Thesis Portfolio

A SPACE-BASED SOLUTION TO IMPROVE ROADWAY SAFETY AND EFFICIENCY IN VIRGINIA: REAL-TIME WINTER WEATHER DATA FOR NAVIGATION

(Technical Report)

TECHNOLOGICAL MOMENTUM IN THE ASTEROID MINING INDUSTRY

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Jimmy Smith
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TECHNOLOGICAL MOMENTUM IN THE ASTEROID MINING INDUSTRY

A Research Paper submitted to the Department of Engineering and Society
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By

Jimmy Smith

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

ABSTRACT

While the prospect of asteroid mining may seem like science fiction, an endeavor for the distant future, the technology to harvest space resources exists and the means to do so are being brought about by the current Technological Momentum being gathered by the private space industry. Companies like SpaceX, Blue Origin, Relativity Space and many others are lowering the costs to get to space and, in doing so, making space more accessible to companies beyond that of the current standard of communications, GPS and research satellites. Some of the world's richest people and institutions – such as Jeff Bezos, Elon Musk, Bill Gates and the financial powerhouse Goldman Sachs – have invested millions of dollars of their own into the seedling industry. A recent research paper from the University of Arizona has given merit to these investments, estimating the worth of the asteroid Bennu at approximately $40,000 quadrillion dollars. The incentive is not only financial; however, as many futurists see asteroid mining as humanity's bridge to grow its presence and infrastructure in space, simultaneously easing the burden on Earth's atmosphere associated with terrestrial mining and allowing for the development of related industries on-orbit. By gathering resources in space, it eliminates the need for humans to launch them into space, allowing for the construction of structures in space that would be impossible with the current model of launching things into orbit aboard costly rockets. This push to in-space resource utilization would be a paradigm shift not only for the space industry, but for humanity as a whole.

TECHNOLOGICAL MOMENTUM IN THE ASTEROID MINING INDUSTRY

INTRODUCTION

Humanity's presence in space has come a long way since the Soviet Union put the first human creation – *Sputnik* – into orbit around the Earth in 1957. Almost 65 years after *Sputnik,* Earth's orbits are filled with a myriad of satellites of various purposes, telescopes helping us to learn more about the universe and even a space station that has seen continual human occupation for nearly two decades. There are now talks of decommissioning the International Space Station (ISS) for the creation of private space stations, relieving the strain on the governments that fund it and creating new markets for the private space industry. In a recent report, the economic growth of the private space industry is anticipated to reach $600 billion by the year 2030, which economists say will generate opportunity for national governments and private sectors players, with companies from several industries looking at space to improve and transform their own businesses" (KPMG, 2020). The privatization of space is opening the door for even more industries based in space, perhaps the most significant of which is the asteroid mining industry.

In order to best predict how an asteroid mining industry will affect human society and the ensuing Paradigm Shifts it will cause, it is first necessary to understand how the Technological Momentum in the current private spaceflight industry- and the Paradigm Shifts that have already been triggered - are poised to bring it to fruition. By examining humanity's history of asteroid mining, the current laws pertaining to space resource harvesting, the motivations for it, the technological momentum amassing in private space and its potential for growth, its societal impacts can be better anticipated

As with many of today's commonplace technology, asteroid mining was once considered an endeavor relegated to the world of science-fiction; however, the recent boom in the private

space industry has made it an industry poised to change the world. Over the past few decades several asteroid mining companies have emerged with the support of tech giants such as Mark Zuckerberg and Larry Page; as well as support from the financial titan Goldman Sachs (Edwards, 2017). The reason for the interest in such a fantastical idea is the seemingly infinite source of resources readily available in space. A representative from Goldman Sachs has said "While the psychological barrier to mining asteroids is high, the actual financial and technological barriers are far lower. Prospecting probes can likely be built for tens of millions of dollars each and Caltech has suggested an asteroid-grabbing spacecraft could cost $2.6 billion" at which point they then predict the world's first trillionaire will make their fortune in space (Wehner, 2018). As of now, if a private person can figure out a way to return even a small fraction of resources available on a single asteroid, they could become the richest human in recorded history, and there is virtually no legislature restricting them from doing so.

HUMANITY'S HISTORY OF ASTEROID MINING

In 2003 the Japanese Aerospace Exploration Agency (JAXA) launched their Hayabusa spacecraft on its 7-year round-trip journey to the asteroid Itokawa. After the two-year journey to Itokawa, Hayabusa landed on the NEO where it would remain for more than a year before starting the return trip in 2007, finally arriving back to Earth in 2010 (O'Callaghan, 2013). Hayabusa's successor – the aptly named Hayabusa2 – launched in 2014 and took the mission of its predecessor a step further by attempting to return a sample from an asteroid back to Earth. In December of 2020, Hayabusa2 successfully completed its mission by returning a sample of the NEO Ryugu safely to the surface of Earth. Hayabusa2's incredible success marked the first time in human history that an asteroid was successfully mined, albeit on a very small scale.

In September of 2016 – just two years after the launch of Hayabusa2 – NASA launched the OSIRIS-REx mission for the purpose of collecting a material sample of the asteroid Bennu and returning it to Earth. In October of 2020, the lander successfully collected a significant sample from the asteroid – marking two successfully "mined" asteroids in the span of a year (Morton, 2020). With the success of the Hayabusa and OSIRIS-REx missions, there is now a proof-of-concept which can serve as a small-scale template for private industries interested in returning asteroid samples back to Earth – not for research, but for profit.

INTERNATIONAL REGULATIONS AND SPACE LAW

It may seem like science fiction, but the idea of asteroid mining has been a topic of legal consideration since the United Nations (UN) established the first regulations pertaining to behavior and actions in outer space. In 1979 the UN Office for Outer Space Affairs (UNOOSA) authored the *Agreement Governing the Activities of States on the Moon and Other Celestial Bodies* where they dictated a need to "establish an international regime, including appropriate procedures, to govern the exploitation of the natural resources of the moon as such exploitation is about to become feasible" (UNOOSA, 1966). While at the time the UNOOSA was focused on the moon due to the climaxing Space Race and the success of the Apollo program, the agreement extended to other celestial bodies to include asteroids. While this may have seemed like a sensible thing for the UN to concern themselves with, no major space faring nation at the time – the United States, Russia and China – signed the agreement, nor have they to this day (Foust, 2015).

Though the *Agreement Governing the Activities of States on the Moon and Other Celestial Bodies* remains largely unsigned, the recently inked *Artemis Accords* have been signed by the US, the UAE, Japan, Luxemburg and several other countries. The purpose of the *Artemis*

Accords is not wholly dissimilar to that of the UNOOSA's treaty, stating in its opening lines that it serves to "establish a common vision via a practical set of principles, guidelines, and best practices to enhance the governance of the civil exploration and use of outer space with the intention of advancing the Artemis Program" (NASA, 2020). The Artemis Program is NASA's next great foray into human space exploration and it intends to construct a space station in lunar orbit and return human beings to the surface of the moon, with the purpose of establishing a consistent human presence in lunar orbit. With consistent presence comes consistent demand for resources, some of which can be extracted from the lunar surface. In addressing the use of these resources, Section 10 of the *Artemis Accords* lays out several points regarding the collection of space resources not only on the moon, but also on other planets, comets and asteroids. The points remain vague, focusing mainly on safety and sustainability in both collection and utilization of space resources, while seemingly remaining committed to the policy put forth in the *Space Act* of 2015 with regards to the actions of private companies.

The lack of regulations pertaining to the collection of space-based resources, and the ever-increasing power and authority private industry is gaining over the government in the world of spaceflight, has the embryonic industry of asteroid mining looming on the horizon. While the US seems content to allow the industry to evolve on its own, Luxemburg has created the Space Resources Initiative (SRI) in which it plans to funnel millions of dollars into private companies with the intention of making themselves the genesis of the industry; though information pertaining to the details of the SRI are scarce (n.a., 2019). While companies and governments around the world aim to break into the world of asteroid mining, they may look to two groundbreaking missions from the past twenty years for reference.

MOTIVATIONS

Monetary returns from asteroid mining have the potential to dwarf those amassed by even the most infamous of Earth-based resource exploiters such as Rockefeller and J. Paul Getty. In a recent study published by the American Astronomical Society, the asteroid dubbed *(16) Psyche* was given an estimated value of $10,000 quadrillion dollars, which is more than the entire Earth's combined economy (Becker et. al., 2020). Returning even a small fraction of a percent of the total worth of the asteroid's resources could supply a private citizen with enough wealth to buy the United States $28 trillion debt multiple times over.

Regardless of the potential returns asteroid mining presents, some experts still remain skeptical the start-up capital required for the establishment of such a fantastical industry would be worthwhile. Skeptics claim that the cost to mine asteroids is not economical when the resources are available here on Earth, while also citing scientist's and engineer's ability to circumvent the use of expensive or rare metals in manufacturing (Fickling, 2020). Those skeptics have seemingly been validated up to this point – with the most promising of the asteroid mining companies, Planetary Resources and Deep Space Industries (DSI), recently being bought out and dissolved – however; he misses the larger point of the entire endeavor. The true value of asteroid mining is not to return resources to Earth, but rather to use them in space.

Utilizing resources harvested via asteroid mining in space is where the industry holds most of its value, both moral and monetary. Collection of resources in space can lead to the processing or refinement of resources in space, where toxic byproducts cannot pollute the Earth's atmosphere and contribute to global warming. These in-space refineries open the door for additional industries revolving around on-orbit construction, which utilize the materials collected via asteroid mining and refined in space, creating a positive-feedback loop of supply and demand

largely independent of the Earth. For example, a proposal for a space station built from iron using the same methods as the ISS would be ludicrous due to the magnitude of thrust needed to transport the heavy materials to space, but iron ore recovered from asteroids could be processed and used to construct any number of structures or vehicles in space, where mass is not a constraining factor. This creates a through line that connects the growing efforts to curb global warming to the momentum of the private space industry, potentially generating a whole new network of actors to facilitate the growth of the asteroid mining industry. The collection of resources in space has other benefits as well.

Through asteroid mining, Liquid oxygen and liquid hydrogen – the constituents of rocket fuel – can be harvested and stored in LEO for refueling purposes, preventing the need for spacecraft to carry excess propellant for deep space missions (Andrews et. al., 2013). This would greatly reduce cost and complexity of deep space missions. Additionally, the construction of large-scale, human-class transit vehicles on-orbit can allow for crewed missions deep into the solar system that were not feasible before, further expanding humanity's presence in the solar system. Acclaimed aerospace engineer and president of *The Mars Society* Robert Zubrin claims that this is the best chance for humanity to not only save our own planet – by reducing the strain on our atmosphere and the effects of climate change – but also expand and colonize others (Zubrin, 2019).

Much the same way the advent of the automobile spurred changes in societies around the world and the birth of thousands of other industries that weren't possible or conceivable before, asteroid mining has the potential to do the same for space. Before the automobile there were no gas stations, paved roads, motels, diners, automotive maintenance shops or city suburbs. These things didn't exist because there was no demand or means for them. After the invention of the

automobile, a vast and fractal network of industries either centralized on or facilitated by the automobile - many of which would have been hard to conceive of before its invention – spread and revolutionized society (ushistory.org, n.d.). Once asteroids begin to be mined and processed in space, the demand for in-space infrastructure will increase. The demand in industrial infrastructure - such as construction, processing plants and spaceports - will lead to an increased demand for private astronauts, causing a corresponding increase in the need for human related infrastructure in space - such as dining, travel, recreation and healthcare.

TECHNOLOGICAL MOMENTUM IN THE PRIVATE SPACE INDUSTRY

Since Peter Diamandis' famed "X-Prize" competition was won in 2004 – when Mojave Aerospace Ventures' SpaceShipOne became the first privately manufactured and flown spacecraft – the private spaceflight industry has jumped genres to reside in the realm of non-fiction (Fernholz, 2018). In 2002, two years before the X-Prize was won, Elon Musk started his own private spaceflight company SpaceX with the goal of "enabling humans to live on other planets" (Musk, 2021). Facilitated by George W. Bush's amendments to the Regan era *Commercial Space Launch Act* – which encouraged the development of commercial human spaceflight – SpaceX has become a titan of the aerospace industry, becoming the first private company to develop a reusable liquid rocket booster – the Falcon 9 – greatly reducing launch costs. SpaceX has also recently become the first private company to launch astronauts into space with the success of their DM-2 test which resulted in the final certifications of their Crew Dragon spacecraft capsule.

Two years before Musk started SpaceX, Jeff Bezos – the Amazon CEO and wealthiest human on the planet as of 2017– launched his own private spaceflight company in 2000, which he dubbed Blue Origin. The mission statement of Blue Origin beckons to the ideas of asteroid

mining and its value for slowing global warming, stating that “in order to preserve Earth, our home, for our grandchildren’s grandchildren, we must go to space to tap its unlimited resources and energy” (N.A., 2020). This mission statement was facilitated, much the same way SpaceX’s was, by President Obama in 2015 when he passed the *Commercial Space Launch Competitiveness Act* (SPACE Act) which explicitly allows private companies to "engage in the commercial exploration and exploitation of space resources" (McCarthy, 2015). Though other companies seeking to exploit space resources have also emerged, most notably the aforementioned and now defunct Planetary Resources – founded by X Prize creator and aerospace icon Peter Diamandis – and Deep Space Industries, Blue Origin and SpaceX have the added advantage of being both founded and funded by the richest human on the planet – Bezos – and the only person to unseat him in the last 4 years – Musk – respectively. Companies with that amount of capital behind them have the luxury of expected and planned failures, something that is almost essential when pushing the boundaries of space capabilities.

The increasing focus on reusability and efficiency in space can also be seen in the recent aerospace start-up Relativity Space, a company which seeks to create a high-output production factory of completely 3D printed rocket engines and launch vehicles. Relativity claims their flagship engine – *Terran 1* – can go from raw material to flight ready in 60 days, a staggeringly short timeline compared to current industry standards (Sheetz, 2021). By automating the process of manufacturing rocket engines, Relativity can drastically reduce production costs while increasing efficiency, making it easier for more start-up companies to break into the space industry by purchasing either Relativity’s “over the counter” engines or rideshares on their launch vehicles. With the lowered cost of entry into the market, space can become a bastion for more industries than just small satellites and government launch providers. Companies can focus

on technologies relevant to activities in space rather than that of the rocket engines and launch vehicles needed to get there, whose complexities and costs deter many potential start-ups and investors. The freedom to focus on novel space technologies and systems will allow for more rapid developments in the field and a more feasible means to adopt SpaceX's failure driven design approach.

In March of 2021, SpaceX landed their Starship prototype – known as SN11 – on a landing pad in Texas, demonstrating the viability of their dramatic "belly flop" maneuver and again pushing the limits of what is possible in aerospace. About 5 min after landing, SN11 exploded due to a methane leak, most likely due to the higher than desired landing velocity. Regardless of whether you consider this a success or not, the fact that SpaceX is willing to burn through Starship prototypes with mere weeks in between tests that see multimillion dollar vehicles destroyed puts them at a large developmental advantage. This failure driven design process is a business model that has propelled SpaceX to an aerospace giant, toppling former launch vehicle provider United Launch Alliance (ULA). With the cost per kilogram of launching payloads to space decreasing every year, and companies like SpaceX and Relativity engineering even larger drops with their reusability and efficiency, the idea of failure driven design can more readily be applied to space-based industries. Perhaps a budding space mining company's first lander misses an asteroid entirely, doomed to some lonely parabolic orbit about our sun, if the SpaceX model were to be employed the engineers designing the lander can tweak the relevant hardware and/ or software and launch another with a relatively short turnaround. Obviously, this design process will not be as expedited as the Starship design, as the round-trip mission times to asteroids are several orders of magnitude larger than those of Starship's tests, but the principles behind it are the same.

With the explosion of these companies into the spaceflight industry over the last two decades – and their overwhelming success – the United States' spaceflight infrastructure has seen a shift from the days of NASA as the creator and executor of all space missions, to one now where the iconic agency serves mostly as an independent verification entity, facilitator and launch site provider for private launch vehicles and spacecrafts. This tectonic Paradigm Shift, which has seen responsibility from the government and NASA move to private industry, has allowed the private spaceflight industry to amass a significant amount of Technological Momentum that is pushing it towards revolutionizing not only spaceflight, but the world.

STS CONCEPTS

Technological momentum is an STS theory that says technology is influenced by society and, in turn, influences society. The theory was first posed by Thomas Hughes in 1994 as an alternative to the dichotomy posed by the Technological Determinism and Social Construction theories (Hughes, 1994). In the context of the privatization of space, private industries are given the freedom to innovate and pursue lofty goals, which in turn attracts ambitious engineers who are passionate about the company's goals, which then accelerates the progress of technological advancement and perpetuates the cycle, effectively drawing engineering talent from government agencies to the private sector. This pivoting of technology development – as well as the doubling down of the "hands-off" type policy implemented by the government through the *SPACE Act* – has lit the proverbial fuse to an industry that has not yet exploded to its full scale. Once the first private company displays the capability to harvest resources from near-Earth objects (NEOs), a new branch of industry with potentially world-changing profits will have been established and the paradigms of what many people think is possible will shift.

The Paradigm Shift was first brought forward as an STS theory by Thomas Kuhn in his paper *The Structure of Scientific Revolutions*, where he explained a frame through which researchers could view how technology can lead to shifts in well-established societal norms (Kuhn, 1962). It is easy to see how an endeavor such as asteroid mining could lead to changes in societal norms; however, the impact of the shifts has the potential to be of magnitudes beyond any previously measured on the societal Richter Scale. Not only will the first successful private asteroid mining company generate a paradigm shift in industry, it will precipitate a proverbial domino effect of subsequent paradigm shifts by opening space to exponentially more people. Along the way many smaller scale paradigm shifts have occurred, including the aforementioned shift in responsibility from NASA to private industry.

CONCLUSION

Though some are skeptical of asteroid mining, the potential the industry carries for monetary gain, space infrastructure development and the evolution of human society as a whole – paired with the ever-growing technological momentum of the private space industry – has seemingly made it an inevitability. The technology for asteroid mining exists, as has been shown by Hayabusa and OSIRIS-REx on a small scale, and with the monetary resources of current space barons Elon Musk and Jeff Bezos, the only thing the industry needs is time. Much the same way many experts in the industry thought SpaceX would never overthrow ULA with their failure driven design approach, skeptics believe the start-up costs of asteroid mining make it a fantastical idea with no foothold in economic reality. It took SpaceX less than two decades to grow from a rag-tag group of ambitious engineers with a common dream of revolutionizing the space industry to the titan they are today. Paradigms exist until they do not, and the foundation upon which has been built the paradigm that ambitious space companies will not survive due to

high start-up costs is becoming ever more fragile by the year. Though it is impossible to exactly predict the societal changes that will occur with the birth and growth of a global asteroid mining industry, it is clear that once the pioneering asteroid mining company breaks down the barriers, the proverbial floodgates will open, buoying humanity up to the stars, changing human society forever.

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