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3D Printing in Space

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In recent years, additive manufacturing, often referred to as "3D printing," has captured the public's imagination. The technology could contribute positively to space missions, for example, by enabling in-orbit manufacture of replacement parts and, perhaps someday, substantially in the future, entire spacecraft. Additive manufacturing can also help to re-imagine a new space architecture that is not constrained by the design and manufacturing confines of gravity, current manufacturing processes, and launch-related structural stresses. However, there has been a substantial degree of exaggeration, even hype, about the technology's capabilities in the short term. The specific benefits and potential scope of additive manufacturing remain undetermined. Substantial gaps exist between the vision for additive manufacturing in space and the limitations of the technology. Additive manufacturing in and of itself is not a solution, but presents potential opportunities as a tool in a broad toolkit of options for space-based activities. *3D Printing in Space* evaluates the prospects of in-space additive manufacturing. The report examines the potential promises and challenges of in-space additive manufacturing and outlines the next steps for NASA and the United States Air Force to develop the technology.

Background

Additive manufacturing as a commercial technology that builds three-dimensional parts directly from computer files has existed since the 1980s and has been evaluated for space-based use since the late 1990s. In its most basic form, additive manufacturing involves the process of adding material on top of some kind of build platform and printing layer after layer until an object is produced; this is opposed to more conventional and commonly used manufacturing methods of removing material from a larger object. Currently, most additive manufacturing techniques involve the use of only a single material, such as a plastic or metal, and thus require that functional parts consisting of more than one material be developed by separate machines and undergo finishing and assembly.

Additive manufacturing is already in use in the biomedical and aerospace fields. Because of the promise additive manufacturing holds for the future of space flight, the National Aeronautics and Space Administration (NASA), the Air Force Space Command, and the Air Force Research Laboratory tasked the National Research Council to conduct a study of the prospects for the use of additive manufacturing in space. Although there are other government space actors, the recommendations of the report focus on NASA and Air Force missions.

A 1999 low-gravity test of additive manufacturing aboard a KC-135 "Vomit Comet." This early work was sponsored by NASA's Marshall Space Flight Center. Image Credit: NASA

The Promise and Potential of Space-based Additive Manufacturing

There are numerous potential benefits to using additive manufacturing in space. Additive manufacturing offers unique economic incentives for space operations by cutting raw material costs, reducing payload sizes, and eliminating the need to frequently launch spare or replacement parts into orbit. The report encourages further evaluation of the costs and benefits of additive manufacturing in space.

> **Recommendation: As the technology evolves and when projects utilizing this technology are considered, NASA and the Air Force should jointly undertake a cost-benefit analysis of the role of space-based additive manufacturing in the construction of smaller, more reliable, less massive satellite systems or their key components.**

The application of additive manufacturing to the space environment could likely lead to a change in ideas and concepts of what satellites look like, how they are designed, and what they can do. It enables development of structures, such as ultra-lightweight antennas, entirely unlike those needed in the high-gravity environment of Earth or to survive the rigors of space launch. Even the lack of gravity could lead to new manufacturing techniques not available to ground-based systems.

Because additive manufacturing may provide totally new manufacturing capabilities, it would be a mistake to make additive manufacturing decisions based entirely upon cost-benefit determinations of existing products and functionalities. Doing so might eliminate valuable opportunities to advance capabilities with this new technology.

> **Recommendation: Actual costs of the reproduction of components or spacecraft should not be the sole criterion for evaluation of the benefits of additive manufacturing; criteria should also include the value of creating structures and functionalities not feasible before.**

The Challenges of Space-based Additive Manufacturing

Multiple limitations preclude fully automated additive manufacturing in space from becoming an immediate reality. The vacuum of space, zero gravity, and intense thermal fluctuations all pose extreme and harsh environmental obstacles. Furthermore, various constraints falling under cost, human oversight, and a lack of understanding of material properties in space also hinder the advancement of this technology.

Aerospace systems have critical missions and must meet rigorous standards for quality and reliability—standards that are set to ensure mission success. The basic technology of additive manufacturing is still young and there are some fundamental issues that must be resolved before space-based applications can be derived: producing and verifying consistent production quality; standardizing design software, file formats, and equipment parameters; and understanding the relationship between materials, their structural properties, and production techniques. In order to benefit from additive manufacturing approaches, the manufacturing community—with government involvement—will have to address the issues of qualification and certification.

> **Recommendation: NASA and the Air Force should jointly cooperate—and possibly involve additional parties, including other government agencies as well as industry—to research, identify, develop, and gain consensus on standard qualification and certification methodologies for different applications. This cooperation can be undertaken within the framework of a public-private partnership such as America Makes.**

Additive manufacturing in space is even more of a systems engineering and industrial logistics problem than additive manufacturing on the ground. Transplanting additive manufacturing capability to space requires consideration of how the supporting infrastructure needs to be evolved to operate in the new environment. As additive manufacturing currently requires extensive human participation, in-space manufacturing is likely to have a more significant impact on crewed space missions than for robotic spaceflight, especially in the short-term.

> **Recommendation: When considering moving additive manufacturing technology to the space environment, any person or organization developing plans should include in their planning the infrastructure required to enable fabrication processes based on additive-manufacturing, such as power, robotics, and even human presence. Studies examining the types of infrastructure should be undertaken in tandem with the development of the additive manufacturing technology itself.**

NASA and Additive Manufacturing

Currently, NASA is the leader in space-based additive manufacturing. NASA first evaluated the technology in the late 1990s, and plans to begin conducting experiments using a plastics-based 3D printer aboard the International Space Station (ISS) starting in late 2014. Many NASA field centers are currently conducting experiments with additive manufacturing on the ground. In order to enable efficient development and application of this technology, greater investment, planning, and coordination is necessary.

Recommendation: NASA should consider additional investments in the education and training of both materials scientists with specific expertise in additive manufacturing and spacecraft designers and engineers with deep knowledge of the use and development of additively manufactured systems.

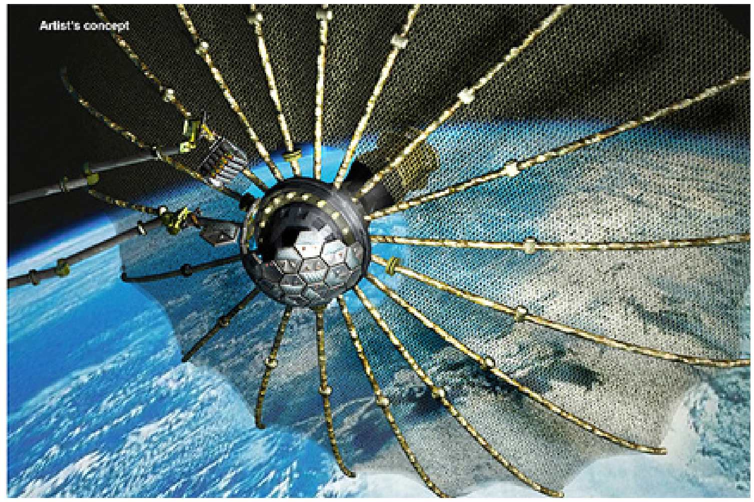
Recommendation: NASA should sponsor a space-based additive manufacturing workshop to bring together current experts in the field to share ideas and identify possible research projects in the short term (1-5 years) and medium term (5-10 years).

Recommendation: NASA should quickly identify additive manufacturing experiments for all areas of ISS utilization planning and identify any additive manufacturing experiments worthy of flight that it can develop and test aboard the ISS during its remaining 10 years of service and determine if they are worthy of flight. NASA currently has methods for providing research grant funding for basic research on additive manufacturing. The agency should closely evaluate funded research options to determine which would allow the most rapid transition of additive manufacturing to the ISS.

Recommendations: NASA should convene an agency-wide space-based additive manufacturing working group to define and validate an agency-level roadmap, with short- and longer-term goals for evaluating the possible advantages of additive manufacturing in space, and with implications for terrestrial additive manufacturing as well. The roadmap should take into consideration efficiencies in cost and risk management. NASA should build on the considerable experience gained from the Space Technology Roadmaps. (See the full report for recommended roadmap objectives.)

Recommendation: NASA should seek opportunities for cooperation and joint development with other organizations interested in space-based additive manufacturing, including the Air Force, the European Space Agency, the Japanese Space Agency, other foreign partners, and commercial firms.

Because of its broad reaching activities involving additive manufacturing, NASA could consider establishing or co-sponsoring an ongoing technology interchange forum devoted to additive manufacturing engineering technologies, focusing on serving all NASA centers, universities, small companies, and other organizations.



Artist illustration of the Defense Advanced Research Projects Agency's (DARPA's) Phoenix program. In this illustration a robotic spacecraft is attaching new components to an antenna harvested from a decommissioned spacecraft. Credit: DARPA

The Air Force and Additive Manufacturing

The report finds NASA's requirement for space-based additive manufacturing to be more clearly defined than the Air Force's requirements. The report's authoring committee was informed that the Air Force's most pressing requirement is to reduce the cost of launching payloads to orbit. At the present time, it is too early to be certain that space-based additive manufacturing will make it possible to reduce the cost of space launch. It is also too early to determine how the Air Force may best make use of this technology, although its potential for the deployment of structures too large or fragile to fit in current launch vehicle payload shrouds could prove attractive for some national security missions. Like NASA, the Air Force can achieve a more efficient use of additive manufacturing by examining its needs for space-based manufacturing, increasing investments in research and training, and engaging in greater planning and cooperation.

Recommendation: The Air Force should conduct a systems-analytical study of the operational utility of spacecraft and spacecraft components produced in space using additive manufacturing compared to other existing production methods. There is at present a lack of knowledge to credibly determine whether or not development of an Air Force-specific space-based additive manufacturing production facility would achieve its expected benefit. Given that such a fabrication center would be highly complex and expensive, a detailed system assessment and cost-benefit analysis is advisable.

Recommendation: The Air Force should continue to invest in additive manufacturing technologies, with a specific focus on their applicability to existing and new space applications, and invest in selected flight experiments.

Recommendation: The Air Force should consider additional investments in the education and training of both materials scientists with specific expertise in additive manufacturing and spacecraft designers and engineers with deep knowledge of the use and development of additively manufactured systems.

Recommendation: The Air Force should establish a roadmap with short- and longer-term goals for evaluating the possible advantages of additive manufacturing in space. The Air Force should build on the considerable experience gained from other Air Force technology development roadmaps. (See the full report for recommended roadmap objectives.)

Recommendation: The Air Force should make every effort to cooperate with NASA on in-space additive manufacturing technology development, including conducting research on the International Space Station.

Committee on Space-Based Additive Manufacturing: Robert H. Latiff, R. Latiff Associates, *Chair*; **Elizabeth R. Cantwell**, Lawrence Livermore National Laboratory, *Vice Chair*; **Peter M. Banks**, Red Planet Capital Partners; **Andrew S. Bicos**, The Boeing Company; **Ravi B. Deo**, EMBR; **John W. Hines**, Senior Technology Advisor, Independent Consultant; **Bhavya Lal**, IDA Science and Technology Policy Institute; **Sandra H. Magnus**, American Institute of Aeronautics and Astronautics; **Thomas E. Maultsby**, Rubicon, LLC; **Michael T. Mcgrath**, University of Colorado, Boulder; **Lyle H. Schwartz**, Air Force Office of Scientific Research (retired); **Ivan E. Sutherland**, Portland State University; **Ryan Wicker**, University of Texas, El Paso; **Paul K. Wright**, Berkeley Energy and Climate Institute, University of California, Berkeley

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Copies of the report are available free of charge from http://www.nap.edu.

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