Solid Freeform Fabrication: An Enabling Technology for Future Space Missions

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ABSTRACT

The emerging class of direct manufacturing processes known as Solid Freeform Fabrication (SFF) employs a focused energy beam and metal feedstock to build structural parts directly from computer aided design (CAD) data. Some variations on existing SFF techniques have potential for application in space for a variety of different missions. This paper will focus on three different applications ranging from near to far term to demonstrate the widespread potential of this technology for space-based applications. One application is the on-orbit construction of large space structures, on the order of tens of meters to a kilometer in size. Such structures are too large to launch intact even in a deployable design; their extreme size necessitates assembly or erection of such structures in space. A low-earth orbiting satellite with a SFF system employing a high-energy beam for high deposition rates could be employed to construct large space structures using feedstock launched from Earth. A second potential application is a small, multifunctional system that could be used by astronauts on long-duration human exploration missions to manufacture spare parts. Supportability of human exploration missions is essential, and a SFF system would provide flexibility in the ability to repair or fabricate any part that may be damaged or broken during the mission. The system envisioned would also have machining and welding capabilities to increase its utility on a mission where mass and volume are extremely limited. A third example of an SFF application in space is a miniaturized automated system for structural health monitoring and repair. If damage is detected using a low power beam scan, the beam power can be increased to perform repairs within the spacecraft or satellite structure without the requirement of human interaction or commands. Due to low gravity environment for all of these applications, wire feedstock is preferred to powder from a containment, handling, and safety standpoint. The energy beams may be either electron beam or laser, and the developments required for either energy source to achieve success in these applications will be discussed.

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INTRODUCTION

There are numerous barriers to working in space which have historically defined the missions that can be performed. These barriers can be divided into two general categories: launch issues and mission issues. Launch issues stem from the extremely high cost associated with getting into space and the physical limitations on the payloads that are imposed by existing launch capabilities. These issues include physical factors such as overall payload size, weight and the payload's ability to withstand g-forces during launch. Mission issues are limitations on the payload in service and include power, resupply, and maintenance. The most significant mission issue is the ability to generate sufficient power for effective operation of the spacecraft and other auxiliary functions. Solar arrays are often used to convert solar energy into electricity. However, the greater the distance away from the sun, the less effective solar arrays are for collecting energy and converting it into electricity. Alternate power sources such as nuclear power provide high energy density, but have other safety and radiation issues. Thus, the energy efficiency of the spacecraft and its associated auxiliary functions is of high importance. Another mission issue is the need for continuing support of the spacecraft either for resupply of consumables depleted during operation or for maintenance. The efficiency by which consumables are used is important, as is the plan for resupply when the consumables are depleted. In addition, the spacecraft should be designed to minimize maintenance, or allow for remote or automatic maintenance performed by the spacecraft itself, thereby eliminating costly on-orbit service.

Several direct Solid Freeform Fabrication (SFF) technologies have been developed over the past decade. These techniques are used to produce three-dimensional plastic, ceramic, or metallic parts directly from computer-aided design (CAD) data. The ability to produce structural metallic parts by a layer-additive process in which metal feedstock is injected into a molten pool created by a high energy beam is of particular interest for space-based applications.[1] Advantages of such a process include the ability to build fully dense parts with excellent mechanical properties in the as-deposited condition, and the ability to build relatively fine details, thus reducing or eliminating post-build machining requirements.[2]

There are many missions that can potentially benefit from the development of on-orbit SFF capabilities. Three specific missions ranging from near to long-term in applicability are envisioned and described herein: construction of extremely large space structures, supportability of long-term human exploration missions, and autonomous structural health monitoring and repair. If SFF equipment can be designed to operate in the space environment within the available power, then SFF can be an enabling technology for these applications.

LARGE SPACE STRUCTURES

Several concepts were developed in the 1970s for on-orbit fabrication of large space structures. They typically consisted of launching equipment which would form flat stock, either composite[3] or metallic[4], into triangular cross-section beams which would then be joined with pre-manufactured cross members into triangular struts. The disadvantage of these approaches is a lack of flexibility, as they can only build strut-type structures of predefined geometry. Since that time, three other concepts have dominated the designs for large space structures: deployable, erectable, or inflatable.[5]

SFF is an alternative technology for fabricating structures on-orbit that cannot be launched due to size and/or weight limitations of current launch capabilities. One such structure is a next-generation telescope with the ability to examine deep space by arranging a huge network of collectors. These collectors would need to be supported by a rigid truss structure on the order of tens of meters to a kilometer in size. Designers have been clever at devising methods by which space structures can be efficiently packaged for launch, but this application far exceeds current launch capacities.

In addition, the loads on structures in space are very different from those in a gravity environment or during launch. Most space structures are currently designed and constructed on Earth, then subjected to the high loads of launch. Structures designed and built in this manner must be over designed for in-space service in order to survive the launch loads. Fabricated on-orbit, large space structures can be designed and built to the high stiffnesses required for space structures, without having to endure a gravity field or high launch accelerations.

Deployable Structures

Deployable structures (Fig. 1) are designed and constructed on Earth with mechanisms to fold up into a small package for launch. Once in orbit, they are deployed, much like opening an umbrella. Typical deployable structures are linearly deployed booms, masts or hinged panels. These structures involve complex designs of hinged joints to fold the structure up into an efficient package for launching. Once the package reaches the desired altitude, the structure can be either manually or automatically deployed. Disadvantages of deployable structures include limited structural configurations due to the design constraints required to fold and deploy the structure. In addition to complexity, the hinged mechanisms increase weight and reduce stiffness of the final structure. Deployable structures are still limited by the total size and weight allowances of current launch capabilities, since they are typically designed to be launched in a single package. Finally, failure to fully deploy can lead to total loss of the spacecraft, limitation of capabilities, or the need for expensive on-orbit repairs.

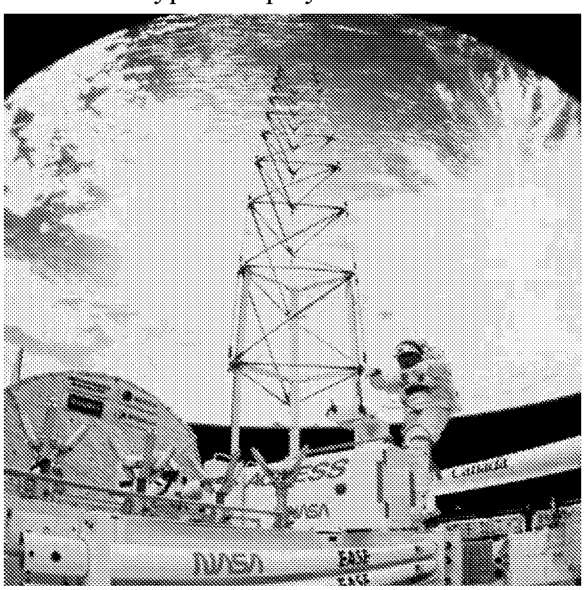

Figure 1. Deployable truss structure on Space Shuttle Atlantis.

Erectable Structures

Erectable structures (Fig. 2) are constructed on Earth as separate joints and struts, launched in pieces, and then assembled on-orbit. Erectable structures require a complex indexing system to ensure the proper sequencing for assembly. However, erectable structures can be transported in multiple launches to allow for larger structures to be built on-orbit. To fully assemble the structure, either autonomous or remotely operated robotics or the risk and cost associated with a significant amount of extravehicular activity for astronauts is required. The joint designs for these structures are complex; they must be designed to ensure proper attachment and accurate alignment and locking of the nodes and struts together during on-orbit assembly. The complex joint design also increases the weight and cost of the structure. Finally, tethering or a capture capability is required to ensure that loose components or tools required for assembly do not float away during assembly of the erectable structure.

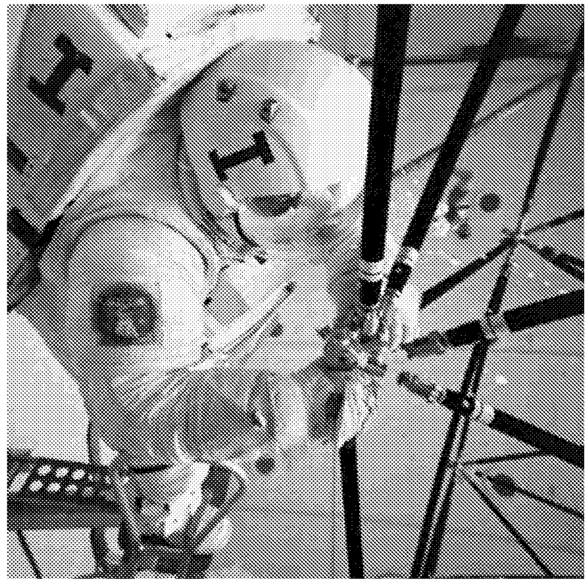

Figure 2. Astronaut assembly of 14-meter dia. erectable structure.

Inflatable Structures

Inflatable structures (Fig. 3) employ a thin polymeric membrane, which is folded before launch and inflated like a balloon to form the final structure on-orbit. Inflatable structures are low in mass and can be packaged in small volumes for launch. Once on-orbit, they are deployed to shape with a low-pressure inflation gas, then rigidized by pressure stabilization using the inflation gas. Alternatively, inflated structures can be made from self-rigidizable polymers that can be cured in place through exposure to heat or UV radiation. Potential applications include solar arrays, communications antennas, radar antennas, thermal/light shields, and solar sails. The polymers used for these structures may not have adequate mechanical properties, particularly stiffness, for many in-space applications. In addition, these structures are at increased risk of loss of function from puncture by space debris or from degradation of the polymeric material by atomic oxygen and radiation present in the space environment. Usage of inflatable structures is limited by their ability to achieve dimensional precision and maintain required tolerances. Finally, the need to carry the inflation gas and means for rigidizing the structure increases the weight and volume of the payload.

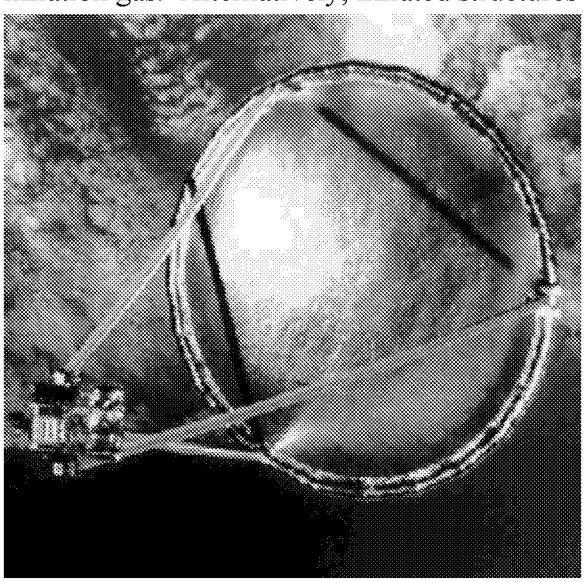

Figure 3. Spartan-207 inflatable antenna experiment.

Application of Solid Freeform Fabrication for Large Space Structures

SFF can be used to construct large space structures with fewer limitations than deployable, erectable or inflatable approaches. Due to assembly and deployment requirements for both deployable and erectable structures, the freeform fabricated structure would be simpler in design, and thus lighter weight. In space, the primary structural design factor is stiffness. Being constructed in a single continuous metallic part, the freeform fabricated structure would have better stiffness than either a hinged deployable member or an inflatable polymeric structure. The useful life of a SFF metallic structure is greater than that of an inflatable polymeric structure because metals are less susceptible to atomic oxygen and radiation degradation and better able to tolerate space debris impact in the space environment. Finally, since the freeform fabricated structure would be fabricated in space, size is no limitation because additional metal feedstock is all that is required to construct a larger structure. Feedstock materials are relatively unaffected by launch loads, so resupply can exploit low cost launch options.

SFF processes could be used to fabricate extremely large space structures, either entirely from raw feedstock or by modifying as necessary and joining pre-manufactured parts together into a three-dimensional structure. A depot with SFF capabilities could be established in low Earth orbit to construct a large structure that would be adequate for in-space applications. Initially, feedstock would be supplied on inexpensive unmanned launches and held for deposition. In the near-term, the Space Shuttle External Tank could be carried into orbit rather than being jettisoned during launch and allowed to burn up in the Earth's atmosphere. The additional cost to bring the external tank into orbit on launching is low, and each expended tank would provide 66,000 pounds of aluminum-lithium alloy that could be converted into useable feedstock form. For depots located farther from the Earth in the distant future, raw materials could be mined and processed from lunar, asteroid, or other planetary sources, avoiding the cost of launch from Earth's gravity well.

To enable the construction of large space structures using a space-based SFF capability, the SFF system must be able to achieve extremely high deposition rates within the host depot's ability to generate power. For fabrication of large space structures, the ability to deposit with a high level of detail is not as important as the ability to achieve high deposition rates with high feedstock capture rates. However, large scale dimensional accuracy is critical. The depot will require dynamic stability with the structure being built to ensure that on-orbit vibrations do not result in misalignment or failure of the structure being fabricated. With development of closed-loop process controls and autonomous or remote operation controls, the SFF system could manufacture structures in low Earth orbit with a communications link to enable ground-based operation, programming, and control.

SUPPORTABILITY OF LONG-TERM HUMAN EXPLORATION MISSIONS

The ability to perform repairs in space improves the viability and efficiency of long-term missions by permitting designs that allow for failures to occur rather than requiring redundancy and over design. Having the capability of repairing or building replacement parts on orbit has the potential for reducing the amount of parasitic weight from spare parts, which may never be used but are necessary to ensure the required safety margins for the mission. Supportability is particularly critical when failure of the mission cannot be tolerated, such as in human exploration missions. Repair or replacement of parts on board the International Space Station relies on bringing spare parts along or resupplying as needed from Earth. This is acceptable because of relatively frequent rendezvous scheduled for support and resupply. However, for long duration missions that are beyond low Earth orbit, resupply from Earth becomes difficult to impossible.

One long-term mission in which SFF has potential applications is a human exploration mission to Mars. The closest approach between Earth and Mars varies from 34×10^6 to 63×10^6 miles (55×10^6 to 102×10^6 km) due to their elliptical orbits and different orbital periods. Two scenarios are feasible, depending upon the trajectory taken and the time spent on Mars. With existing launch and propulsion systems, the round-trip travel times are 400-650 days for a short-stay mission lasting only 30-90 days on Mars (Fig. 4), or 250-350 days transit time for a long-stay, fast transit mission lasting 600+ days on Mars (Fig. 5). The open launch window only occurs once approximately every two years: between these optimal times for launch, Earth and Mars are in opposition, with the Sun between them.[6] Due to such a restrictive launch window, resupply or repair from Earth is impossible, necessitating bringing everything for the duration of the mission along.

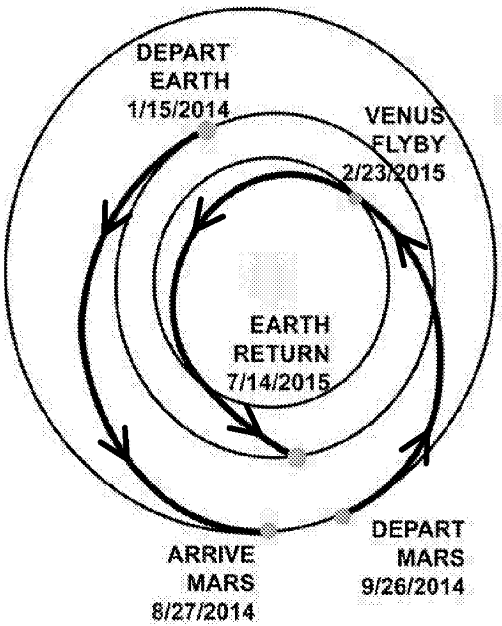

Figure 4. Trajectories for short stay mission.

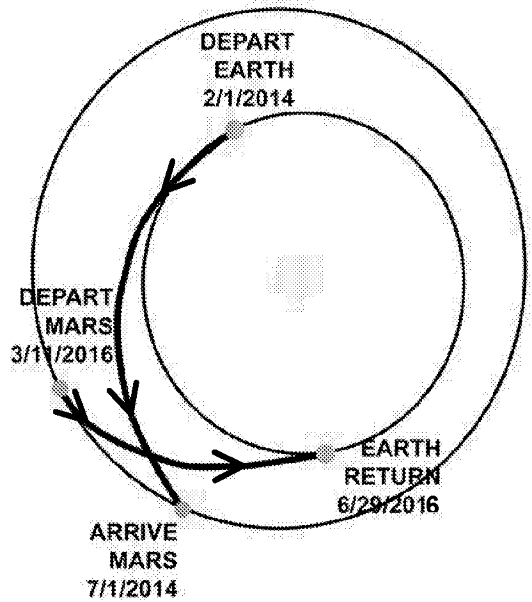

Figure 5. Trajectories for fast transit mission.

A compact SFF system with multifunctional capabilities provides significant supportability for a human exploration mission to Mars. A SFF system would alleviate the need to stock spare parts for all possible failures, and provides a means for fabricating replacement parts or repairing damaged parts. Recycling damaged parts back into feedstock for the SFF system can minimize consumable feedstock materials. This would reduce volume and weight allowed for spare parts, and eliminate the need to stow failed parts for the remainder of the mission. As a multifunctional tool, the SFF system also increases flexibility and allows for failure of components without jeopardizing the safety and success of the mission.

The SFF system must be compact in size, and operable at low power with high energy and feedstock efficiency. For maximum effectiveness, the SFF system should be capable of multiple additive and subtractive tasks, such as the ability to build up a new part, repair or weld a broken part, and machine to finish a built part or alter an existing part. The system should also be capable of processing a wide range of metals found on a spacecraft, including aluminum, titanium, copper, nickel and steel. A high degree of autonomy in the operation and control of the system minimizes astronaut training and allows for the possibility of ground-based personnel performing remote programming, operation, and control.

STRUCTURAL HEALTH MONITORING AND REPAIR

Spacecraft and other high value space structures with extremely long mission lifetimes may benefit from periodic structural inspection to monitor and assess damage progression. The ability to monitor the health of the spacecraft structure would allow for structural designs that are less conservative, which may enable larger payloads, longer durations, and/or farther distances to be traveled with less concern for structural failure. A miniature, multifunctional SFF system could be constructed to accompany spacecraft for space exploration. This miniature system would perform health monitoring of the spacecraft by autonomously patrolling throughout the structure while operating in a non-destructive mode to detect damage. The health monitoring could be achieved using conventional non-destructive evaluation techniques or by operating the energy beam in a low power mode to scan the spacecraft structure. In this mode, the miniature system would search for evidence of damage such as impact damage from micrometeoroid strikes, fatigue cracking, or malfunctioning or improperly deployed attachments like antennas. When damage was identified, the SFF system would communicate with the host spacecraft to log the damage site and determine the proper course of action (i.e., continue to monitor the site or perform a repair). If the decision were made to perform a repair, the beam power could be increased to perform machining, welding, or adding new material as needed to achieve a suitable repair. After completing the repair, the SFF system would conduct another scan to non-destructively verify the repair. Finally, the repair outcome would be communicated back to the host spacecraft to be recorded, and the SFF system would continue to move about the structure performing health monitoring scans.

Technical advances required for achieving such a system are far-reaching. These include the ability to miniaturize the entire system and integrate the capabilities of non-destructive evaluation for flaw detection and multiple repair functions (including depositing material, machining, drilling, and welding). Since the system must be extremely small, it must have highly efficient power generation and usage, as well as efficient feedstock usage. Resupply of consumables will be difficult to impossible, so this system must also be capable of generating power and reprocessing waste materials back into useable feedstock. Finally, it needs to be capable of autonomous operation, with logic built in to detect damage, identify a solution plan, perform the repair, non-destructively evaluate the repair, and transmit information or record the repair to a maintenance log.

SFF ADVANCES REQUIRED TO ENABLE SPACE MISSIONS

Several space missions have been described where SFF provides significant technology enhancements. However, review of the state of the art illustrates that further developments are required to meet all of the unique requirements for operation in a space environment (low or zero gravity, vacuum, and extreme temperatures), and account for launch issues (size, weight, and launch loads) and mission issues (power, resupply, and maintenance). The two specific components of the SFF system that are most affected by the launch, mission, and environmental issues are the feedstock and the energy beam.

For any of these missions, the SFF system must be capable of working with materials used for space structures, including a broad range of metals such as aluminum, titanium, copper, nickel and steel. In addition, the repairs or replacement parts must be permanent, and the process must repeatably produce high quality parts that are functional in the as-produced form. Closed-loop process control is imperative to achieve the repeatability, dimensional tolerances, and high quality necessary for space-based missions. Secondary processing such as binder burnout, final consolidation or densification must be eliminated, or limited to those like heat treatment that are achievable with the same equipment. Furthermore, the mechanical and physical properties in the as-built condition must be equivalent to those of the original part.

Most ground-based SFF systems use powdered metal feedstock which requires gravity and/or flowing gas to direct the powder into the molten pool. Powder usage efficiencies in these systems vary, but can be as low as 10%, depending upon the specific SFF process. Containment and handling of powdered metal pose significant safety issues in a low or zero gravity environment. The use of wire feedstock eliminates the need for flowing gas, and provides nearly 100% feedstock usage efficiency, which is critical when resupply is extremely costly and difficult to impossible.

The energy beam source in most current ground-based SFF systems is either a high power CO_2 or Nd:YAG laser. However, CO_2 and Nd:YAG lasers with sufficient power to perform high deposition rate SFF require too much support equipment (water chiller, power generator) and maintenance, and are not energy-efficient enough for the applications described, having beam power efficiencies on the order of only 5-10%. Although some of these issues can be improved with technological advances, the cost to reduce size, weight, maintenance, and power inefficiency in these lasers is unattractive solely for space application. Of all lasers presently available, diode lasers have the highest potential for applications in space because they are compact in size, durable, require less maintenance and support equipment, and have higher power efficiency (up to 40-50%). A considerable amount of research in the laser community is being conducted to achieve a point-focused beam from a diode laser, with sufficient power density to perform SFF. Another obstacle inherent with laser power is that in general, laser energy does not couple well with reflective materials, particularly aluminum and copper. Since significant portions of space structures are constructed of aluminum, this is probably the largest drawback to laser-based SFF systems for space applications.[7]

An alternative energy beam source is a focused electron beam, which has greater than 90% power efficiency and nearly 100% coupling efficiency with electrically conductive materials. The vacuum of space can be used as the process environment, eliminating the need for a vacuum chamber and pumping system for ground-based electron beam freeform fabrication. Electron beams will produce energetic x-rays if the accelerating voltage is too high, but this hazard can be minimized by limiting the beam power and performing the operation on the outside of the spacecraft where the spacecraft structure will provide shielding for astronauts and sensitive equipment. Maintenance issues need to be addressed to ensure long filament lifetime, but otherwise, electron beams appear to satisfy size, weight, and power requirements for space-based applications.

Finally, the system must be small and lightweight for applications in space due to extremely tight space limitations and high launch costs. Miniaturization, automation for either autonomous or remotely controlled operation and control, and multifunctionality are all keys to achieving a universal tool with potential for inclusion on space missions. Continued rapid advances in the size, power, and speed of computers are expected to permit the needed miniaturization and control capabilities. Although lasers and electron beams are capable of performing numerous functions, research is necessary to design an SFF system with a wide range of tunability. Plus, the processing parameters and techniques must be developed to be able to use the same SFF system for performing multiple processing operations. All of these developments are technically challenging but feasible.

SFF TECHNOLOGY DEVELOPMENT AT LANGLEY RESEARCH CENTER

In order to address current SFF technology issues, NASA Langley Research Center (LaRC) is developing two electron beam freeform fabrication (EB F^3) systems. The first is a ground-based system that comprises a high power electron beam gun and dual wire feeders capable of independent, simultaneous operation. Positioning is programmable through six axes of motion (X, Y, Z, gun tilt, and positioner tilt and rotate), within a build envelope of 60 in. x 24 in. x 24 in. (1.5 m x 0.6 m x 0.6 m). The electron beam requires a vacuum in the range of $5x10^{-5}$ torr ($6.5x10^{-3}$ Pa), so the ground-based EB F^3 system is housed in a large vacuum chamber.

Research with the ground-based equipment at NASA LaRC will focus on correlating processing, microstructure, and mechanical properties to optimize the EB F^3 process to ensure high quality, reproducible parts. Processing parameters will be developed for aluminum, aluminum-lithium, titanium, and other alloys of interest for aerospace structures. The dual wire feeders will allow investigation of both high deposition rates and fine details through application of large or fine diameter wires. Experiments will also evaluate the ability of this process to produce unitized structures with complex geometries and functionally graded compositions.

The second EB F^3 system (Fig. 6) is portable and comprises a small vacuum chamber, a low power electron beam gun, four axis motion control system (X, Y, Z and rotation), single wire feeder, and a data acquisition and control system. This portable EB F^3 system will be used to study the effect of microgravity on build geometry and solidification microstructure. This small system is currently under development for flight

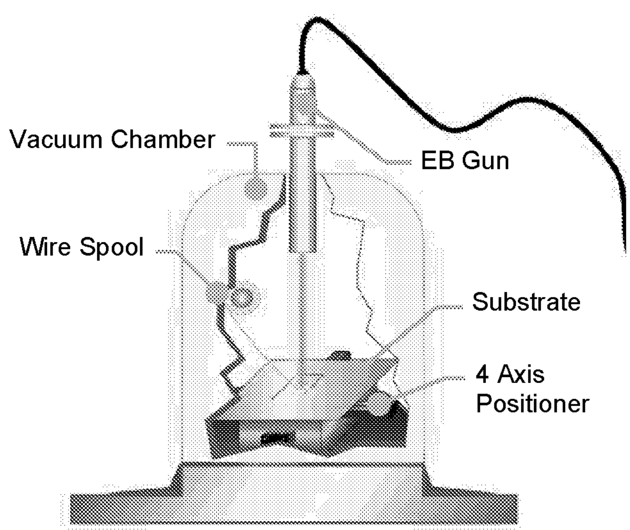

Figure 6. Electron beam SFF microgravity demonstrator schematic.

experiments on NASA's KC-135. This research aircraft is flown in parabolic trajectories resulting in alternating cycles of zero-gravity transitioning to 2g (twice the gravitational force at sea level on Earth). Each cycle provides 30-40 seconds of weightlessness, and a typical series will repeat the parabolic trajectory 35 to 40 times. Proof-of-concept flights on the KC-135 are required as a step to certifying space flight hardware.

CONCLUDING REMARKS

Emerging SFF technologies enable significant advances in new missions for space in the areas of fabrication of large space structures, supportability of long-term human exploration missions, and autonomous structural health monitoring and repair. Several developments are required for SFF equipment to be capable of operating in the space environment, including high power efficiency, good coupling between the beam and the materials being processed, high deposition rates with efficient use of feedstock and consumables, reproducible production of high quality parts, and autonomous operation in a microgravity environment. Wire-fed electron beam freeform fabrication techniques are being developed at NASA Langley Research Center to address many of these issues.

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