light at different wavelengths. It involves analyzing the changes in the polarization state of light as it interacts with matter.

It is the most common method for probing objects that exist without atmosphere of their own. In this technique, a polarizing material is employed, which rotates in front of a photometer to measure the amount and direction of polarization. These measurements are influenced by both the mineralogy and texture of the asteroid's surface. For example, metallic surfaces tend to exhibit lower polarization levels.

polarization is measured at different phase angles, which are the angles between Earth, asteroid and Sun. At zero-degree angle, the asteroid is directly opposite the Sun from Earth.

To meet the angle requirement, it becomes essential to conduct observations over an extended period of weeks or months in order to gather sufficient data. By doing so, it becomes possible to create a polarization curve by plotting the amount of polarization against the phase angle. For example, observe fig 2

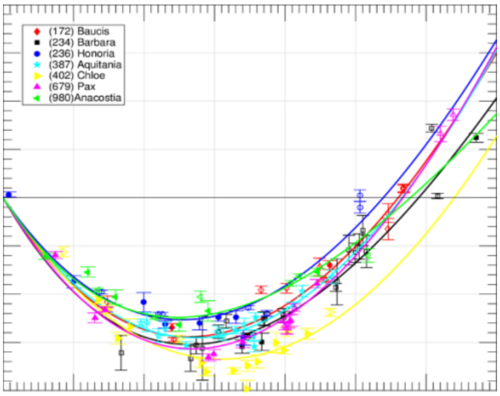

Figure 2: Phase-polarization curves derived for Barbarian asteroids using new polarimetric data presented in this work. The parameters of interest in this curve are: depth of the negative portion, the slope of the positive branch and the phase angle where it changes from positive to negative. These variables correlate strongly with albedos and can be compared to lab measurements to estimate the observed material.

Spectropolarimetry expands upon polarimetry by considering multiple bands of wavelength, allowing for the observation of wavelength-dependent linear polarization in scattered light. The practicality of spectropolarimetric observations is currently under evaluation to determine whether its additional information can reveal distinct characteristics that may go unnoticed by other methods.

E. Hyperspectral imaging

The main limitation of multi-spectral sensor systems, as highlighted by Chauhan et al. (2015), is the sampling of a limited spectral range using only a few broad channels. This limitation significantly hampers the accurate identification of mineral species and the quantitative assessment of mineralogical composition.

Hyperspectral imaging is akin to other electromagnetic observations, but it sets itself apart by employing a large number of finely spaced spectral bands. Typically, hundreds of narrow and contiguous spectral bands are utilized, resulting in highly detailed spectral reflectance data across the UV- NIR region.

Therefore, employing hyperspectral imaging enables the extraction of highly accurate information regarding the texture and composition of objects, surpassing the capabilities of the multispectral technique. This method allows for comprehensive analysis and precise characterization of fine details.

For example, here’s a Comparison of reflectance spectra between two of the S/A/R/V asteroids.

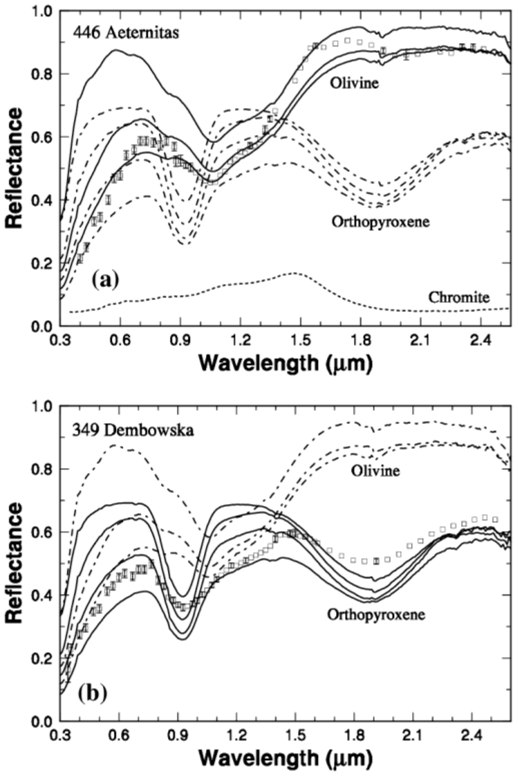

Figure 3: (a)446 Aeternitas, untreated and laserirradiated olivine and orthopyroxene samples (Yamada et al., 1998), and chromite powder (RELAB Database), (b) 349 Dembowska and untreated and laser-irradiated olivine and orthopyroxene samples (Yamada et al., 1998).

If plotted against wavelength, the reflectance values show a spectral reflectance curve. In the figure above we can see certain transition metal ions are displayed as transitions in the NIR region, whereas silicates are displayed in the mid- and thermal-infrared regions of the electromagnetic spectrum.

Conclusively, Hyperspectral imaging acquires data in numerous narrow and closely spaced spectral bands. This results in a highly detailed spectral signature for each pixel in the image, enabling the identification and analysis of specific materials and their properties based on their unique spectral characteristics.

F. LIDAR (Light detection and ranging)

Lidar systems employ high-energy laser beams, typically in the form of short pulses, which are emitted towards the asteroid. The laser pulses interact with the surface, and the reflected light is detected by a sensitive receiver. The precise timing of the emitted and received laser pulses allows for accurate calculation of the distance between the sensor and the asteroid surface.

By scanning the laser pulses over the surface in a controlled manner, Lidar systems generate a point cloud of distance measurements. These

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measurements are then processed to create highly detailed 3D maps of the asteroid's topography and surface features.

Lidar provides several advantages for asteroid mining. Firstly, it offers high-resolution data, allowing for precise mapping and modeling of the asteroid surface. This information is vital for mission planning, landing site selection, and understanding the geological characteristics of the asteroid.

III. METHODOLOGY & APPROACH

Given that the primary objective of asteroid mining is to extract resources, it is crucial to have a well-defined strategy for prospecting, gathering, processing, and delivering commodities. The effectiveness and success of the entire operation hinge on establishing a robust and functional plan for these essential stages.
We propose a possible mission architecture which will be
The mission architecture presented herein seeks to maximize resource extraction while considering the challenges and opportunities presented by asteroid mining.

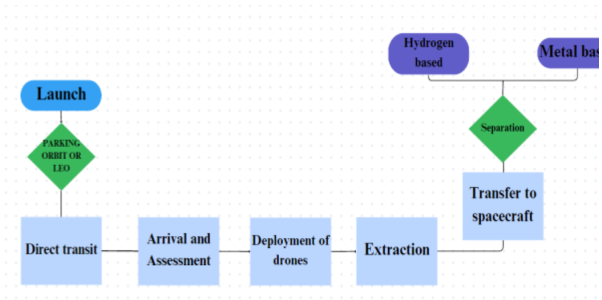

Figure 4: A flowchart illustrating the primary elements and processes involved in a hypothetical asteroid harvesting mission, starting from Earth and concluding with the return journey, while omitting minor steps and specific details.

T1 Launch and Transit Phase:

The spacecraft carrying mining equipment, drones, and processing facilities is launched from Earth.

The spacecraft undergoes a transit phase to reach the target asteroid's orbit.

T2 Arrival and Assessment Phase:

Upon arrival at the asteroid's orbit, the spacecraft enters a stable position relative to the asteroid.

Initial assessments are conducted to gather information about the asteroid's composition, surface features, and potential resource-rich regions.

Remote sensing techniques, such as spectroscopy and imaging, are employed to characterize the asteroid's mineral composition and identify valuable resources.

T3 Deployment of Drones:

Multiple drones equipped with sampling and mining capabilities are deployed from the spacecraft.

These drones autonomously navigate the asteroid's surface, collecting samples and performing mineralogical analysis.

Advanced imaging and spectroscopic sensors on the drones aid in identifying regions with higher concentrations of valuable resources.

T4 Resource Extraction and Collection:

The drones employ various mining techniques, such as drilling, excavation, or blasting, to extract resources from the identified areas. Extracted materials, including ores, regolith, or water ice, are collected and stored within containers carried by the drones.

T5 Transfer to Spacecraft:

Once the drones have collected a sufficient amount of resources, they return to the spacecraft.

The collected load from each drone is transferred and securely stored within designated compartments on the spacecraft.

T6 Separation of Extracted Materials:

Once the drones have collected the resources from the asteroid's surface, a crucial step in the mission architecture involves the separation of the extracted materials. This process focuses on dividing the resources into two primary categories: hydrogen-based materials and metal-based materials.

T6.1 Hydrogen-based materials:

The collected resources that contain hydrogen, such as water ice or hydrated minerals, are targeted for extraction of hydrogen as a fuel source.

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Specialized processing techniques, such as electrolysis, may be employed to separate hydrogen from other compounds and capture it for fuel generation purposes.

The extracted hydrogen is stored and utilized for various applications, including rocket propellant, energy generation through fuel cells, or as a component in in-space manufacturing processes

T6.2 Metal-Based Materials:

The remaining collected resources, which predominantly consist of metal-rich ores or regolith, undergo a separate processing path for metal extraction and refinement.

Techniques such as smelting or chemical processes are employed to extract valuable metals from the ore or regolith.

These extracted metals can be utilized for various purposes, including construction of space structures, manufacturing of components, or trade and commercial use.

T7 Processing and Refining:

The spacecraft houses onboard processing facilities that refine and process the collected resources.

Various techniques, such as smelting, electrolysis, or chemical processes, are employed to extract and purify valuable elements or compounds.

T8 Storage and Payload Preparation:

Processed resources are carefully stored within the spacecraft, ready for future utilization or potential transport back to Earth or other destinations.

The spacecraft is designed to handle and accommodate different types of resources efficiently.

T9 Return or Utilization:

Depending on the mission objectives, the spacecraft may return to Earth with the extracted resources for further analysis or commercial use.

Alternatively, the resources may be utilized in space for in-situ manufacturing, refueling, or supporting future space missions.

T10 Mission Conclusion and Analysis:

Once the extraction and processing operations are completed, a comprehensive analysis of the mission's success, resource yield, and lessons learned is conducted.

The findings help in refining future asteroid mining missions and improving techniques for resource extraction and utilization.

IV. ECONOMIC FEASIBLITY

The economic viability of planetary mining is a complex and evolving issue that involves a variety of factors and perspectives. While the idea of extracting valuable material from giant planets has great potential, several key factors need to be examined to determine its economic feasibility.

Resource Value and Demand: The economic feasibility of asteroid mining heavily relies on the value and demand for the extracted resources. Valuable resources such as rare metals, precious metals, and water (in the form of hydrogen and oxygen) can have substantial market value and drive the profitability of mining operations. The assessment of market demand, price stability, and potential customers for these resources is crucial in determining the economic prospects of asteroid mining.

Extraction Costs: The cost of extracting resources from asteroids is a major factor in assessing economic feasibility. It involves various expenses, including mission planning, spacecraft development and launch, robotic mining operations, processing facilities, and return transportation of extracted resources. These costs encompass a range of technical, logistical, and operational challenges that must be carefully evaluated to ensure that the extraction costs can be justified by the potential revenue generated from the resources.

Technological Advancements: The economic feasibility of asteroid mining is influenced by advancements in mining technologies and techniques. The development of efficient and cost-effective mining systems, robotic automation, resource extraction methods, and in-space processing capabilities can significantly impact the overall economics of the project. Technological innovations and improvements can lead to reduced extraction costs, increased resource recovery rates, and enhanced operational efficiency, making asteroid mining more economically viable.

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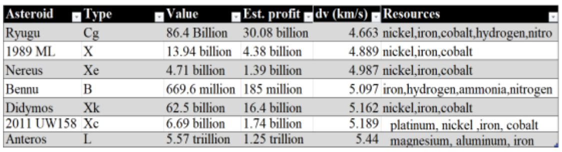
In April 24, 2012, the Keck Institute for Space Studies (KISS) conducted a feasibility study on an asteroid capture-and-return mission, as documented by David in their publication. The study primarily emphasized the technological aspects and logistical considerations involved in moving a Near-Earth Asteroid (NEA) weighing approximately 500 tons and measuring 7 meters in diameter. The objective was to place the NEA into lunar orbit by the year 2025. By positioning the asteroid in lunar orbit, it would serve as a strategic location for conducting further analysis, experiments, and research. This endeavour aimed to enhance our understanding and knowledge of asteroid-related matters, contributing to advancements in the field.

Some of the most accessible asteroids for exploitation and their properties are presented in a tabular form below:



Asteroid	Type	Value	Est. profit	dv (km/s)	Resources
Ryugu	Cg	86.4 Billion	30.08 billion	4.663	nickel,iron,cobalt,hydrogen,nitro
1989 ML	X	13.94 billion	4.38 billion	4.889	nickel,iron,cobalt
Nereus	Xe	4.71 billion	1.39 billion	4.987	nickel,iron,cobalt
Bennu	B	669.6 million	185 million	5.097	iron,hydrogen,ammonia,nitrogen
Didymos	Xk	62.5 billion	16.4 billion	5.162	nickel,iron,cobalt
2011 UW158	Xc	6.69 billion	1.74 billion	5.189	platinum, nickel ,iron, cobalt
Anteros	L	5.57 triillion	1.25 trillion	5.44	magnesium, aluminum, iron

Table: This brief table explores the estimated profit associated with these accessible asteroids, considering the rich abundance of resources they contain and the growing demand for such materials in various industries.

V. RESULTS:

Efficient Resource Prospecting:

The deployment of multiple drones in the mission architecture enables efficient resource prospecting on the asteroid's surface. These drones autonomously navigate and collect samples from identified regions of interest, maximizing the chances of extracting valuable resources while minimizing resource wastage.

Targeted Resource Extraction:

By focusing on specific areas of interest, the mission architecture ensures a targeted approach to resource extraction. The deployed drones gather samples from the identified regions, increasing the likelihood of acquiring valuable resources and optimizing the overall extraction process.

Versatile Resource Utilization:

One of the key advantages of the mission architecture is its ability to separate the extracted materials into hydrogen-based and metal-based categories. This separation enables the efficient utilization of resources for different purposes. The hydrogen-based materials are processed to extract hydrogen, which can be used as a fuel source for various applications. The metal-based materials undergo refining processes to extract valuable metals for construction, manufacturing, or trade purposes.

In-Space Processing and Refining:

The spacecraft in the architecture is equipped with onboard processing and refining facilities. This capability allows for the in-space processing of the collected resources, eliminating the need to transport raw materials back to Earth for processing. In-space processing reduces costs, conserves resources, and enhances the overall efficiency of the mission.

Fuel Generation:

The extraction of hydrogen from the hydrogen-based materials offers significant advantages in terms of fuel generation. The extracted hydrogen can be utilized as a clean and efficient fuel source for rocket propulsion, energy generation in fuel cells, and supporting in-space operations. This fuel generation capability enhances the mission's sustainability and self-sufficiency.

Metal Extraction and Use: The mission plan focuses on extracting and exploiting precious metals from the collection. Metallurgical materials treated by a finishing process eliminate the desired metallurgy. This metal can be used for construction, building materials, or even traded for valuables. The infrastructure emphasizes the importance of metal extraction to support aerospace infrastructure development and employment opportunities.

Sustainability and independence: Mission construction that leverages in-house resources encourages sustainable development and reduces reliance on limited Earth resources for future space exploration and colonization The ability to extract material from asteroids in and out contribute to the long-term sustainability of space missions and enhance the chances of establishing sustainable space colonies.

VI. DISCUSSION

Mission feasibility and operational efficiency: The above-mentioned mission plan demonstrates a viable and well-organized approach to mining asteroids. By employing less manned aircraft once the spacecraft has reached planetary orbit, the mission improves efficiency and enhances extractable material Extractive collection at systematically and inserted into the spacecraft ensures a systematic and coordinated recovery operation.

Separation and Treatment: The step-in mission planning involving the separation of separated materials, especially for hydrogen-based and metal-based materials, is an integral part of the mining process. The hydrogen extracted from the asteroid can be used as a fuel, while the metal is useful in a variety of industrial applications. Proper separation and subsequent handling of these materials is essential to maximize economic returns.

Technological Advances and Challenges: The dialogue recognizes the importance of advanced technologies in planetary mining. Successful execution of the mission program depends on state-of-the-art unmanned aerial vehicles capable of efficiently transferring cargo from the surface of the planet to the spacecraft and using No. Meeting challenges Continued research and innovation in these areas is critical to increase the efficiency and effectiveness of planetary mining.

Economic Feasibility and Resource Capacity: The mission architecture holds significant economic potential for targeting asteroids rich in valuable resources. Using remote sensing techniques such as spectropolarimetry and hyperspectral imaging, the mission aims to identify asteroids with high mineral and metal content, maximizing the potential for profitable resource extraction Successful execution of the mission has the potential to provide substantial economic returns through recovery and utilization of these valuable resources.

Environmental Considerations: The discussion emphasizes the importance of environmental considerations in asteroid mining. While mission architecture focuses on efficient resource disposal, it is equally important to minimize potential environmental impacts. Efforts to ensure sustainable mining practices, including space waste reduction and pollution prevention, are essential to terrestrial planetary mining efforts have achieved long-term operation and sustainability to strike a balance between extraction and environmental protection.

VII.CONCLUSION

In conclusion, the field of planetary mining holds great promise for the exploration and exploitation of space resources. The mission plan presented in this paper provides a comprehensive and efficient framework for extracting valuable resources from asteroids. Utilizing advanced technologies such as remote sensing, spectropolarimetry, hyperspectral imaging, and drones, the architecture increases the potential for accurate results while solving key challenges in the field the

The findings of this study illustrate the economic benefits of planetary mining, with hypothesized benefits from the identification and evaluation of accessible planets These celestial bodies contain precious metals, earth elements of their own making and, abundant storage of water, and other valuables resources. The findings of this study illustrate the economic benefits of planetary mining, with projected benefits from the discovery and measurement of accessible planets These celestial bodies contain precious metals, rare earth elements and other valuable resources that are in high demand across various industries. The anticipated profitability of extracting and utilizing these resources underscores the significant economic opportunities that asteroid mining offers

Moreover, the mission architecture underscores the importance of technological advancements and innovation. Continuous research and development efforts are essential for overcoming the unique challenges associated with mining in space, including asteroid characterization, robotic extraction, and in-space processing. Collaborative endeavours among space agencies, private companies, and research institutions are instrumental in driving the progress of technologies that will enable efficient and sustainable asteroid mining operations.

Environmental considerations play a crucial role in shaping the future of asteroid mining. Embracing sustainable practices, responsible resource utilization, and effective mitigation of potential environmental impacts are paramount. Striking a balance between resource extraction and the preservation of celestial bodies and space ecosystems is vital to ensure the long-term viability and ethical conduct of asteroid mining endeavours.

Additionally, the successful implementation of the presented mission architecture hinges on the establishment of a supportive legal and regulatory framework. International collaboration and coordination are imperative for defining clear property rights, mining rights, and resource ownership guidelines. Such frameworks will provide stability, foster investment, and facilitate international cooperation in the exploration and exploitation of space resources.

In summary, the mission architecture outlined in this paper offers a comprehensive and practical roadmap for asteroid mining. It highlights the economic potential, technological advancements, and environmental considerations associated with this

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emerging field. By venturing into asteroid mining, humanity can unlock new frontiers of resource availability, drive technological innovation, and shape the future of space exploration and utilization. Collaboration, research, and responsible practices will be paramount as we embark on this exciting journey, tapping into the vast resources hidden within our celestial neighbours and paving the way for a prosperous and sustainable future in space.

However, numerous unresolved challenges remain in the field of asteroid mining. One such challenge pertains to the absence of standardized and universally accepted space laws. Varying national approaches towards space travel and commercialization create potential discrepancies and may give rise to future conflicts in outer space, which could have significant implications for Earth and its nations.

Additionally, while financial feasibility reports indicate the profitability of asteroid mining, some uncertainties persist. Much of the available information is speculative, and unknown variables could introduce critical errors into mining operations. Therefore, careful consideration and further research are necessary to mitigate risks and address the unknown factors associated with asteroid mining.

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