Crafting Resilience: Additive Manufacturing for Rover Mission Sustainability

Victor A. Zaharia[1]
Florida Institute of Technology, Melbourne, Florida, 32901, USA

This paper explores the integration of Additive Manufacturing (AM) into rover missions for extended space exploration. Rovers, vital for in-depth celestial body analysis, face longevity challenges addressed by innovative solutions like AM. Charting the evolution from lunar to Martian rovers, the study underscores the consistent trend of enhancing capabilities across generations. Laser Powder Bed Fusion (LPBF) and Direct Energy Deposition (DED), two prevalent AM methods, are assessed for their application in rover missions, with LPBF offering precision but facing cleaning challenges, and DED providing versatility despite precision limitations. AM's role lies in on-site production, facilitating structural replacements, and recycling materials for sustainable long-term missions. Logistics involve a hybrid LPBF-DED system, capitalizing on mission-specific requirements. As the satellite launch market advances, incorporating reusable stages, resupply missions become cost-effective. This proposal envisions a future where rovers evolve dynamically through AM, ensuring adaptability, longevity, and cost-effectiveness in space exploration.

I. The Introduction of Space Rovers and their Pioneering Impact

As humans expand their presence in the solar system, uncrewed missions are drafted and completed before undertaking crewed ones, minimizing the risk to human life while gaining valuable insights. Satellites contribute significantly by mapping geography and understanding geology. However, to delve deeper into the intricacies of a celestial body, rovers have become a valuable tool for data acquisition. Their surface exploration offers a wealth of direct information important for determining the feasibility of crewed missions in the future. An example of data obtained would be from the Opportunity rover discovering veins of gypsum on Mars, pointing to the existence of water. [1] A discovery of this magnitude allows for future Mars missions to be designed with this detail in mind, potentially reducing costs and expanding the scope on the types of experiments that can be carried out to gather further data.

In this pursuit of celestial exploration, engineers have confronted the challenge of ensuring a rover's mission endurance. Currently, the constraint of fixed payload mass during rocket launches poses challenges, with "…minor incremental progress…" being made due to advances in material science and methods of manufacturing. [2] Once on route, impromptu problems become difficult to resolve, especially when if occur hundreds of thousands of kilometers away from Earth. Addressing these challenges requires innovative approaches, emphasizing the need for strategic planning and adaptable solutions in the quest to explore and extend the human reach within the solar system and beyond. Here, additive manufacturing (AM) emerges as a modern solution to a problem as old as space exploration itself, allowing on-site production of tools and infrastructure, enhancing the rover's capabilities and mission duration.

During the time of the Cold War, heavy investment in engineering provided solutions to creating a vehicle capable of withstanding the harsh environments of different planets and moons. The inception of rover's dates back as far as 1963 with the Surveyor Lunar Rover Vehicle (SLRV) which had never flown but served as a path to future designs of rovers. The Soviet Lunokhod, or Moonwalker, claimed the title of being the first rover in space as well as the first rover to land on the Moon on November 17, 1970. [3] Progress marched on and once the Moon had been visited by Neil Armstrong and Buzz Aldrin in 1969, the world set their eyes on Mars. The main challenge facing new rover design was the distance the rover had to operate from Earth. Moon rovers operated on a "move and wait strategy" due

---

[1] Undergraduate Student, Department of Aerospace, Physics, and Space Sciences, AIAA Student Member (1418890).

to the proximity to Earth, but such a strategy would be impossible on Mars as the delay from human input would range from “7-30 minutes”. [3] As such, new methods of operation needed to be designed, developed and tested. With the technological limitations at the time during the 1980’s a technique called Computer Aided Remote Driving (CARD) allowed for rover operations and range to increase. CARD served its purpose by taking images of the terrain on Mars, transmitting it to Earth where a path would be decided upon and have the directions sent back to Mars for the Rover to execute. Due to cost limitations and advances in microelectronics, rover design shifted to the category of micro-rovers. This laid the foundation for the National Aeronautics and Space Administration (NASA) to achieve success in its Sojourner mission to Mars. A modern rover, such as the Curiosity rover, which is also known by the name of Mars Science Laboratory rover (MSL), currently incorporates the latest technology for surveying the Martian landscape as well as collecting surface samples.

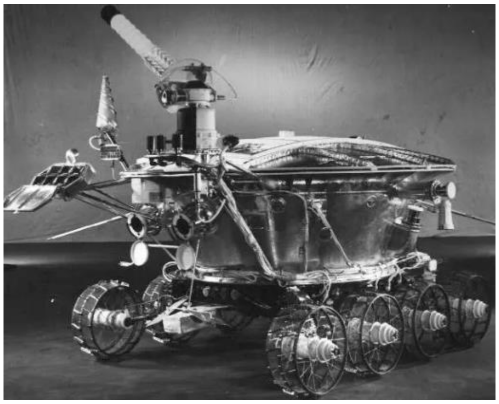

Fig. 1 Soviet Moon lander Lunokhod 1 [4]

Fig. 2 NASA Perseverance Mars rover [5]

Across successive generations of rovers, a discernible pattern emerges, revealing a consistent trend. Each iteration exhibits an augmentation in vehicle capabilities, notably extending the range and enhancing the variety of tasks achievable, whether autonomously or through human input. The Perseverance rover, for example, had an expected mission life of one Martian year which equates to about 687 Earth Days. At the time of writing this paper, the rover has surpassed 1000 Earth days. [6] When comparing this to the aforementioned Soviet Lunokhod, the lunar rover, the vehicle life was 11 lunar days which equates to about 325 Earth Days. [7] The conditions the vehicle is exposed to either on the Moon or Mars is demanding and poses their own set of problems that require individual solutions. It is therefore important when creating the next generation of rover vehicles that this trend is followed and improved upon.

II. Incorporating Additive Manufacturing

With the continued trend of incorporating the latest technological advancements to achieve greater efficiencies, AM is the next logical step to developing the next generation of rovers. When compared to traditional manufacturing techniques such as subtractive manufacturing (SM) which involves removing material and mass, AM achieves the opposite via “…layer by layer manufacturing based on a common feedstock,”. [8] Currently, there exists numerous methods of AM that has applications across multiple engineering disciplines, ranging from civil engineering to aerospace engineering. There have been numerous aerospace companies that have adopted and utilized AM due to its versatility in terms of rapid prototyping and the ability to create highly complex geometries that traditional SM is either incapable of doing or has high costs attached that prohibit it being a viable option. As such, it is important to take a look at the two main types of AM applied in the aerospace sector as well as the drawbacks to consider when attempting to create extend rover capabilities.

A. Laser Powder Bed Fusion (LPBF)

Compared to traditional AM techniques of using a jet to disperse material and pile it layer by layer, LPBD utilizes a laser to “…melt or sinter the feedstock material for bonding layer-by-layer.” [9] As such, this method of printing employs the use of metal powder as the “ink”. The use of a specialized metal powder composition, designed according to the intended application, imparts superior mechanical and thermal properties compared to materials widely adopted in commercial settings. Numerous aerospace companies have adopted this method of printing such as Blue Origin, NASA, Relativity, SpaceX, implying it is a valuable asset in terms of meeting the demands set for mission success in harsh environments in terms of temperature fluctuations, vibration, and other forms of stress that the part or object is expected to be able to withstand. [8] Due to the use of lasers as the method of targeting where the metal powder needs to be heated to melt, a high degree of accuracy is achieved, allowing for microprinting with an achievable minimum layer thickness of 15 μm. [9] This ability to create intricate parts of small dimensions makes it a valuable machine to be used for missions requiring an extreme degree of precision. Once this method of AM develops further and offers electronic device integration, the ability to create new circuits through use of semiconducting materials offers in-site solutions that are immediate and cost-effective. Rather than having a mission terminate due to a failure of an instrument, this opens the door to the possibility of being able to replace said instrument on-site rather than sending a second mission, saving both cost and time, which are directly associated with one another in the world of aerospace.

As with anything engineering-related, there are limitations and drawbacks to employing a specific type of AM, to which LPBF as a technique has complications that need to be discussed. Since AM machines that use powder use lasers to melt specific regions to create a layer of a part, the excess heat can cause powder to melt in regions where it was not specifically targeted around the part. This traps excess powder where it "…can be either released during part functioning, …, or can solidify during part heat treatment." [10] The listed situations would render the component unable to fulfill the designated task due to the uncertainties associated with the alteration of properties caused by excess material. With this in mind, the part that needs to be created needs to take into account this possibility. The process of cleaning the part from the bed of powder is perhaps the biggest drawback of any powder-based AM. The post-processing needed to ensure the part is to standard and is capable of meeting the design requirements from stress, vibration, and thermal perspective usually requires human intervention. There is a risk posed to the human that would normally handle the de-powdering and cleaning of the part once it has been completed. The only human intervention would be sending the correct commands to have the part printed, then the part would need to be cleaned, collected, and placed at the proper location via commands send to a robotic arm either in the AM machine or attached to the rover itself. In order to ensure the maximum operating capability, a procedure would need to be devised that does not require the presence of a human to transport the part to and from where it needs to go.

B. Directed Energy Deposition (DED)

Similar to LPBF, DED also uses a high energy source to melt the selected material but holds a larger domain of where the technology can be applied. The noteworthy difference, is the further set of applications DED holds, which ranges from "…filling cracks, retrofitting manufactured parts, and repairing high-value metal parts." [11] A second benefit is the ability to deposit large volumes of material at a rapid pace. The values range from 0.5 kg/h for Laser Engineered Net Shaping (LENS) to 10 kg/h for Wire Plus Arc Additive Manufacturing (WAAM). [11] Another notable advantage, outlined by Svetlizky, is the potential for DED machines to incorporate a hybrid system bridging AM and SM. Having a hybrid system can allow for corrections to a created part in the event of a failure on the AM side of the manufacturing. Having insurance that there is a method to adjust the part through SM instead of having to start over is efficient and makes the most of the material that is available. The second point of being able to print in a zero-gravity environment offers flexibility of where the printing system can be applied. Allowing the creation of parts in space offers in-situ solutions rather than once again relying on a rescue mission to be fielded which once again costs time and money but also increases the need for human intervention, which is something that cannot be relied upon the further a mission is away from Earth.

In the pursuit of success, there is no solution that fits every problem; therefore it is important to discuss the limitations of the DED method of AM. An issue that plagues most AM techniques is the shrinking and deformation that occurs during the manufacturing process. Uneven layers, improper temperatures, all act as obstacles in the pursuit of an ideal part. [11] One limitation that serves as the most difficult aspect to grasp logistically is the low powder efficiency when multiple powders are used for a print. Having any form of waste limits the lifespan of the system which again requires a separate mission to resupply which reduces the credibility of the system and disqualifies it from being a viable option for a mission such as ensuring the longevity of a rover when operating for long periods of time. Another issue to report is the lack of precision when compared to the previously mentioned LPBF, which limits the capability of producing microprints if they are needed. As there are numerous uncertainties and a multitude of ways a mission can go wrong, having the resources available to navigate around failure provides flexibility to ensure a mission does not end prematurely.

III. Extending Mission Capabilities and Rover Lifespan

For an aerospace mission to last a specific amount of time, it needs the ability to withstand a wide range of conditions as well as prepare for the unknown that may arise when said mission is taking place. With this in mind, it is important to have a contingency plan that is able to respond to various problems that may result during the mission life of a rover. Having described the capabilities of AM as well as its flexibility as a manufacturing method, modifications can be made to a rover to ensure the mission it was designed for is completed regardless of whatever problems that may be encountered.

Although careful mission planning can try to account for issues such as terrain and how to navigate it, this still leaves the rover in a static phase. Static in this case implies that the rover that is sent does not change and is expected to operate without any modification to the hardware. When operating for prolonged periods of time without change to a structure, failure can happen. There are various reasons why a part or mechanism would fail, but the goal is to navigate around that issue and find a feasible solution. Similar to how the human body is constantly replacing old cells with new ones, or rather why a part is replaced on a plane or car, a similar approach can be applied to a rover mission. A relevant example that directly displays why damage to a rover severely hampers the mission is with the Mars Curiosity rover's wheels. Ever since the first signs of wheel damage were observed on sol 411 in the form of holes, they have grown, which in the long run will "slow the progress of Curiosity and to limit the paths the mission can choose to explore." [12]. Since a part such as a wheel is constantly under stress both static and dynamic, it would naturally wear down with time. Having a method of replacing the damaged wheel would not only allow the rover to regain its full mission capability, but it would also extend the life of the rover itself. Implementing AM by having an on-site machine to fabricate and replace the wheel would usher in the next generation of rover design and mission planning.

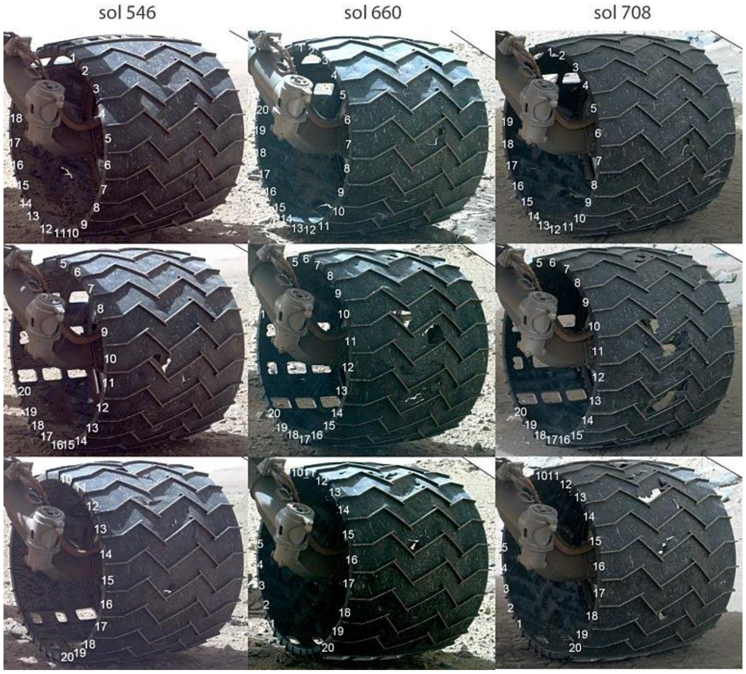

Fig. 3 Damage to Curiosity rover's wheels [10]

An important consideration that needs to be noted is the way AM would be incorporated into a rover mission would look different to how it currently is on Earth. There are several factors that would need to be identified where new procedures and solutions would be created to allow for the seamless transition away from static, as defined earlier, to a replacement-oriented approach. AM would have the greatest application, with the current methods of printing, in replacing structural components of a rover. Through the gained experience and knowledge from both Lunar and Martian rovers, causes of failure have been identified and solutions have been engineered to prevent them, however each celestial body represents a new challenges with even more unknowns that would require a large investment of time and money which in the current space age is difficult to come by. Therefore the present situation of rovers allows for the excellent opportunity to field test the idea of incorporating AM to a mission to not only extend a rover's service life, but rather serve a as a platform that can assist with any other task that requires a part to be made. This is why the idea of applying in-site AM, with its current capability and understanding, as a toolkit that can fix the structural damages endured during a mission is attractive and can be relied on for future generations of rovers.

When taking a look at the current methods of repairing a rover outside Earth's atmosphere, the major advantage gained by having AM sent as a part of a mission alongside a rover can truly be understood. As mentioned before, when sending a mission to another celestial body, the payload mass is fixed. This is perhaps the most limiting aspect of any mission, because unlike Earth, resources are not readily available. This necessitates the application of in-situ resource utilization. The main challenge with this concept lies in the fact that, in many instances, the resources required for a specific task are not readily accessible, posing difficulties in integration into current design philosophies. Rovers primarily serve the purpose of exploring to determine the available resources. As such, rovers have their limitations outside of structural fatigue. Issuing repairs to a rover that is hundreds of thousands, if not millions of kilometers, in its current capability, do not involve the changing of pieces. Rather, with the current model, "…fixes to very mechanical problems are to use that instrument differently". [13] In the simplest of terms, this requires using what resources are currently available to the rover and finding a creative solution that resolves the problem it was facing. This model is not sustainable. In the event the rover faces an issue with either its structure or instrumentation and cannot under its own power find a solution, capability is reduced or the mission ends. As such, AM comes in as the option that allows for repairs to several problems the rover is plagued with. In the event AM is able to produce electronic devices, it opens the door to instrumentation replacement, allowing the mission to continue its work until a catastrophic failure or until the material in the AM machine runs out. The benefit of AM is that it would primarily require resupply missions which is overall cheaper when compared to a crewed launch.

As the technology for AM improves, there is no telling how and where it could be applied outside of Earth. There is still time that is required for this technology to mature as well as evolve, but that is a common sight in the field of engineering. The important aspect to consider is that the machine capable of AM would need to be adapted to match its operating environment. There is also the question of logistics in operating such a machine.

IV. Additive Manufacturing Logistics

In suggesting a new standard, there is a need to devise a comprehensive plan outlining the implementation details to ensure the effective execution of this standard. With the idea of implementing AM to rover missions, it is necessary to consider the logistics of how this system will operate. Recall earlier, the use of AM will allow for missions to continue for long periods of time with little to no human interaction except for sending instructions of what needs to be printed, repaired or augmented.

The ideal AM system for rover mission sustainability would need to be able to account for a wide range of challenges as well as the ability to rely on itself, similar to how rovers currently operate. Two primary methods of AM have been discussed due to their prevalence in the aerospace sector: LPBF and DED. In their discussion, the main benefits and drawbacks of each system were highlighted, displaying how LPBF AM can achieve extreme detail whereas DED has a greater flexibility of what it can print and can operate in zero-gravity environments. With current AM technology, a hybrid system between LPBF and DED would serve as an effective platform to manufacture the necessary parts for a rover to continue to operate, even in the event of a part failing.

A major benefit that AM observes is the ability to send feedstock in a compact form. Whether it is in a spool or in a powdered form, the feedstock requires little space when packed as payload. Parts that would normally be too tall or too wide to fit in a rocket could be sent in their raw material form and assembled on site wherever the mission is taking place. Less focus on size and more on mass allows for a wider range of rocket classes to be able to send missions wherever they are needed off Earth. Their versatile supply methods maintain a continuous option to dispatch materials, positioning Earth as the central hub and rover missions as outposts.

A major advantage this proposal has is the heavy investment in the Satellite Launch Vehicle (SLV) market. In 2022, the SLV market was valued at 14.5 billion USD and is projected to grow to 45 billion USD in 2032. [14] Current innovators such as SpaceX with their reuseable first stage, Relativity Space with their capacity to print rockets, and newcomers such as Stoke Space with their proposal to have a reusable second stage are driving down the costs of launch. This allows for more missions to space and, with time will also increase the payload mass capabilities of rockets per launch. This makes resupply missions, if they are needed, a cost-efficient method of ensuring an AM outpost on a celestial body is maintained without the need to send humans.

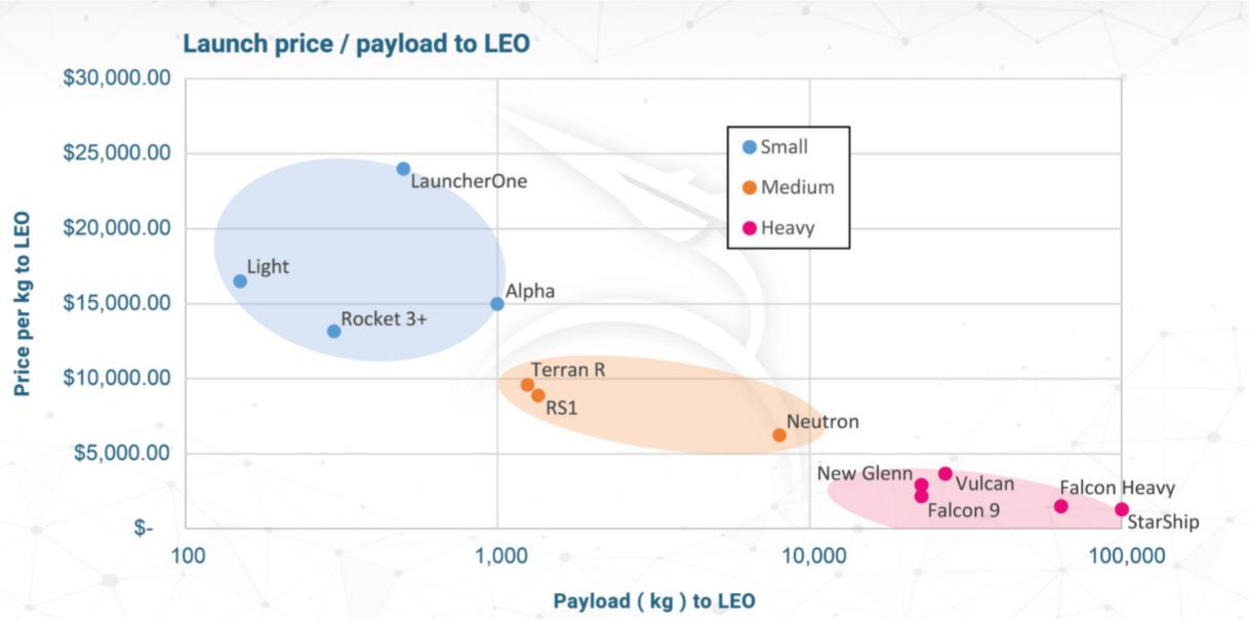

Fig. 4 Launch price for current or emerging launch vehicles (split by class) [15]

A way to augment the proposal of AM in rover missions is the ability to recycle materials after a mission is completed. One of the reasons AM is a competitive candidate in operating alongside rover missions is how the manufacturing process is able to recycle unused material. As described in Section III, both AM techniques use layers of powder both for manufacturing the part and for supporting the part itself during manufacturing. This excess powder can then be reused for future prints, thus minimizing waste that other forms of AM have. Once such instance of reusing metal powder multiple times for AM prints was published in Metal AM detailing “Multiple powder reuse (in up to 30 builds) with periodic rejuvenation of the powder does not appear to have a significant effect on powder characteristics…”. [16] Allowing the reuse of material permits long operating times with minimal need to resupply unless a print requires a large amount of material. Since all the material is already locally in the AM machine, automation can be implemented to easily recycle the material for the next part that needs to be made. This concept does not only extend to unused powder, but also to parts that are no longer needed. Rather than having a part, a drill for example, that was printed, used and is no longer needed occupy space, it can be crushed back into powder to be reused for a later print. There are numerous factors to consider such as the material that is being used and its ability to be reused. Another factor is if a print is applying multiple types of powder to create an alloy, the separation process once the part is crushed is nearly impossible. With this in mind, new techniques would need to be developed to allow for such a concept to work. New methods of AM part construction and material science would be a direct result of creating this new generation of rovers.

With the topic of AM, the question of if there is merit to making or bringing a part or resource regularly comes up and needs to be addressed. Depending on the specifications of a mission outside of Earth’s atmosphere, there is a lower cost associated with manufacturing a part and bringing it from Earth rather than making it in space or on the celestial body. In a paper published by Jones titled *Take Material to Space or Make it There?* the following concerns are raised: Hardware development cost being greater than transport cost as well as the long-term costs associated with maintenance and operations of the hardware. [17] These are valid concerns, but it is also important to consider the scope of the mission being proposed. Short-term missions benefit from taking material as their proximity to Low Earth Orbit (LEO) or Greater Earth Orbit (GEO) means low transport costs. The work of rovers has been to gather data about celestial bodies with no risk to human life. First it was the Moon to which humanity set its eyes upon which required rovers to survey the terrain and determine the conditions to allow for humans to walk on the surface. The same work is being done on Mars with the current generation of rovers. This proposal is to set the basis for missions that extend further into the solar system, to Moons such as Titan and Europa and even beyond the Kuiper Belt. There are other unknowns that will have to be addressed once there are identified as this is an untested concept. This proposal is based upon current technology, therefore in the coming years, new technology may be developed to match the idea of extending the service life of a rover and allow it to operate at a higher efficiency.

V. Conclusion

To expand humanity's reach into the cosmos, gathering information about a celestial body necessitates the use of rovers, which, like any machinery, experience breakdowns over time. The majority of breakdowns result in a mission failure and an inability to continue using the rover to gather this critical data. Additive manufacturing responds to this problem by allowing for a greater degree of operational flexibility alongside providing on-site solutions. The unique capabilities of AM, including material recycling and the creation of intricately designed parts with optimal mechanical as well as thermal properties, distinguish it as a technology ensuring extended mission lifespans. With the costs of rocket launches going down and the space sector growing in value year by year, sending this technology to distant moons and planets is a viable option instead of a fantasy. Instead of having to dedicate payload space to pre-manufactured parts, they can be fabricated and adjusted to meet the specifications as they arrive at their mission site. Having a hybrid system of AM and SM with current technology allow for the greatest range of part creation. Although rovers have been the main point of discussion, applications of this technology extend to commercial sectors as well, not only to the aerospace industry. The fundamental concept of leveraging AM to produce and replace components significantly enhances the overall lifespan of any machine. Implementing this technology would spark the emergence of new design paradigms, placing itself at the forefront in the next era of engineering advancements.

Acknowledgments

V.Z. gives special thanks to Nolan Smith for inspiring the idea of applying AM in new ways previously unknown and would also like to thank the Florida Institute of Technology’s AIAA chapter.

References

[1] mars.nasa.gov. (n.d.). Science results—Nasa. Retrieved March 2, 2024, from https://mars.nasa.gov/mer/mission/science/results/

[2] Aglietti, G. S. (2020). Current challenges and opportunities for space technologies. Frontiers in Space Technologies, 1, 1. https://doi.org/10.3389/frspt.2020.00001

[3] Muirhead, B. K., "Mars rovers, past and future," 2004 IEEE Aerospace Conference Proceedings (IEEE Cat. No.04TH8720), Big Sky, MT, USA, 2004, pp. 134 Vol.1, doi: 10.1109/AERO.2004.1367598.

[4] Howell, E. (2016, December 20). Lunokhod 1: 1st successful lunar rover. Space.Com. https://www.space.com/35090-lunokhod-1.html

[5] NASA, & JPL-Caltech. (n.d.). Mars 2020 rover is roving. NASA Jet Propulsion Laboratory (JPL). Retrieved January 7, 2024, from https://www.jpl.nasa.gov/images/pia23499-mars-2020-rover-is-roving

[6] mars.nasa.gov. (n.d.). Frequently asked questions—Nasa. Retrieved January 7, 2024, from https://mars.nasa.gov/mars2020/mission/faq/

[7] Siddiqi, A. A., (2018). Beyond Earth: A Chronicle of Deep Space Exploration, 1958–2016 (PDF). The NASA history series (second ed.). Washington, DC: NASA History Program Office. p. 98. ISBN 9781626830424. LCCN 2017059404. SP2018-4041.

[8] Blakey-Milner, B., Gradl, P., Snedden, P., Brooks, M., Pitot, J., Lopez, E., Leary, M., Berto, F., Du Plessis, A., Metal additive manufacturing in aerospace: A review, Materials & Design, Volume 209, 2021, 110008, Issn 0264-1275, https://doi.org/10.1016/j.matdes.2021.110008.

[9] Khorasani, A., Gibson, I., Veetil, J.K. et al. A review of technological improvements in laser-based powder bed fusion of metal printers. Int J Adv Manuf Technol 108, 191–209 (2020). https://doi.org/10.1007/s00170-020-05361-3

[10] Ceccanti, F., Giorgetti A., Arcidiacono G., Citti P., "Laser Powder Bed Fusion: A Review on the Design Constraints", *IOP Conference Series: Materials Science and Engineering*, Volume 1038, The 49th AIAS Conference (AIAS 2020) 2nd-5th September 2020, Genova, Italy

[11] Svetlizky, A., Das, M., Zheng, B., Vyatskikh, A. L., Bose, S., Bandyopadhyay, A., Schoenung, J. M., Lavernia, E. J., Eliaz, N., Directed energy deposition (DED) additive manufacturing: Physical characteristics, defects, challenges and applications, Materials Today, Volume 49, 2021, pp. 271-295, Issn 1369-7021, https://doi.org/10.1016/j.mattod.2021.03.020.

[12] Lakdawalla, E. (n.d.). Curiosity wheel damage: The problem and solutions. The Planetary Society. Retrieved January 7, 2024, from https://www.planetary.org/articles/08190630-curiosity-wheel-damage

[13] Yu, A. (n.d.). How NASA repairs its rovers on Mars, without ever touching them. WHYY. Retrieved January 7, 2024, from https://whyy.org/segments/how-nasa-repairs-its-rovers-on-mars-without-ever-touching-them/

[14] Satellite launch vehicle (Slv) market size, share & trend, 2032. (n.d.). Global Market Insights Inc. Retrieved January 7, 2024, from https://www.gminsights.com/industry-analysis/satellite-launch-vehicle-slv-market

[15] Magill, H., Topalov, C. (2022, August 18). Survival of the fittest: Saturation in the space launch industry. SpaceWorks Enterprises, Inc. https://www.spaceworks.aero/survival-of-the-fittest_launch_industry/

[16] Whittaker, D., "Understanding the impact of powder reuse in metal Additive Manufacturing," *Additive Manufacturing with Powder Metallurgy Conference,* AMPM2017, Vol. 3, No.3, Las Vegas, USA, pp. 117–127.

[17] Jones, H., "Take Material to Space or Make It There?", AIAA Paper 2023-0013555, September 2023.