REVIEW ARTICLE

Manufacturing Beyond Earth: A Comprehensive Review of In-Space Additive Manufacturing

Dylan Thai

Walnut High School,400 Pierre Rd, Walnut, CA 91789, Walnut, California, 91789, USA; dylant8899@gmail.com

ABSTRACT: Manufacturing is foundational to the building and functioning of our world and includes creating things from small home objects and tools to large-scale installations. Recently, manufacturing in space has gained a lot of attention for the critical role that on-demand in-space manufacturing can play in reducing mission costs, increasing mission success, and unlocking new frontiers for humanity. Moving manufacturing out of this world into an environment lacking substantial gravitational forces presents unique technical challenges and new opportunities. This review explores the field of additive manufacturing and bio-based manufacturing in space. Using the unique environment space provides, such as microgravity, new materials and products can be created using additive manufacturing methods. We explore and provide an overview of the current state of the art in biomanufacturing, extrusion-based manufacturing, and droplet-driven manufacturing. We also provide insights into how the fields' future could be shaped through space. The advancement of in-space manufacturing methods has the potential to unlock new possibilities for unique materials and manufacturing methods. It has the potential to make space travel more readily available.

KEYWORDS: Aerospace and Aeronautical Engineering; Biomaterials; Additive Manufacturing; extrusion-based manufacturing; droplet-driven metal manufacturing; in-space manufacturing; 3D printing.

Introduction

The defining characteristic of space is the lack of gravity. The absence of a force so universal on Earth enables an entirely new dimension of possibilities. One of these possibilities is utilizing the lack of gravity for manufacturing in space, from bio-manufacturing[1] to droplet-driven metal manufacturing.[2] There are a plethora of in-space manufacturing fields, each with its own unique attributes in space. These attributes include unique manufacturing capabilities in space compared to earth-based manufacturing, varying costs associated with conducting these processes in space, and limitations of the various manufacturing methods in space. For example, manufacturing exotic fibers and glass in space is a frontier that has gained significant attention due to its advantages in promoting higher manufacturing yields, better fiber, and glass quality, mainly when used for the photonics, and increased material ductility.[3] These fibers and glass manufactured in space fulfill a demand in the ever-growing internet and telecommunications markets since the main products of these fibers and glass cables have faster transfer speeds while being more cost-efficient.[3] Although space manufacturing may not be able to fulfill all the world's manufacturing demands, even a small percentage of manufacturing done in space will already significantly benefit Earth. In this work, we review and explore various in-space manufacturing fields and the unique capabilities enabled by manufacturing in space. We present a comparative assessment of these manufacturing fields.

Biomanufacturing:

A significant portion of bio-manufacturing is focused on manufacturing devices for human body systems. Demand for technology that can create full organs or advanced chipset technology is constantly growing, and there is a need for improvements in the existing technology.[4] Bio-manufacturing may use other manufacturing techniques, such as Fused Deposition Modeling (FDM), which uses an extrusion-based process to additively manufacture materials and devices, which can produce products like biosensors[5] or microfluidic devices[6] for lab-on-chip operations.[4,7,8] The characteristic feature of bio-manufacturing processes is the differences in what is made rather than how it is made. Some major products produced in space include tissues[9,10], organs[1,11], and stem cells.[12]

One of the primary applications of 3D bio-printing involves disease modeling and implantation.[9] Being able to create things on a small scale and model them accurately is an advantage given due to the lack of gravity, as structures will not collapse on themselves due to the force of gravity.[13] Modeling in the reduced or no gravity environment gives rise to new physiological properties of the product, which include biomimicking and more complicated microstructures.[9] This allows for more detailed and complicated structures to be modeled for study and usage on Earth. Modeling is the same with gravity and functionality under gravity since the traditional way to model with gravity is to print supportive structures like scaffolds removed by hand afterward. However, the downside is that it may cause issues with the print, as well as being highly complicated and requiring lots of time and precision. Therefore, making it zero or microgravity can help avoid all these issues.

In space bio-manufacturing, two of the largest product categories are organs and tissue. Various human tissues and organs may be manufactured, including cartilage, bone, skeletal muscle, cardiac muscle, and nerves.[12] They all have similar benefits from producing them in space, regarding fragility and usability.

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Presently, many of the manufactured tissues are still unusable, but ideally, *the* manufactured version should be able to replace the natural version completely. In terms of fragility, one of the most significant limiting factors with earth-based bio fabrication is that many different organs and tissues are very fragile in their structure and need to be supported throughout the fabrication process.[12] However, due to the lack of gravity, the need for stabilization after fabrication is not necessary in space, unlike on Earth, and therefore, new products with greater usability are possible when manufactured in space.[12] These research fields, however, are all still in their developmental stages, with only experimental demonstrations thus far, and we have yet to make a proper, commercially viable option for any of them. This stage of development also applies to organs such as eyes, teeth, livers, lungs, intestines, and other reproductive organs.[9] They are all things that have been investigated to elucidate the feasibility and possible benefits of producing in space. The research has been a mix of computational work and physical experiments in space, such as aboard the International Space Station (ISS), where drugs and pharmaceutical tests have also been conducted. Companies are also developing platforms that will allow for further in-space biomanufacturing research.[1] These platforms allow for more experiments by a more comprehensive array of people. Since space travel is costly, dangerous, and lucrative, only some can test their research. However, with innovations, the field should be able to expand and allow for more tests in all fields to be done.

Another key fact to note is the business side of biomanufacturing in space. Research has been done that emphasizes the importance of involving both the public and private sectors of the world, including engineers, chemists, and biologists, to make the idea feasible in the future.[14] A collaborative design must be implemented, such as a dedicated space-based research and development (R&D) hub, which would make the entire process much more efficient and reduce the time for conducting experimental research and the development of innovations. This kind of approach will ensure that technologies can be rapidly prototyped, tested, and refined in space.[14]

Overall, the field of in-space biomanufacturing is filled with many product possibilities. Although they use similar processes, the results vary between usability and fragility, as discussed in this section. In the end, more research still needs to be done in the field of bio-manufacturing, which can hopefully open the door for more discoveries in the future, from new techniques to materials.

Extrusion-Based Manufacturing:

Extrusion-based additive manufacturing is a process similar to traditional 3D printing, as they are both additive manufacturing methods where a material is heated, pushed through a nozzle onto a platform layer by layer, and cooled to make the final product.[2] Extrusion-based manufacturing excels at creating objects with consistent cross-sections and can produce things at a high rate and speed. Extrusion-based manufacturing also has the added benefits of material choice and manufacturing flexibility. It is possible to create things such as concrete through extrusion-based methods, although there are some issues, such as micro-cracks and stress concentrations in the concrete.[15] It can also work with many other materials, from plastics to resin to metal.[16] This flexibility allows more things to be created, from full-functioning medical devices to fun homemade projects. Extrusion-based manufacturing also excels at highly complex, intricate, and customized shapes that would be challenging or impossible to achieve through traditional manufacturing methods.[16]

However, unlike previously discussed manufacturing techniques, extrusion-based manufacturing's most significant benefits from producing in space don't come from the product that is produced but rather from the cost of the production.[17] Shipping anything to space is extremely expensive, costing almost $2 million for one brick from Earth to the moon.[17] The expensive cost of shipping materials to space can be counteracted by shipping one or multiple 3D printers into space and then using these printers to manufacture parts and materials on demand. Although there is currently no capability to manufacture anything large-scale, the process in the future would likely start as it did here on Earth, with mass production of the most cost-effective and reasonable item. Then, given more time and research, economies of scale can step in and allow the manufacturing of more parts if the demand is there, which it likely will be. The flexibility of extrusion-based manufacturing and their ability to print with various materials make it perfect to act as an all-creating device in space.[18]

Extrusion-based manufacturing is one area that has already been extensively researched. MADE In Space, INC is a company that has already tested extrusion-based manufacturing in space aboard the ISS.[19] They focused on no innovations regarding the possibilities of extrusion-based manufacturing. Still, instead, they just focused on testing the feasibility of 3D printing in space and found issues with some mechanisms in some of the 3D printers. One of their more conclusive results demonstrated that the average layer thickness of various parts constructed in microgravity was much thicker compared to their Earth counterparts.[19] This is likely due to the loss of gravity, allowing more material to be printed given the same parameters. The team discovered four main uses for extrusion-based manufacturing in space through their experiment, all of which are feasible and realistic based on the test results. These uses include known and possible repair, known production and assembly, unknown repair and replacement, and new experimental advantages.[20] The mission's primary purpose was to test extrusion-based manufacturing and see what modifications would need to be made. It was a proof-of-concept mission that opened the door wide for future innovations.

Droplet Driven Manufacturing:

Droplet-driven manufacturing, as its name suggests, is a process that utilizes droplets to create products from materials such as metal. Instead of heating a constant stream of filament, as in extrusion-based additive manufacturing, droplet-driven manufacturing uses droplets of molten droplets dispensed onto a substrate to produce a part or shape.[21] This type of manufacturing is most widely used in manufacturing metal parts and metal objects.[22] Advantages of droplet-driven manufacturing, especially with metals, include improved component quality compared to other manufacturing methods, such as 3D print

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ing, as the product is made as one solid piece with one solid material, resulting in less fragile products.[22] Other applications of metal droplet deposition include thermal spraying[23], soldering,[24] and droplet-based 3D printing.[25]

Many experiments have been done within droplet-driven manufacturing, including a physics-based model created to predict the future evolution of height within 3D printing using input-output data. The model it establishes must be versatile and able to work with different printing geometries or shapes.[26] The result of this experiment done by Uduak Inyang-Udoh and Sandipan Mishra was a conv-RNN model that can track height evolution during droplet-based manufacturing.[26] They have identified conditions for stable model training and demonstrated that these conditions relate to the physical stability of the evolution of height. These results suggest that the model can be used for in-process learning, allowing it to adapt as printing data accumulates.[26]

In space, however, droplet-driven manufacturing has lots of research that still needs to be done. Current research is done surrounding the feasibility of droplet-driven manufacturing, as it is a process that relies heavily on gravity, causing the droplets to settle in the presence of gravity, which is not present in microgravity. Research has been done in microgravity environments that simulate space environments to try and discover a way to unlock the possibility of droplet manufacturing.[27] An example of the research would be a study done by Jieguang Huang and others, where they found a way to horizontally eject droplets at a certain velocity to have them pile up properly and work in microgravity environments. The threshold for stable pileup was found to be 5.1 m/s.[27] They also discovered that droplet deposition accuracy depends mainly on the droplet time of flight, which is a ratio of travel distance to initial ejection velocity.[27] Knowing this, future research on the topic can determine what variables to adjust to make manufacturing more accurate and more shapes possible. This opens the door for much more research on droplet-driven manufacturing in the future.

Discussion

With the wildly varying processes and products possible with in-space additive manufacturing, each process and method has advantages and disadvantages. With biomanufacturing, the most significant use cases come from its ability to create things that are impossible to make on Earth.[28] With the possibility of making things such as stem cells or stem cell-derived products, the research done within biomanufacturing can be executed in many unique ways in microgravity to help save many lives. The cost of biomanufacturing is reasonable, too. Most experiments and processes use forms of additive manufacturing, such as utilizing its flexibility to create the desired products.[14]

However, one issue that has yet to be explored is transportation. In the future, when full organs can be made in space, there needs to be thought into how to transport these organs or other parts back down to Earth before they expire or lose their usefulness. Another idea is to simulate zero-gravity environments on Earth using drop towers or sub-orbital flights.[29] This would allow for shorter transportation times, as the organs or vital biomaterials could be made on Earth in things such as drop towers that simulate the microgravity environment of space. Finally, one option would be to conduct surgeries or operations requiring the manufactured bio-materials in space so that transportation would be eliminated. This way, the device can be directly used after manufacturing, but this comes with its own logistical complications and problems. With these logistics problems, it needs to be researched further. Science and technology need to be developed before we can consider factors like logistics. However, one benefit of this idea's feasibility is that space travel and tourism are becoming more readily accessible to all.[30] There is no definitive number or percentage, but the articles all cited that it would increase significantly. Many compare it to the shift to air travel during the 20th century, with a 1.5 billion passenger increase from 1990 to 2000. Due to this, there will be both an increased demand for surgeries in space and during travel and an increase in availability for surgeons and other medical professionals in space. Although costs will still be high, especially initially, often, these surgeries are life-threatening and are the only reason such a trip is justified. In that case, money is less of a factor than life is. If the individual is willing to pay to go to space, they should be able to pay to fly back down. The fact that space travel is more possible now for common folk also demonstrates the overall trend for space travel. It is estimated that prices as low as $60,000 are possible, according to one study.[31] Space travel is becoming cheaper, safer, and more accessible, which is a sign of the possibility of future space surgeries.[32]

3D printing in space is an area that has already been extensively researched. A perfect future is when space agencies ship up many large 3D printers and raw materials, and the printers do the fabrication and assembly in space. This ideal scenario would significantly reduce costs through weight reduction and more space saved on the spacecraft. There would no longer be a need to ship fragile parts covered with protective material or large and unwieldy objects that take up unnecessary space. Having additive manufacturing methods could make these things once they get to space. The added flexibility is another advantage since instead of the space agency has to ship up new parts, tools, or other equipment; space crews could print these parts on demand, allowing for on-the-fly adaptations to complex environments and situations.[33] Crews can make spare parts for all types of machines on the fly, rather than bringing up hundreds of thousands of extra parts for the hundreds of devices on things such as the ISS.[34] This flexibility in manufacturing is also applicable to bio-manufacturing, where various additive manufacturing processes are used to manufacture organs or other vital parts of a human body that would otherwise be impossible to ship from Earth promptly. This idea can aid the future of space travel and colonization of other planets, where transplants may not be readily available. Additive manufacturing is the alternative for places like the moon or Mars and the future of all space exploration.

Droplet-driven and extrusion-based manufacturing would become key in future space travel and exploration. Both methods excel at manufacturing things for industrial purposes due to their material selection and consistency. Extrusion-based manufacturing could be utilized to create things like columns or pipes for structures. In contrast, drop-driven manufacturing can be used to create anything from circuits to key components that need to be precisely made with metal. Unlike biomanufacturing, transportation is less of a problem as it is likely, not time-critical, and the only barrier would be the cost of transporting heavy metal parts back down to Earth. However, the price of these space-manufactured parts will also likely be high, so the economics should balance out to have a net zero or even a net gain in profit.

Conclusion

As humanity looks outward toward space as a frontier for exploration and opportunity, the need for flexible and reliable manufacturing techniques becomes more relevant. Space travel, in and of itself, is an exciting endeavor. Still, in addition to exploration, the possibility of new devices and methods of manufacturing various objects that were never possible before is another potential outcome of space travel. Bio-manufacturing is one area that has garnered much attention for its ability to create tissue, organs, and even stem cells that solve relevant problems for human life in space and on Earth. Bio-manufacturing in space has seen relevant strides in creating functional tissues and organs, for example, eyes, intestines, and hearts. Yet, a lot of work is still being done to improve these products' usability and fragility. Droplet manufacturing and its ability to create custom metal parts of various shapes and sizes for differing applications is another area that has garnered much attention for its ability to create custom parts in space, away from readily available support and supply from Earth. The forefront of the research is currently focused on improving process reliability since most droplet-based manufacturing methods rely heavily on the force of gravity. With more time and research, the process will likely be perfected and utilized as a widely used in-space manufacturing process. Extrusion-based manufacturing, the largest and most heavily researched in-space manufacturing method, has already proven its usefulness and flexibility on Earth. It is now of high interest for in-space manufacturing. Tests on the international space station and drop towers demonstrate the benefits of in-space extrusion-based manufacturing, such as stability, flexibility, and cost. With more research and development, in-space manufacturing could allow humans to live farther than ever before, far beyond the reach that was ever thought possible. In addition, in-space manufacturing may also enable world-changing technologies and processes that are never possible on Earth. The future is one where every advantage of space can be utilized in manufacturing for the benefit of all humans.

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Author

Dylan Thai is an eleventh-grader attending Walnut High School. He hopes to major in Mechanical or Aerospace engineering and continue in the STEM field. He enjoys competing in FRC with his team and being the trombone band captain in the Walnut High School Blue Thunder Band and Colorguard.