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Additive Manufacturing in Space

Overcoming the Challenge of Full-Scale Manufacturing in Space

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Abstract

Additive manufacturing technologies, like 3D printing, are a relatively new and promising method for manufacturing complex parts. There are several benefits of utilizing additive manufacturing over the more traditional subtractive manufacturing. A couple of the benefits are the reduced waste, shortened manufacturing time, and the ability to produce complex geometries. In recent years, this new manufacturing technology has started to be implemented in space so that astronauts have the ability to manufacture like never before. Traditional manufacturing is too labor intensive and waste producing to make it a viable manufacturing option for the astronauts. In this essay, current work on 3D printing in space will be discussed, as well as ideas for where this technology could progress by the year 2035, and how a global manufacturing enterprise focusing on developing and implementing this technology should operate.

Introduction

Additive manufacturing technology has allowed for the progression of manufacturing, creating many new avenues that were not previously viable using subtractive manufacturing techniques. Subtractive manufacturing, also known as traditional manufacturing, involves starting with raw material larger than the desired finished part, and removing the extraneous material. This is usually done through the use of machines like lathes, drills, CNC and manual mills, and saws. This traditional method of manufacturing requires parts to be designed around the limitations of the machining process and also wastes material and ultimately money. In contrast, additive manufacturing produces parts by converting a digital 3D drawing into many slices and printing the object layer-by-layer; allowing complex parts to be produced fairly easily. Companies have already started to research and develop technologies that will enable humans and robots alike to use additive manufacturing in space. By the year 2035, a global manufacturing enterprise should seek to have successfully implemented full-scale 3D printing in space for a variety of applications.

Current Work

As additive manufacturing on Earth grew to be more popular and commonly used, researchers and industry leaders alike started to recognize the benefits a technology like 3D printing would have for astronauts in space applications. Over the past few years, several projects involving additive manufacturing in space have emerged. Below is an outline and brief description of a few of the projects currently in use or development that further advance the full-scale implementation of this manufacturing method.

Zero-G Printer

In September of 2014, the company Made In Space, in partnership with NASA, created a 3D printer that operates in zero gravity environments, called the Zero-G Printer. This was a breakthrough because until this point, there was no way for parts to be created via additive manufacturing in a zero gravity environment like the International Space Station (ISS). This machine was able to aid in the understanding on the effect of microgravity on the additive manufacturing process as well the parts that were manufactured. The primary role for the device was to create simple tools and parts for a variety of applications. This includes wrenches, screwdrivers, and even medical devices like finger splints. The main challenges faced when creating the printer were the filtering of toxic gases and nanoparticles, and ensuring that the printer could withstand the forces of a rocket launch.

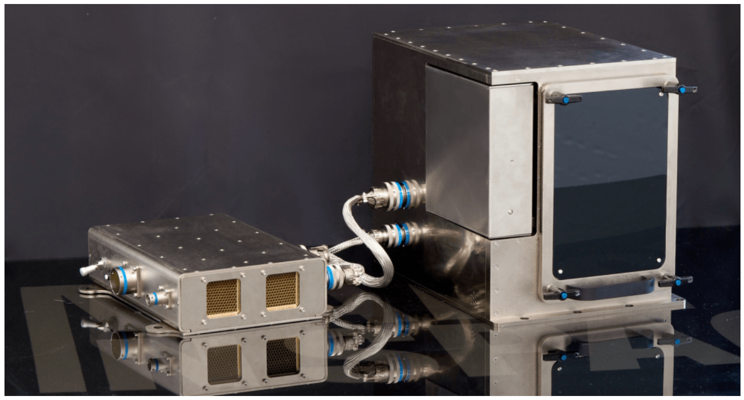

Figure 1: Zero-G Printer from Made In Space [1]

Additive Manufacturing Facility (AMF)

The Additive Manufacturing Facility (AMF) is an updated attempt at creating a more permanent solution to 3D printing in space. This piece of equipment was also produced by Made In Space and was launched a couple years later in March 2016. This device expanded upon the design of the Zero-G Printer and made it a more inclusive and robust manufacturing system. The printer was designed so that it could easily be integrated into the ISS's EXPRESS racks meant for storing experiments onboard. This allows for the equipment to be out of the way of the ISS crew members. Another advancement of the device is that it has the ability to print in a variety of space grade materials. For example, a medical device like a finger splint would utilize a different material from parts used for heat shielding. Unlike the Zero-G Printer, the AMF was designed to have modular subsystems to allow for easy repair and replacement of parts by astronauts in the case of failure. This aids in ensuring the AMF can last the entire duration of the ISS' lifespan. Currently, the material properties, dimensions, and resolution of identical parts created on Earth and in space are being compared to establish a database that can be used for future extraterrestrial design decisions.

Figure 2: Additive Manufacturing Facility (AMF) [2]

Archinaut & SpiderFab

Beyond creating common plastic tools and devices using a reimagined version of a terrestrial 3D printer, 3D printing in space can also be applied to large scale structures such as satellites and eventually whole space vehicles. These are exactly the missions of the Archinaut

Program by Made In Space and the SpiderFab Program by Tethers Unlimited Incorporated (TUI). According to Made In Space, "Archinaut is a technology platform that enables autonomous manufacture and assembly of spacecraft systems on orbit" [3]. These systems utilize a complementary combination of additive manufacturing and robotic assembly to create large structures in the vacuum of space.

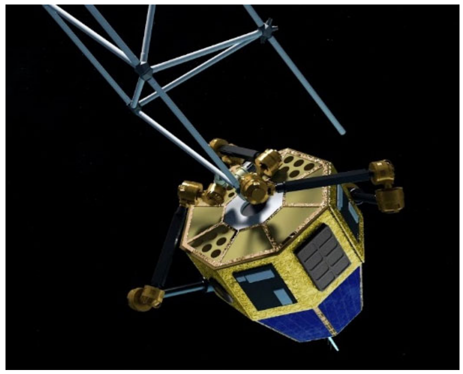

Figure 4: The Archinaut: ULISSES 3D printing and assembling a boom structure [4]

There are several benefits to manufacturing these structures in space as opposed to on Earth. One of these benefits is the reduced cost and logistics of launching a new satellite into space. Designers are no longer going to be limited by the payload shroud size or survivability requirements. Another benefit is that whole stations and satellites can be assembled without requiring an astronaut to aid in the process. This allows for construction to be independent of astronaut availability which, in turn, creates a higher production rate. Also, because the system being created does not have to survive the rigors of being launched, designers are able to be creative and utilize design techniques that would not be feasible for terrestrial use. Funded in November 2015, the Archinaut is still under development, but in the Summer of 2017 the 3D Printing capability was proved through Thermal Vacuum Testing. Made In Space also plans on completing the Thermal Vacuum Tests for their robotic arm systems in the year 2018. While less is known about the progress of the SpiderFab, the CEO of TUI, Robert Hoyt, was quoted saying, "…we think we could get to be able to build very large support structures for antennas and solar arrays, and those sorts of components, in the early 2020s" [5].

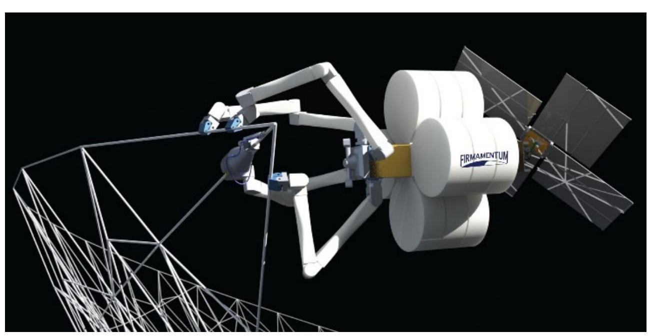

Figure 5: Rendering of TUI's SpiderFab printing truss structures for large dish [6]

Refabricator

Another important technological advancement for additive manufacturing in space is the ability to recycle 3D prints so that new parts can be created with the same material. Between 2015 and 2018, TUI developed a machine called the Refabricator. The Refabricator can function as a normal 3D printer but also has the ability to melt down previous prints and transform the material back into feedstock. This closed-cycle manufacturing process is advantageous for space applications because, according to NASA, "…it costs $10,000 to put a pound of payload in Earth orbit" [7]. Therefore, substantial financial savings can be made by recycling instead of constantly resupplying raw material. Also, waste in space will be reduced because now there is a way to reuse prints that no longer serve a purpose. A useful feature of this device is that it requires very little astronaut intervention. This is because the entire process if run by technicians on Earth, with the astronaut only interfacing with the machine when adding recyclable material or removing a finished print. This allows for astronauts to spend their valuable time performing other tasks.

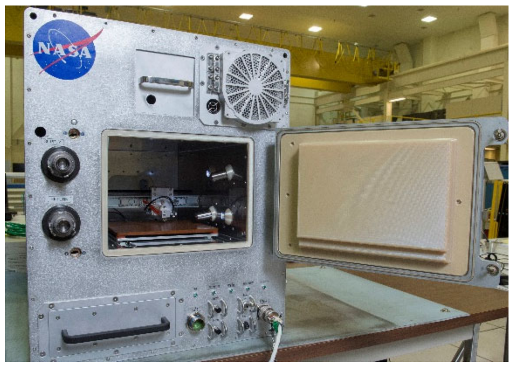

Figure 6: TUI's Refabricator, capable of printing and recycling print material [8]

The Possibilities

With all of the recent work being completed in this field, the knowledge gained from these ventures will be able to provide important data on how additive manufacturing in space differs from Earth. Between now and the year 2035 this technology will have advanced even more to manufacture in ways never before seen. There are many applications of this technology that will make what once seemed like an impossible task a reality. Some of these farfetched applications include, but are not limited to, the already proposed projects of NASA's FabLab and the European Space Agency's (ESA) Moon Village. Also, this technology now opens the door to bringing old, previously unfeasible ideas to life. For example, it can now be possible to print and assemble a Solar-Based Solar Power satellite entirely in space.

NASA FabLab

As previously mentioned, the FabLab project with NASA is one of the next steps in advancing this technology. Essentially, the FabLab is to be a new manufacturing device that can make prints in many aerospace grade materials, including metals, at the same time. This allows for more complicated, multi-material systems to be manufactured. This is unlike the AMF described above because the AMF, while printing with multiple materials, is limited to plastics currently. The long term goal of additive manufacturing in space is to be able to provide everything that an astronaut may need on a journey, and metal 3D printing is essential to accomplishing that goal. Similarly to the AMF, the machine will be mostly autonomous because it is controlled by an operator on Earth. To use the FabLab, all the astronaut has to do is select a part from a catalogue and press button to have the part made.

ESA Moon Village

Another, slightly different approach to additive manufacturing in space is not to create small plastic or metal parts, but to actually assemble buildings on planets and moons by utilizing the natural resources of the area. The ESA have proposed a plan to build a “Moon Village” on Earth’s moon in the next 15 years. The current idea is to have inflatable domes that can then be covered with another dome made of 3D printed regolith to protect inhabitants from the environment. Using material already abundant at the destination allows for these structures to be produced relatively inexpensively because no raw material needs to be sent into space; ultimately reducing the cost. Currently, the plan is to use a lunar rover that has the capability of collecting material and using it to create these structure layer by layer. Figures 7 and 8 below show a concept of what this process would look like.

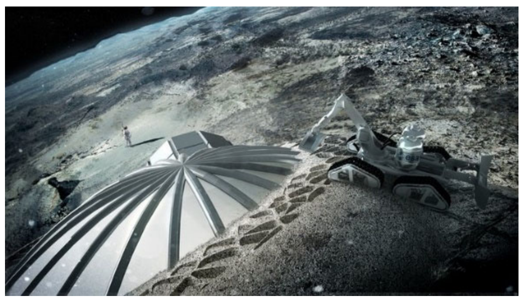

Figure 7: Concept showing lunar rover printing over inflatable dome [9]

Figure 8: Concept of finished building [10]

Space-Based Solar Power

Space-Based Solar Power is a problem solving idea that has been around for decades. Essentially the idea is to have a massive space structure that is able to collect energy from the sun, and transmit that energy down to earth using either microwaves or lasers. It is advantageous to capture energy above the atmosphere because losses will be minimized and energy can constantly be stored because day and night does not make a difference in space. This technological advancement would be a major step towards solving the world’s energy problem because one of these devices could provide enough energy to supply millions of people. Figure 9 below shows just one of the proposed concepts for space-based solar power. The image shows two sections of large reflective arrays that concentrate on PV panels. These PV cells generate electrical power that is the transmitted to earth via microwaves.

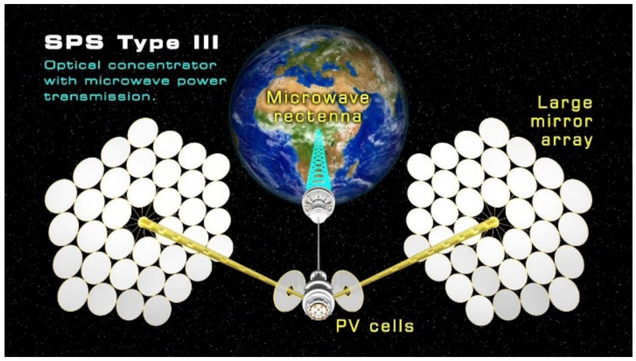

Figure 9: Space-Based Solar Power Concept [11]

While a lot of thought went into developing these concepts, none of them were ever economically feasible because they would cost tens of billions of dollars to make a reality due to reliance on over a hundred launches to supply material and assemble. Using a technology like the Archinaut or SpiderFab, making structures like this can actually become a reality. All of the support structures can be created through additive manufacturing and even the reflective arrays used for concentrating solar energy can be applied by the SpiderFab. The only additional components that may need to be launched would be the non-printable electronic systems. With a greatly reduced cost to manufacture, these massive satellites can soon be a reality.

Research Challenges

In order to fully implement additive manufacturing technologies for a global manufacturing enterprise in the year 2035, several research challenges will need to be addressed. While parts are already being manufactured on the ISS, there is still a lot of work to be done for perfecting the technology. A few of the areas that the proposed company need to further develop are our understanding of the effect of microgravity on the additive manufacturing process, printing in the vacuum of space, and establishing infrastructure to complete long term goals.

Effect of Microgravity

When investigating the effect of microgravity on 3D printing, one of the most fundamental research areas is how microgravity impacts the additive manufacturing process. It is fairly well understood at this point how to accurately manufacture a part using a 3-axis driven 3D printer on Earth, in a thermally controlled environment at 1g. The challenge is to adapt all of the subsystems and components of a conventional 3D printer to be able to accurately reproduce the part file input in microgravity. So any gravity or fluid dependent processes will need to be designed in a way for the same operation to be performed without gravity. Also, any additive manufacturing process that creates or uses loose particles should be avoided because floating debris can potentially damage the spacecraft or harm the astronauts.

The lack of gravity could also provide some benefits for the design of the system. Designing anything for use in space is fundamentally different than designing for Earth. For all of human history design has been reliant on overcoming or adapting to gravity. However, engineers can go about designing these machines with creativity. For example, maybe a 3D printer can utilize several extruder heads that build the parts from the center outward. Imagine having six printer heads covering all sides of a part. This potentially allows for much quicker print times because there is no gravity to hold back the manufacturing process.

Printing in Open Space Environment

The next step after completely overcoming the design challenges of microgravity 3D printing is to move the process from a controlled environment like the ISS and into the vacuum of space. This is crucial for making the technology for the Archinaut or SpiderFab concepts a reality. There are a few benefits to moving manufacturing out of a space vehicle and into space. One of these benefits is that the machine would no longer be taking up valuable volume aboard a vehicle. This is good for all parties involved because NASA can utilize that volume for another system, the machine designers can forgo some of the strict design requirements of the ISS, and the machine now has potential for larger parts to be printed. However before doing so, more data needs to be collected from tests done by prototypes aboard test vehicles or in Thermal Vacuum Chambers that simulate the environment of space. Another important aspect to consider is the ability to print in a thermally dynamic environment. The Committee on Space-Based Additive Manufacturing explains in their publication *3D Printing in Space* that "Both the operation and performance of the manufacturing system and the dimensional accuracy of the product being produced will be impacted [by the thermal environment]. For example, maintaining accurate physical dimensions throughout the day/night cycle and subsequent thermal fluctuations will be challenging" [12]. A potential solution to this problem is to use a space sunshade to have some control over the thermal conditions the additive manufacturing device is experiencing.

Establishing Infrastructure

To facilitate full scale production via additive manufacturing in space, it is important to establish infrastructure. There needs to be a way to generate and store power, as well as a way to transfer the power to the machines. A possible method is to use a solar power system. Also, there needs to be a way for either humans or robots to interact directly with the machines to perform repairs, load feedstock, remove finished parts, etc. Considering the extreme costs and logistics behind sustaining human life in space, robotic arm systems would the preferred method of direct interaction. These robots could be preprogrammed to perform certain actions and/or be controllable by humans from earth or a space station. These are only a few of the infrastructure considerations that need to be studied and tested before full-scale implementation in space.

Proposed Company Profile and Partnerships

It is crucial for a global manufacturing enterprise seeking to advance additive manufacturing in space to allocate resources to prototyping and testing new technologies in this field. The first step is to perfect the art of additive manufacturing in zero gravity through research and development and extensive testing on the ISS and other Low Earth Orbit (LEO) testing vehicles. By the year 2035 this task should be close to complete if not earlier. Then, like on Earth, large scale implementation is logically the next challenge. This includes manufacturing buildings on the moon or other planets, printing satellites, solar arrays, antennas, modular space vehicles, etc. The possibilities are endless for what can be created with additive manufacturing once technologies like the Archinaut and SpiderFab become a reality and are improved upon.

In order to succeed with this mission, our company would need to forge several partnerships both in the space industry and academia. A list of the proposed partnerships to be made can be seen below:

Industry	Academia
NASA	IUT of Cachan (Paris, France)
ESA	Clausthal University of Technology (Clausthal-Zellerfeld, Germany)
Made In Space	Florida State University (FSU)
Tethers Unlimited Inc. (TUI)	Florida A&M University
Sierra Nevada Corporation (SNC)	
Dynavac	
Planetary Resources	

In regards to industry partnerships, NASA and the ESA are obvious partners for our company's mission. NASA will be able to provide valuable knowledge and resources from its vast experience in space and the ESA will be a necessary partner to make projects like their proposed Moon Village a reality. Made In Space and TUI are other industry leaders that our company should connect with because they have already completed a lot of the leg work for adapting additive manufacturing technologies for space; both inside and outside of a space station. A couple of companies that could aid in completing the necessary prototype and functional testing are the SNC and Dynavac. The SNC has a vehicle called the Dream Chaser that functions as a testing ground for experiments in LEO that could be used for our experiments. Dynavac is an industry leading company that provides complete space simulation tests using Thermal Vacuum Chambers. This is another way for robotics and printing systems to be tested. Finally, Planetary Resources is a company working on using local material from the moon or other planets to create objects. Partnering with them would help the process of creating buildings on Mars or the moon.

For academic partnerships, the options are more open. There are several engineering and technology institutions that contract work can be distributed to, but listed in the table above are just a few that are currently working on projects for this field. IUT of Cachan in Paris, France is working on creating nanosatellites that have the ability to 3D print structures outside of a space station. Partnering with them could help accomplish the goal of large scale printing in a vacuum. Clausthal University of Technology in Germany is furthering research on 3D printing metal materials in space. This would be a huge step forward because many of the structures currently in space are metal, so if a replacement part were needed it could accurately be recreated for a low cost and without delay. And finally, FSU and Florida A&M are working together to develop a way to 3D print carbon nanotube structures in space for use as vehicles, structures, and power systems [13].

Conclusion

In conclusion, the way forward for a global manufacturing enterprise in the year 2035 is to commit to investing resources into the field of additive manufacturing in space. As mentioned above, the main areas of research that need to be addressed are perfecting zero gravity 3D printing, building infrastructure, and printing directly in the vacuum of space. There are several industry leading companies and research institutions that will be able to provide valuable assistance for completing our company's objective.

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