Establishment of Lunar Factories and Manufacturing as a Precursor Towards Full-Fledged Endeavors of Lunar Resource Utilization

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ABSTRACT: There is a lot of interest regarding the exploration and exploitation of the lunar surface towards in-situ resource utilization and mining activities. While these plans talk about establishing facilities that promote and initiate mining activities, there is a lot of uncertainty regarding the economic viability of such an initiative. Mining technologies are inherently expensive and difficult to set up. The abrasive nature of lunar dust and maintenance necessary towards such an initiative would lead to difficulty in justifying the economics of the activity. However, there is a lot of incentive and interest towards space manufactured objects. A product manufactured in space is lucrative, sparks interest in society towards its ownership, and could be a potential spark in promoting the start of a lunar economy. Materials such as ZBLAN which have a long list of scientific applications have manufacturing restrictions on earth owing to their unique properties. Presently, small-scale production of ZBLAN is carried out onboard the ISS. Materials research, healthcare studies, in-space manufacturing can be the first of many activities that can be carried out on the lunar surface. The establishment of dedicated facilities which manufacture exotic materials similar to ZBLAN that are limited due to the gravitation on earth could be a precursor towards the establishment of a fully-fledged lunar economy. The products manufactured on the lunar surface could also justify the economic viability of such an initiative and spark interest towards more capital-intensive activities on the Moon's surface. This can also include products manufactured using Microwave, Laser Sintering, and powdered fusion process of lunar regolith towards additively manufactured substances that can be used for colonization of the lunar surface or exotic sale on earth. In this paper, the authors explore the technical requirements, regions of interest on the lunar surface that can be considered for the establishment of the first factories and calculate the economic viability of such an initiative in line with present technologies of space transportation.

1. Introduction

The Moon has a colossal number of metals such as Iron, Aluminum, Calcium, Magnesium and Titanium that have been identified after various investigatory attempts by National Aeronautics and Space Administration (NASA), European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), Indian Space Research Organization (ISRO) and other outer-space organizations. In fact, rare metals like Neodymium and Lanthanum have also been found on the Moon. NASA's Lunar Reconnaissance Orbiter Spacecraft has played a crucial role in this discovery. Although the scientists were trying to get their hands on the ice found at the bottom of the Moon's craters, they ended up discovering several metal oxides traces beneath its surface. The discovery indicated the possible glut of metals that may be available at the Moon's surface and that could be procured after mining it. In comparison with the composition of metals that are found on Earth, the close resemblance of Moon's composition with its parent planet (the one that it orbits, Earth) is credited to the theory that the Moon was formed after the collision between a Mars-size celestial body and the Earth. In fact, there are abundant regions on the Lunar Surface that are richer in metal-constitution as compared with Earth.

Apart from metals, the Lunar surface is an affluent repository of rare stable Helium Isotope called Helium-3 or simply, H-3. With the massive potential to be used as a clean fuel, H-3 is expected to amplify the future of Nuclear Fusion Power Plants. The clean aspect of its utility is indicated by its ability to produce high volumes of energy without inhibiting its surroundings with radioactive particles. Produced as a by-product of Lithium-bombardment by natural neutrons or by underwater weapons testing etc, it is largely found as a primordial substance in the Earth's mantle. High temperatures are required to achieve H-3 fusion reactions, making it difficult to be found on the Earth. Nonetheless, extensive research in this area confirms that large H-3 deposits (1.5 to 16 ppb at sun-shone areas and up to 50 ppb at permanently shadowed areas) are present on the upper layer of the Moon's regolith.

Planetary explorations by the ISRO's Mission Chandrayaan-1 and NASA have also pointed at the evidence of water-molecules present in different forms in the lunar atmosphere. Scientists specified that the interaction of Oxygen trapped in the lunar soil with the protons available in its atmosphere could be the reason behind the moisture-production. Although the infrared spectrometers suggested that water-bearing minerals were largely found at the poles, further expeditions point out the likelihood of water-traces to be present at different locations of the Moon.

Lunar Mining, which is considered as an innovative and sustainable programme, attempts to draw three important resources from the Moon's surface: H-3, water and other metal oxides. Given that water is crucial for agricultural activities and life-support in Space; H-3 could be an effective substitute for a cleaner fuel; and rare metals could change the face of emerging technologies, the Lunar Mining Missions are presently driving the fore-front of today's Space Technology.

After bidding for lunar-mining contracts with private space companies, NASA has selected four start-up companies namely, Lunar Outpost, Inspace Japan, Inspace Europe and Masten Space Systems to carry out the designated missions. Public-private partnerships not only bring down the cost of total mission planning and execution, but also sets a precedent for how game-changing, material collection from extra-terrestrial bodies can be. Also, the independent commercial organizations can move at a much faster pace, contrary to the mission slowdowns often observed as a result of governmental red-rape.

There are some government projects around the globe that are attempting to explore the various parts of the Lunar Surface such as NASA's Artemis Program, ISRO's Lunar Exploration Chandrayaan Mission and ESA-ROSCOSMOS collaborative Luna Resurs Mission. JAXA is developing a baseball-sized transformable rover that is expected to be launched in 2022 on HAKUTO-R lander. The rover will be utilized to perform lunar-photography and collect lunar-dust samples. Another rover by JAXA will be sent in collaboration with the USA in a lander called "Rashid". Multiple plans of action, some independent and some collaborative, are proposed to carry out the vision of lunar exploration.

2. Ongoing Missions

The intriguing concept of lunar mining has kept all scientists, space agencies and multiple businessmen on their toes- the rocky satellite is a house for many precious resources that can be game-changing for the future of human beings on Earth. The first human-spaceflight lunar landing took place in 1969 while the last crewed mission was successfully conducted in 1972. Since then, only unmanned missions have been launched to the Moon. Past missions such as Lunokhod 1 & 2, Apollo Lunar Rover Vehicle and Chandrayaan-2 are now expected to be followed by Carnegie Mellon Rover, VIPER, Chandrayaan-3, Yaoki, Unity, Hakuto-R, Rashid and Asagumo Mission etc. It is imperative to discuss some important futuristic Lunar Missions by numerous space agencies all over the world.

2.1. Artemis Program by NASA

Pushing the barriers of space exploration and technologies, the human spaceflight program by NASA, Artemis, expects to re-launch humans on the Moon, specifically at the Lunar Southern Pole after 32 years by 2024. The name of this program finds its roots with the Goddess of the Moon, the twin sister of Apollo- Artemis. Starting in 2017, the frontier goal of the Artemis Program is to launch the first woman to the Moon; followed by the plan to establish lunar colonies that could sustainably house human beings on the Moon for an extended period of time. In the long run, the extraction of important resources such as rare metals, water and Helium-3 is planned for. Later on, this entire expedition will be a stepping stone towards humankind's journey to a Martian Reality. This undertaking will lay a foundation for us to land on Mars and eventually establish a living environment on that planet.

The Artemis Program is primarily a coalition of partnerships between NASA, ESA, other commercial/academic space-contractors and space-agencies from various other nations. The participating countries are required to sign the Artemis Accords in order to build mutual cooperation. The Artemis Accords describe has 13 sections and each section describes a unique feature of global-space collaboration such as its purpose & scope, implementation, transparency, interoperability, emergency assistance, registration of space objects, release of scientific data, persevering outer space heritage, space resources, deconfliction of space activities, orbital debris and lastly, final provisions. The mutual interest of all adjoining nations in space exploration needs a framework and set of rules in order to maintain its usefulness, cooperation, coordination, establishment and commercial growth.

The next step of humanity to the Moon sets a narrative that can inspire several generations to come, to explore beyond their imagination and break all glass ceilings. Built on the solid foundation of 50 years of stellar exploration and discoveries, the program prepares to build an efficient, robust architecture of human-robotic existence on and all around the lunar surface. The monumental shifts will attempt to set-up a sustainable course of human-presence on the Moon, something similar to the International Space Station (ISS)'s constant presence in Space.

The program status assessment consists of nine different stages, suggested by renowned experts from NASA and other aerospace companies. Management and cross-integration of projects, program schedule, technical risks, systems engineering, program integration etc are described in this status assessment. The SLS engines of the Orion Crew Module- two solid boosters with four RS-25 liquid rocket engines will be used to launch the Artemis Spacecraft to the Moon. Much ahead of the schedule, the ground tests have been successfully conducted in a simulated space-like environment.

2.2. Chandrayaan Program by ISRO

The highly complex Indian lunar mission, Chandrayaan Programme, consists of an orbiter, lander and rover to explore the apparently less explored Lunar South Pole. The scientific knowledge from this program will be formulated using a comprehensive use of seismograph, mineral discovery, topography, chemistry, material science and identification of thermo-physical features of regolith. All this would indicate the composition of the Moon and invoke more futuristic breakthroughs.

The first part of this mission, Chandrayaan-1 (C-1) was successfully launched way back in October 2008 using PSLV-XL Rocket. Operated until 2009, the mission was a substantial milestone of the Indian Space Program- making India the 4th nation to position its flag on the Moon. Contrary to the expectation of 2 years workability, the mission ran for 312 days during which it was able to provide a complete map of regolith chemical composition and 3-D topography of that zone. The reasons attributed to its failure are one, failure of its optical device that uses the position of stars using photocells also known as a star-tracker; two, inadequate thermal shielding; and three, the failure of power-supply units. Ultimately, the communication with the spacecraft was lost.

Chandrayaan-2 (C-2) was the second lunar mission of this series that was developed by ISRO and launched in July 2019. Fully developed indigenously, the mission components were- Vikram Lander, lunar orbiter and a lunar rover called Pragyan. Similar to the previous part of the mission, the idea behind this launch was again to study the variation of lunar regolith composition, find out the location of lunar water deposits and map the topography of the Moon. Eight scientific payloads for the orbiter and two payloads for the rover were sent on C-2. Extra payloads could not be carried due to weight-restrictions, therefore international tie-ups with NASA and ESA did not take place for this mission. Unfortunately, the mission remained unsuccessful as the communication with Vikram lander was lost as a result of software glitch and hard-landing. Deviation of the lander's trajectory resulted in the loss of signal, followed by inability of the software to make a trajectory correction. The descent velocity was too high at about 59m/s, causing the spaceflight to come down crashing on the lunar surface. The failure was followed by more failed attempts by ISRO and NASA to establish communication with it.

2.3. Luna-Resurs Collaborative Program Between Roscosmos & ESA

Luna-27 is yet another lunar mission planned as a collaboration between the Russian space agency, Roscosmos & ESA that will also send the spacecraft to the Lunar South Pole-Aitken Basin which is situated at a far sight of the Moon. Its mission intends, as contrary to its contemporaries, to find minerals and gases like nitrogen, hydrogen, carbon dioxide, ammonia, sulphur etc on the lunar surface. The long-term vision of this collaboration is for Russia to build a crewed base on the Moon's south side. It would accelerate both commercial and scientific progress in space technology. ESA will develop an automated landing system and also contain a drilling module that will penetrate up to 6m deep inside the lunar surface to collect the cemented ice-samples. The lander will contain 15 different types of payloads that will analyze the plasma of the exosphere, regolith composition and other seismic activities on the Moon.

2.4. Miscellaneous Programs/Activities

The Fiber Optical Manufacturing in Space (FOMS) is a technique of manufacturing optical fiber under the free-fall conditions in Space, thereby making them of the highest quality possible. A fluoride-based optical-fiber, ZBLAN can perform up to hundred times better than the existing silica-based optical fiber cables. But under the influence of gravity, production on ZBLAN is a difficult task, given, it gets hindered by the formation of impurities due to crystallization under gravity.

Small-scale manufacturing of ZBLAN has been ongoing onboard ISS under the program, Made in Space. The Glass Alloy Manufacturing Machine, an experimental module developed to produce optical fiber on ISS allows the glass alloys to form without inhibiting it with redundant impurities due to absence of gravity. The optical-fiber industry is expected to grow to a humongous $5.3B by 2023 and has been growing at a yearly rapid rate of nearly 20 percent. Optical fibers find their application in telecommunications, medical devices, remote sensing payloads, thermal imaging and thermal resistance systems etc. If the in-space production of ZBLAN turns out to be veracious, it could change the face of optical-fiber communication. It will offer much higher bandwidth, exponential rise in transmission speed and enable faster performance of 5G communication, 4K streaming and virtual reality (VR) applications etc. Lower attenuation and wider wavelength will reduce the need for repeaters, thereby reducing the risk of data-leakage and instead enhance the network security.

3. Lunar Mining

3.1. Lunar Surface Mining Techniques

The proposed lunar mining projects will primarily require a substantial amount of monetary investment, followed by an impeccable level of technological advancement, intensive understanding of soil mechanics, excavation research and development and the feasibility of manufacturing on the lunar surface. The conventional techniques that are workable on the Earth may not function well on the Moon, therefore unorthodox methods must be devised in order to support the lunar environment and its accompanying challenges. Smart procedures should be adopted that may require least use of machinery, moving parts and material handling, produce minimal thermal radiation and have maximum dependence on the resources available on the

Moon. Variety of findings from the previous research expeditions have indicated that oxygen can be obtained after electrowinning it from the silicate rocks. Further, silicates could be reduced with Carbon, or the impure Fluorine soil etc, all within the premises of Lunar Environment.

Top layer of lunar soil, known as *regolith***,** is greatly an amalgamation of silica and iron and consists of blocky, fine, particulate and grained matter. Lunar excavation is yet relatively unexplored; therefore, applied and basic research must be carried out to establish effective mining prototypes. Handling regolith itself is a complicated task and additional research is required to specify the techniques that should be adopted for this purpose.

Considering the facet of mining, some vital features of regolith such as surface roughness and thermal & structural properties must be well-investigated. In simple terms, the tribological features become considerably significant here. Also, the effect of wide-ranging atmospheric conditions like low-pressure and zero-gravity etc needs to be taken into consideration. Techniques like hot pressing, liquification, sintering and 3D printing etc can be utilized to convert unprocessed regolith into usable structural components. It can be combined with carbon-nanotubes and other epoxies, ballast glass fiber and PETG mixture etc to make a reinforced composite material. In fact, reinforcement of regolith with fiber glass is reported to have shown a commendable increase in strength/weight ratio. Steps Involved in Lunar Mining.

3.2. Manufacturing on the Moon

Establishment of In-Space Manufacturing (ISM) infrastructure involves a complex process. Given that currently the ISM activities are limited to the Lower Earth Orbit, it is rather referred to as In-Orbit Manufacturing. The specialty of this technique is that it utilizes the zero-gravity and vacuum environment in space and therefore, such production is infeasible in the Earth's atmosphere. The In-Situ Resource Utilization (ISRU) will advance the sustainability of in-space exploration missions. Eventually, such an establishment of manufacturing units on the Moon will significantly cut down the mission costs and make the Moon voyage an affordable scientific experiment. Manufacturing processes such as welding had been performed by Russian Cosmonauts in 1969 using Aluminum, Stainless Steel & Titanium.

NASA's Skylab Space Station was launched in 1973 to perform scientific experiments and manufacture new products using on-board facilities such as a crystal growth chamber, electron beam gun and an electric furnace. To begin with, the ultraclean vacuum environment in Space produces high-purity materials, the surface tension on liquids acts equally from all directions thereby making a perfectly round liquid droplet, extreme temperature locations offer a thermal gradient for multi-purpose research zones etc [2].

The surface of the Moon has a wide-ranging share of sunlight, while some zones are highly exposed to the Sun, there are zones that have not experienced sunlight in a billion years [1]. Considering that Solar Energy provides a readily available energy source to the space-missions, setting up of manufacturing plants will require an accurate topographical study of the Moon's surface. Simple utilization of thermally-fused materials can be done to manufacture stable structures and can later be used for assembling a lunar habitat. Another consideration to make for these lunar manufacturing plants is the contrast between the production conditions on the

Earth and in the Moon's microgravity environment. Some modifications must be done to ensure that the production remains effective in its new-found environment.

Performing some manufacturing processes like casting can be a cumbersome process as the liquid metal flows through the channel under the influence of gravity. New injection techniques must be developed to overcome this ambiguity. The heating can be performed using the Sun rays. Other standard procedures like welding, rolling, machining and forging can still be done effectively using power-presses and subsequent cooling mechanisms. Additional precision tools can be made use of for surface finish machining processes.

Another relatively new method for manufacturing that can be used on the lunar surface is 3D Printing technique. With an upper-hand over all processes, using 3D printing, the need for importing equipment from the Earth can be overcome by simply in-situ production of equipment on the Moon itself [3]. The on-demand method of making components makes deep space explorations a feasible and self-sufficient program. Further, more complicated methods must be devised for the extraction of material from the Moon's surface. Some additive manufacturing techniques that can be applicable for lunar colony establishment are defined below-

- **i.** ***Material Extrusion***: A continuous flow of material is thrown out of an injector that melts the input powder ink by heating it. Controlling temperature, pressure and deposition speed of material injection can change the bonding of different layers. Polymer ink can be used for this process.
- **ii.** ***Binder Jetting*****:** A liquid binder material is used to compact multiple layers of powder material. This is an advanced technique that intends to build parts using a specific blending method. All sorts of materials such as metals, polymers or ceramics can be used for this method.
- **iii.** ***Sheet Lamination***: In this process, multiple sheets are layered on top of each other to make a desired shape. In case of heterogeneous usage of different layers, combining processes like ultrasonic welding must be used. Further, the unused material can be removed by the means of laser cutting.
- **iv.** ***Stereolithography***: An ultraviolet (UV) light from a laser jet is passed on a liquid polymer resin material inside a vat chamber. The parts that need to be made are selectively solidified inside the vat and the extra resin is removed.

3.3. Lunar Mining Techniques

Dr. Amelia Grieg, Assistant Professor of Mechanical Engineering at University of Texas at El Paso, USA leads a project known as "ablative arc mining (AAM)" that would allow the extraction of water, precious metals and other minerals from the Moon's surface simultaneously. A focused electric arc will be directed at the regolith to sublimate the water ice from the regolith and turn it into water vapor. The breakage of water vapor into ionized particles will be captured by the electric field around the regolith and will enable the enrapturement of other miscellaneous materials as well. While previous mining techniques used the concept of "thermal ablation", the inadequacy of this method urgently needed a corrective attempt. In thermal ablation, the frozen water turned into vapor because of heating would get easily lost in the Moon's thin atmosphere, therefore ionizing of vapors became imperative.

Expectedly, even the ablative arc mining method has a few downsides of its own. Initially, the power required to produce an electric arc in the Moon's thin atmosphere is extremely high. And then, a robust robotic system is needed to work fully-automatically to make an autonomous set-up. Need for a robotic system arises as not enough astronauts are planned to be sent to the Moon so far, thereby cutting short the human-labor needed to perform the AAM technique [4].

3.4. Establishment of Lunar Factories

Non-terrestrial environment of the Moon poses a great technological challenge at the establishment of lunar colonies or factories in the near future. Given the high costs associated with sending mass to the Moon, an effective way to counter this challenge is to establish a Moon Village as a next step in the human-spaceflight exploration program. Such an initiative will not only accelerate multidisciplinary research, it will also expand the survivability of mankind in a non-habitable environment on the Moon. A lunar outpost will consist of several complex modules such as propulsion units, life-support system, topological mapping etc. Protective structures must be built to withstand harsh environmental conditions that may be extremely hostile and unsuitable for survival.

To build infrastructure on or around the Moon, the materials and equipment will be required to be transported from the Earth. The cost of such transportation runs into some multi-billions, making it economically infeasible and costly. It cuts short the urgency of the mission and not enough progress takes place because of this massive challenge. This challenge can be tackled if initially, effective equipment is sent from the Earth for techniques like additive manufacturing using 3D printing. Moon's regolith can be used as the raw material and its constituents could be extracted for different applications.

There are three stages involved in the establishment of a lunar colony. The first stage is to send prefabricated shell modules from the Earth; the second stage is to send pre-outfitted structural shell components; and third stage is the in-situ development of components on the Moon by the means of additive manufacturing techniques. Some structural concepts, ideated so far is i) spherical inflatable, ii) cable structure in a crater, iii) three-hinged arch and iv) lunar lava tubes.

4. Conclusion

Futuristic but possible, the Lunar Mining missions are at the verge of becoming a reality. Extensive research has been going on to come up with a final plan of action for how to go about the entire mission. Concepts like in-situ production using additive manufacturing, scrutiny of regolith composition, extraction of rare metals, capturing Helium-3 gas and collection of water from the Moon are work in progress. Missions like NASA's Artemis, ISRO's Chandrayaan-3 and Roscosmos & ESA's Luna-27 are planned to make lunar exploration a reality.

Establishment of a lunar economy shall be an amalgamation of several parts such as material science, manufacturing, transportation, excavation, construction and in-space tests and experiments etc. Data collected so far indicates the possibility of such a concept to come true and further research should be carried out in this regard. A lunar colony capable of providing life-support will enable a sustainable status of human-presence on the Moon.

The manufacturing processes that may be feasible on the Earth may not work well in the lunar environment; therefore, new techniques are needed to be developed. Some manufacturing experiments have been conducted onboard the International Space Station and at NASA's Skylab. ZBLAN optical fiber has been produced with high-purity and 100x more transmission power indicating that microgravity environment can be highly advantageous for the production of optical fibers.

Lunar mining is a complex procedure and in order to collect the regolith content with efficacy, an ablative arc mining (AAM) method is investigated in this paper. The expectation from lunar mining is to acquire high volumes of precious minerals and other resources from the Moon and bring them to the Earth. The associated challenges need to be resolved for the implementation of such futuristic plans.

In-situ Resource Utilization (ISRU) is indeed the first constructive step towards the establishment of a Lunar Colony, thereby establishing a full-fledged utilization of the available resources. Additive manufacturing, if performed successfully on the Moon, can be a monumental step towards such a futuristic vision. Making a sustainable Moon Village means that it can be self-reliant, fully autonomous and be useful for the future of Space science and technologies. If successful, a smooth shift to cleaner energy fuel, better resource utilization and an inter-planetary residence of human beings may be possible.

5. References

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