3D Printing in Space: Enabling New Markets and Accelerating the Growth of Orbital Infrastructure

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ABSTRACT

Consistent constraints on what can be built for space have existed throughout the life of the space program. Limits have been placed on size, weight, and structural durability (due to launch) of every craft or piece of equipment that has been sent into orbit. Additionally, extended missions require that replacement parts must either be stockpiled or sent up from earth, causing a substantial time delay. If, instead, equipment and spacecraft could be manufactured in the zero gravity environment of space, these constraints could be overcome. This would enable the creation of structures of nearly limitless size and intricacy that could not be launched, and in some cases could never be manufactured on earth. Extended missions could reduce weight in spare parts and overcome the dependency on earth. Current 3D printing technologies can provide a platform for this type of fundamental shift in space manufacturing.

INTRODUCTION

To visit the asteroids, Mars, and beyond, we need to fundamentally change the manufacturing technologies that enable space travel. The largest hurdle of pioneering human space travel is that we must bring everything needed to survive with us. “Bringing it all” is simply too costly, space is too isolated, and development is too difficult to plan for every what-if scenario. In-situ resource utilization (ISRU) will therefore eventually be an important part of space missions. Local resources will be extracted and useful structures will be built out of these resources.

Although we have not yet extracted resources from the Moon or Mars for ISRU, we can develop the other component of ISRU, namely space-based manufacturing, even today using additive manufacturing techniques. Additive manufacturing refers to a collection of processes, many of which are often known as "3D printing." This technology offers the ability to build a wide variety of components, from spacecraft structural elements to the dinette sets of future Mars habitats, in space. In contrast to traditional (subtractive) manufacturing, such as that which uses a mill or lathe, 3D printing consists of manufacturing materials layer by layer, with little or no wasted material. The capabilities of 3D printing are rapidly increasing in terms of size, cost, complexity, and types of printable materials (over 25 different materials can be printed, including aerospace grade metals, and some printers can achieve resolutions as low as 16 microns [4]. To apply additive manufacturing to space, we must develop printing techniques for use in microgravity environments and eventually integrate this with robotic assembly of manufactured parts.

3D Printing Technologies: From Prototypes to Products

Since its invention, the technology involved in 3D printing has often been used by architects and engineers in building prototypes and models, but has been improving dramatically in terms of attainable resolution, number of printable materials, and number of simultaneously-printable materials in some techniques such as Fused Deposition Modeling (described below). Low-quantity customized products have proven to be the most commercially important for the 3D printing industry, such as dental retainers or prosthetic limbs. Recently the shell of an entire car was 3D printed and assembled, including the transparent glass [3].

The customizability of 3D printing makes it an ideal candidate for printing a wide range of structures in space. Plastic printing was tested in microgravity in 1999, and the printed structures were found to be indistinguishable from those printed on ground, except that certain geometries such as suspended beams could be printed in microgravity with no support material [5]. However, commercially-available options for 3D printing have progressed far beyond what was available in 1999, and several important questions remain unanswered from the 1999 study, such as some ambiguous test results and the printability of space-grade materials in microgravity.

Comparison of Additive Manufacturing Methods

We have focused on four printing technologies that seem viable for near-future or long-term space applications:

- Electron beam freeform fabrication (EBF3) uses a high powered electron beam to melt a coil of metal into a small pool, and the part is then built as the pool is selectively cooled and hardened.
- Selective laser sintering (SLS) uses a laser to melt a powder feedstock in layers that are fused together to create a part, and there is a related method using an electron beam rather than a laser.
- Fab@Home and Fused Deposition Modeling (FDM) both use an ejection head (much like a printer), but Fab@Home extrudes substances that are paste-like at room temperature and are later hardened by annealing [10], while FDM melts the feedstock in order to extrude it, and the material hardens immediately upon deposition.

All of these approaches allow flexibility in material selection, and can be selected for specific applications.

One technique that we have purposefully omitted is stereolithography, which uses lasers to selectively harden layers of liquid. This omission is due to the physical properties of liquids in a zero gravity environment, making this technology difficult to implement for space applications.

3D Printing Method	Plastic or Metal	Zero G Capability	Vacuum Compatibility
EBF3	Metal	Under-development	Required
Fab @ Home	Metal & Plastic	Not Tested	Material Dependent
SLS	Metal & Plastic	No	Yes
FDM	Plastic	Yes	Material Dependent

Figure 1 Comparison of Additive Manufacturing Technologies

Powder-based technologies require much more feedstock than extrusion technologies (EBF3, SLS, FDM, and Fab@Home), although the unmelted powder can be reused. Powder-based printers in their current form also rely on gravity and may be difficult to implement safely in space due to the difficulty of ensuring adequate powder containment in microgravity, which includes the difficulty of ensuring that no powder remains on the final printed structure. EBF3 is a promising metal-printing technology being pursued at NASA Langley Research Center [4], but uses relatively high power and at this stage significant post-processing is required on the printed parts.

Fab@Home can typically deposit a wider range of materials than FDM but requires an oven to bake and cure the parts, and parts often shrink upon annealing, requiring special design considerations.

FDM is a promising technology since it requires relatively low power, attains high resolution, and wastes no feedstock material. FDM has traditionally been used to print non-space rated plastics, but on Earth these parts are routinely coated in metal after printing, which may enable them to withstand the space environment if this technique can be applied in space. Alternatively, more research is needed to determine if FDM can be used to directly print teflon, PEEK, or other space-compatible materials such as certain nanocomposites [7], [8].

Two of these technologies have been tested in zero-g (FDM and EBF3) and have been found to work as satisfactorily in zero-g as they do in 1 g.

3D Printing Method	Breadth of Materials	Finest Resolution	Space Rated Materials?
EBF3	Steel, Copper, Aluminum, Titanium, Alloys	2.54 mm	Yes
Fab @ Home	Plastics and Stainless Steel	.4 mm	Yes (Stainless Steel)
SLS	Metals, Alloys, Plastics, Rubbers, Glass	70 microns	Yes (Metals and Alloys)
FDM	ABS, ABSi, Polycarbonate, Ultem 9085, and PC-ABS	40 microns	Yes (PC-ABS)

Figure 2 Feedstock Materials Based on Printing Technology

A large range of materials can currently be printed, including metals, alloys, plastics, rubber, and glass. The list is growing on Earth, and as new technologies are developed, they can be leveraged for space. The resolution of these printers, especially FDM and SLS, has dropped considerably over the past decade, allowing for the possibility to one day print circuits and very intricate structures.

Additionally, three of the four technologies offer solutions for space-rated parts, and FDM should have a solution in the near future.

Due to the ability of SLS to work with sand and glass powders, it is conceivable that this technology could use Moon regolith as a feedstock. This could be done with little modification due to the low gravity environment.

3D Printing Method	Mass	Volume	Printing dimensions	Cost
EBF3	818 kg	1.5m^3	15x15x15 cm	$250k
Fab @ Home	40 kg	0.5 m^3	10x10x10 cm	$7k
SLS	1125 kg	2 m^3	25x25x35 cm	$100-300k
FDM	35 kg	0.42 m^3	25x25x25 cm	$10-50k

Figure 3 3D Printer Size and Cost Comparison

All 3D printing options considered here have low enough power consumption that they could be implemented on the ISS. FDM and Fab@Home typically use less than 100 W, while EBF3 uses a 3 kW electron beam gun.

Furthermore, all these options are small enough to be implemented on the ISS. FDM and Fab@Home can be extremely small and light, as evidenced by the Makerbot, an FDM system which can also serve as a paste extruder and is similar to Fab@Home, which is less than a cubic foot and weighs around 5 kg. EBF3 is typically larger and heavier (on the order of 1 m^3) but could conceivably be reduced in size and implemented on an ISS experiment rack.

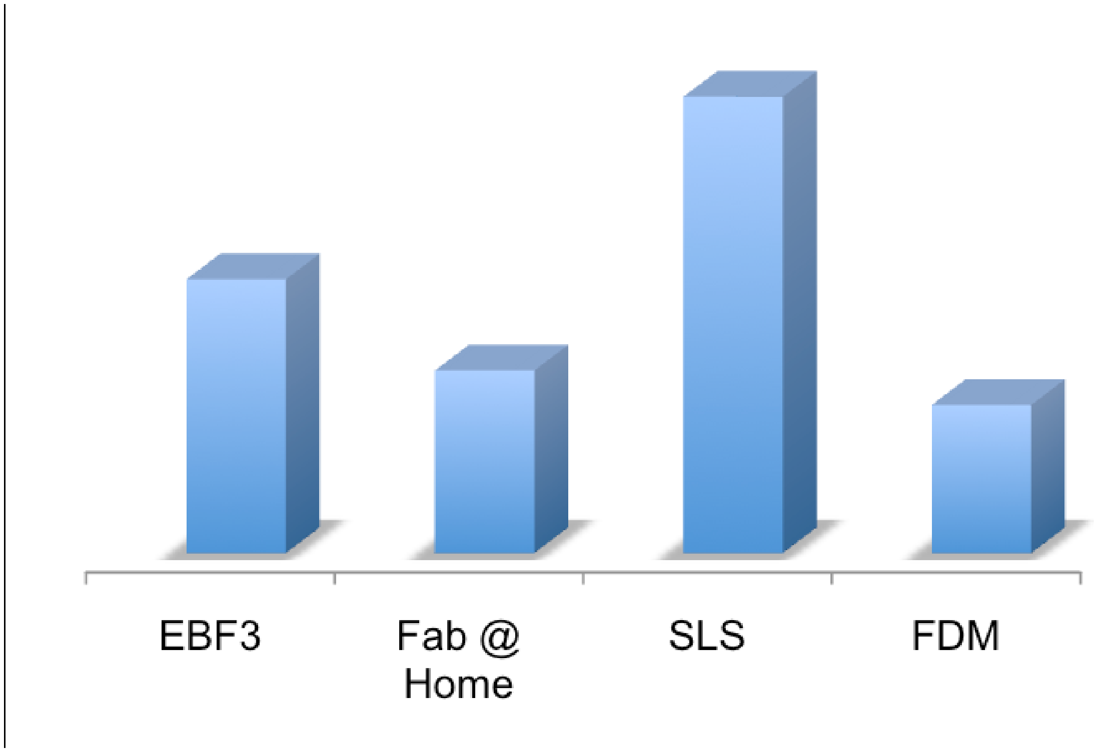

Figure 4 Estimated Flight Development Cost Comparison for Printers

3D Printing as an Enabling Space Technology

When one compares current manufacturing methods for space applications to space-based manufacturing methods, as shown in Figure 5, it becomes clear that the latter solves many inherent problems the space industry has been facing for many decades. The complexities of space infrastructure are rooted in several areas, from ground processing/development to vehicle launching constraints. Many of these potential roadblocks are avoided, however, when all manufacturing takes place in space. Less material will be used to construct infrastructure, as support material needed to withstand launch is no longer needed. Objects can be printed on demand, rather than planning missions with spare parts for redundancy matters. Furthermore, structures much larger than anything previously built in space can be constructed.

Current Manufacturing Methods	In-Space Manufacturing
Space is isolated yet dependent on earth	Missions have a back up plan building in space
Plan for every "what if" scenario	Build what is needed on demand
"Jerry rig" a solution with parts on hand	Print needed part immediately
Many repairs have no immediate solution	Immediately repair what is broken
Must survive extreme forces of launch	Build for main use in space, not launch
Conform to fairing of launch vehicle	Build large structures that can only be built in space
Requires a large workforce	Less hands-on work needed

Figure 5 Advantages of Space Based Manufacturing Over Current Methods

Currently, space is isolated in terms of both distance and time. At the very minimum, any physical aid requires a launch from earth that takes extensive resources and planning. If a mission is out in the solar system beyond Earth orbit, the feasibility of aid is unlikely if not impossible. Because of this, extended missions must plan for every "what-if" scenario, meaning multiple spare parts must be stockpiled, taking up precious cargo space. In the case of a true emergency, without the use of sophisticated manufacturing, astronauts must "jerry-rig" a solution from the parts at their disposal. For many problems, such as a tool-box lost on a spacewalk, there simply is no solution. Space-based manufacturing offers the possibility to design and print broken, lost, or otherwise needed parts immediately, and to build only what is needed for a mission.

Additionally, unnecessary design constraints are placed on everything that is launched, due to the extreme forces incurred, as well as the size constraints of the fairing. This limits what can be sent up to a very small size, and requires that all parts are engineered for the environment where they spend a fraction of their lives (10 minutes of launch vs. a lifetime in zero gravity). Space-based manufacturing allows for these constraints to be ignored altogether, providing the possibility of structures such as a kilometer long antenna.

Space-based manufacturing is not a new idea. It has been contemplated for many decades; first in science fiction, and later in feasibility studies by Gerald K. O'Neill and others. What is novel, though, is the use of 3D printing technologies as the primary manufacturing method. The unique ability of 3D printing technologies is that they provide a single tool that can build a near infinite variety of objects, from specific tools and spare parts to generatively designed structures suited for the constraints of the space environment. When 3D printing technology is used for space manufacturing three essential problems currently facing the space industry will be overcome: fundamental size limits, excess waste, and time delays.

Fundamental Size Limits

Every single human-made object in space to date has been built on the surface of planet Earth. Enormous constraints are placed on the design of all space infrastructures because of the requirement of launching from Earth's gravity well. The fundamental limits of chemical rockets have created a regime of building spacecraft and launch payloads to conform to the cylindrical fairing of the typical rocket nose cone. Unfortunately, this has severely limited the growth of space infrastructure over the last few decades, as any object ever built for space has needed to fit within a launch vehicle. Even the largest human-made structure in space, the International Space Station, had to be conformed to the launch vehicle of the Space Shuttle. While the ISS was built in modular components, each component was constrained to the shuttle payload volume.

When the launch vehicle constraint is removed from space manufacturing, the building of more advanced structures will be possible because launch from Earth will no longer be an issue. Even if feedstock for the 3D printers needs to be launched, this will be far more effective than launching the actual object, since the feedstock will be able to survive the launch and conform to the launch vehicle fairing in a much simpler matter than the payload itself. This advancement will allow for extremely large structures to be built in space that would never have fit in a launch vehicle, much less survived the extremes of launch conditions.

Excess Waste

Added to the launch vehicle fairing constraints are the launch loads that the payload must be able to withstand. During the roughly ten minute launch into low earth orbit the launch vehicle payload will endure tremendous vibrational loads and g-forces several times the force of gravity. This forces the design of typical spacecraft to be "over-engineered" to survive launch. Most structural mass on the spacecraft is there just for the purpose of launch survival. Additionally, current space missions must bring spare parts for emergency and redundancy purposes. These parts represent excess waste, as many of them are used. The International Space Station has over one billion dollars worth of spare parts.

In the zero gravity environment of space little structural mass is needed. It has been estimated that roughly 30% of a spacecraft’s structural mass could be removed if that craft were built in space rather than on Earth. If one were to make the rough distinction of separating a spacecraft mass into two parts, "smart mass" and "structural mass," a spacecraft built in space would have more "smart mass" than "structural mass" compared to a spacecraft of equal total mass that was built and launched from Earth. Essentially, this means that a spacecraft built in space will become much more useful, as less of its mass is needed for supporting structure.

Future space missions will not need to bring spare parts; instead a 3D printer will be used to print parts on demand. If an astronaut on the ISS today were to break a vital tool, he would be left with very few options. He may decide to wait for the next resupply mission to bring a replacement tool, but considering the cost of these missions and scarcity of launches, this option is unlikely to prove feasible. What is most likely is for him to contrive a new tool using parts found around the station. Conversely, if a 3D printer were on board, this astronaut would be able to print out an exact duplicate of the tool that broke. What is even more interesting is that once the task was complete, the tool could then be recycled back into feedstock to be used for a future printing purpose. The future of space colonization greatly depends on the ability to be 100% self sustaining, and 3D printing offers part of this solution.

Time Delays

The final key problem 3D printing will solve for the space industry are the time delays associated with design, build, and execution of a mission. A typical space mission today takes several years, and in most cases at least a decade, to go from concept to flight. This is largely due to the extreme cost of space access, which necessitates maximization of the capabilities of each mission. This leads to lengthy design times and the employment of enormous amounts of labor. As a result, very few space missions are ever completed, which in turn puts a high price on space hardware, as space rating becomes a costly process when only a few of each piece of hardware will be used.

When 3D printing of spacecraft, structures, and spare parts is done in space, the time delay problem will be solved. Rather than spending decades designing a spacecraft on Earth and testing it, the designs will simply be uploaded to the 3D printer in space and build on demand. This will allow for more missions to be employed in rapid succession, resulting in a much more thorough ability to explore the universe. Time delays in cargo resupply to the space station will also be mitigated, as the 3D printer in use on a space station could be used to manufacture what is needed immediately. A Mars mission will not have the luxury of depending on Earth for resupply.

Benefits of a Low Gravity Manufacturing Environment

Low gravity is anticipated to offer an ideal environment for increasing the scale of manufacturing by one or more orders of magnitude vs. conventional systems in use today. For example, a pool of molten metal will begin to deform under gravitational forces long before it cools and becomes rigid. In space, the limiting forces are adhesion and surface tension rather than gravity, enabling a much larger droplet size to cling to its target.

Microgravity could also enable much larger bladders for precision shaped low-pressure forms for the Carbonyl process of vapor deposition, enabling custom tanks or pressure vessels to be made using iron and nickel plating. Radiators, tubes, fluidic components and high-pressure tanks can be made using vapor deposition techniques. Vacuum will enable plasma spray or other thin film coating technologies to be applied on a large scale without the need for containment and pump down. Thin films of semiconductors enable the in-situ manufacturing of solar cells (as demonstrated in the Wake Shield Facility experiment by NASA), custom sensors or adaptive optics. Other additive manufacturing systems may also benefit from conditions in space.

Markets that will be Enabled by 3D Printing

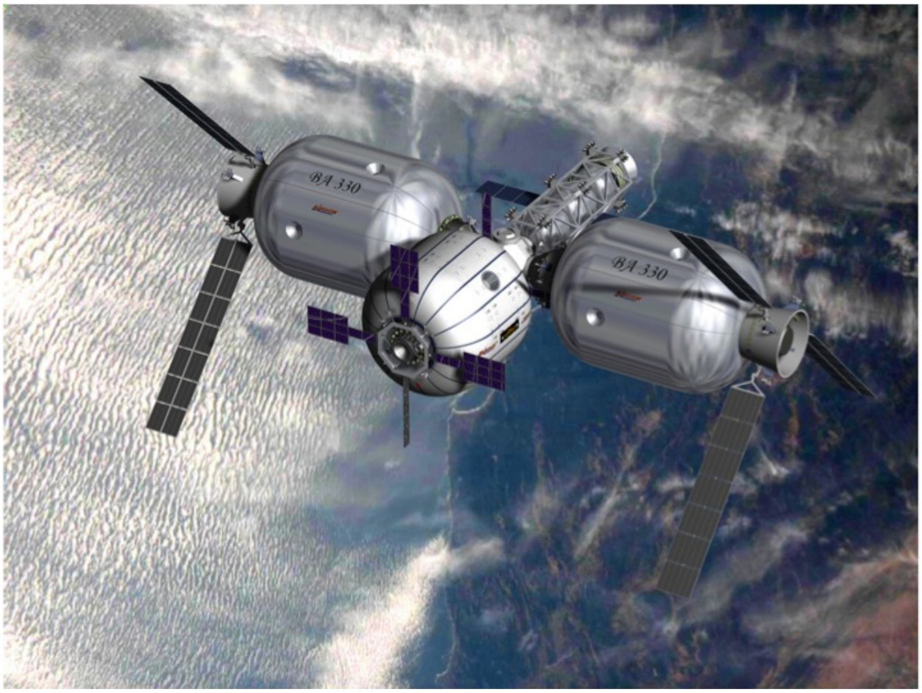

Figure 6: Private Space Station That Could Benefit From a 3D Printer

Developing the technology for in-space additive manufacturing and robotic assembly will enable the emergence of entirely new in-space markets for commercial and government entities, as well as providing the backbone to support NASA's human exploration visions. Examples of in-space market applications of 3D printing include:

- In-Situ fabrication, repair and mission risk reduction
  - Onsite repair or component upgrade for ISS or private space stations
  - Commercial or military satellite reconditioning-on-demand
  - Rocket motor reconditioning (e.g., replacement thrust chambers)
  - Reusable vehicle maintenance & refurbishment
  - Creating new value from space debris raw materials
  - Modification or upgrading of structures and mechanisms
  - Remote human outpost component- and tool-making systems
  - Pre-fabrication and assembly of in-situ habitat components
- Feasibility of creating large-scale space structures
  - Fabrication and assembly of spacecraft larger than current faring constraints
  - Large-scale antenna arrays or optical substrates
  - Components and structure for modular space business parks and condos
  - Tanks or pressure vessels that exceed current launch payload constraints
  - Kilometer-long beams in LEO and GEO
  - Space solar power system components (structural elements, power conduits, vacuum thin film deposition, thermal management systems)
  - Reforming asteroids into G.K. O'Neil space colonies

In-space manufacturing capabilities will depend upon robust in-situ space power (solar or nuclear) combined with adequate material feedstocks such as are delivered from Earth, recycled from orbital debris, or mined from lunar or asteroidal resources, and will therefore contribute to the emergence of a growing in-space economy. Markets and customer profiles are the foundation of the business model, and will form a key element of the future economic viability for Made in Space, Inc. New markets will naturally expand from the early ability to fabricate and assemble spacecraft, satellites, telescopes and devices in space. Early customers for tools, parts and equipment-on-demand will be found on international space stations and Bigelow hotels. Commercial or military satellite reconditioning could then become possible by adding a 3D printing capability to a DARPA-FREND or Orbital Express type servicing spacecraft, expanding into the marketplace beyond low-Earth orbit.

Larger-scale systems in higher orbits would be enabled as manufacturing experience is gained and as bigger manufacturing and assembly plants are built. Kilometer-long beams or two dimensional arrays in geosynchronous orbit could redefine the communications satellite paradigm, where component assemblies progressively add to the capability of a given orbital slot. Instead of replacing an entire spacecraft on a regular delivery schedule and generating an orbital debris event each time (while maintaining the same capability level), a steadily increasing communications capability would be achieved by attaching new spacecraft or delivered components to a growing backbone that provides stationkeeping, power and thermal management functions.

The ultimate vision enabled by this system is the fabrication of Gerard K. O'Neil space colonies, enabling real-estate financing models to migrate to on-orbit condos, industrial parks and recreational facilities and serving as a foundation for human migration into space. New aerospace businesses, such as space-based solar power and low-cost hotels are enabled, where competitive forces could bring prices within reach of the common man.

Human exploration is also seen as a vital long-term customer for space manufacturing systems. An exponential decrease in launch mass and cost is needed to enable human moon, mars, and asteroid missions. This could be achieved by erasing cost and mass from the tail end of the exponential rocket equation, instead of the front end (i.e., cheaper launch vehicles). Manufacturing capabilities for planetary outposts could leverage feedstocks from pre-deployed ISRU facilities, enabling robust surface operations and reducing risk by an order of magnitude. Indeed, robotic ISRU and manufacturing systems could even pre-build storm shelters ahead of human explorers, outfitting them with air, water, food and sufficient propellant to get home.

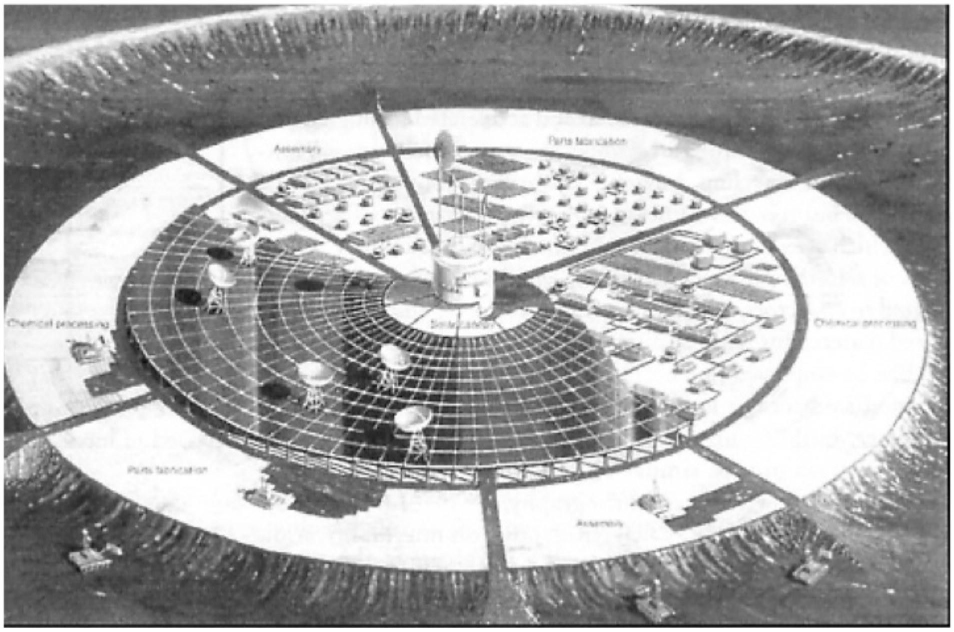

Figure 7: Automated Self Replicating Lunar Factory Concept

The Role of 3D Printing Technology in Orbital Debris Reduction

Earth's orbital environment contains thousands of pieces of space debris that has been accumulating slowly since the first rockets. It is currently understood that this environment poses a significant risk to spacecraft [1], and the conditions are not improving. If the effects of debris on the orbital environment are not mitigated, a higher risk of collisions between debris and functional spacecraft will exist. These collisions will increase the amount of debris substantially as shown in Fig. 1, until the orbital environment, specifically Low Earth Orbit (LEO), will be hazardous to traverse. Even with no future launches the space debris in orbit will increase in the next 200 years by collisions, creating thousands of new pieces of debris, as demonstrated in the 2009 incidental collision between the Iridium 33 and Cosmos 2251 satellites [2]. The debris also can be increased deliberately through anti-satellite weapons testing such as the one performed by China in which the result was a debris halo circling the globe [1].

This serious problem will need to be resolved in the future or the threat of losing a vehicle to a collision with debris will be great and the risk, for both potential human and financial aspects, of a mission will be higher than any return on the investment. It is for this reason that eliminating space debris for governments and private space activities could one day be a profitable business endeavor – if the debris is removed, the risk decreases, and the investment returns would more easily outweigh the investment risks.

In 2008, the United Nations General Assembly adopted a resolution endorsing the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space [9]. The goal would be to de-orbit non-functioning spacecraft and segments that were used to place a spacecraft into orbit. It is estimated that by 2014 international legal standards will be applied to all space faring nations, under treaty, for debris mitigation, and these standards will have provisions aimed at creating and enforcing penalties for nations which fail to comply. This would most likely be in the form of a financial penalty and potentially would be priced by the amount of material left. More complex systems and more vehicle development will be necessary in order to de-orbit waste from an ascent stage or end of life spacecraft. A service could be offered to take care of this aspect of future space flight and the development and added complexity aspects could be avoided, saving a client time and money in the creation of their vehicle. Orbital debris could be used as feedstock for 3D printing technologies if it could be captured, collected, and recycled.

Collecting orbital debris would be a complicated operation involving orbital rendezvous and capture. Damage to the collection craft could easily result, as debris is uncontrolled and its behavior unpredictable in many instances. Larger pieces of debris may be easier to recycle due to their larger mass and detectability. The recycling process will take the debris and separate by material type. This part of the process will be the most difficult to accomplish. Once separated, the material would then be pulverized into powder to be used in the fabrication device. The fabrication device best suited for this type of manufacturing process would be one that utilizes electron beam melting technologies.

Concluding Remarks: What Must Be Done Now

To expedite the advancement of 3D printing technology use in space, three key areas must be focused on: Studying the effects of 3D printing in the microgravity environment, adapting current state of the art 3D printing technologies for the space environment and for the printing of space infrastructure, including long beam structures, and verifying the usefulness of the 3D printer in space by flying a standard printer on board the International Space Station or a private space station.

The 1999 microgravity flight was groundbreaking in 3D printing research, but it left many questions unanswered. At the microscopic level, it is still unclear how a 3D object printed in microgravity differs from one printed in Earth gravity. The 1999 study verified that the concept works, but with little attention to the material properties of the printed object on a detailed level.

The 1999 study also showed evidence of deformation of the printed object, which was explained by the multi-g "pull-out" of the research aircraft. However, these explanations need more evidence to be supported fully. A follow up flight could investigate this phenomenon more closely.

The ultimate goal and use of 3D printing in space is to build the large structures that will be used to construct large scale space infrastructure. An increased focus could be given toward adapting the current state of the art to print large structures here on Earth. This means the re-purposing of today’s printers to print structures that extend far beyond the volume of the printer.

These advancements should lead to the installation of a 3D printer aboard the International Space Station or a private space station, such as the one being developed currently by Bigelow Aerospace. Demonstrating the usefulness of the 3D printer for manufacturing spare parts and unexpectedly needed objects on the space station will encourage the development of the 3D printer for space on a larger scale.

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