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Testimony of

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Introduction

Continuous technological innovation has been foundational to maintaining America's commercial and military superiority on the ground and in space. Made In Space, Inc. (Made In Space, MIS) is developing technologies and business models that will enable and drive people to one day sustainably live and work in space. In 2014, Made In Space hardware successfully produced the first functional objects manufactured off the face of the planet. Today, Made In Space has several in-space manufacturing programs underway and is commercially manufacturing for customers aboard the International Space Station. This success would not be possible without the Small Business Innovation Research Program, public-private partnerships like the In-Space Robotic Manufacturing and Assembly Tipping Point program (IRMA), and access to the International Space Station (ISS).

In the space domain in particular, new capabilities are needed in order to maintain and grow America's edge over others. Space is critical to both the American economy and to our defense apparatus. To this end, Made In Space is developing in-space manufacturable satellites. Using a combination of additive manufacturing and robotic assembly, this capability allows satellites to utilize mass and volume much more efficiently and eliminates design constraints that the harsh mechanical environment of launch places upon spacecraft. In-space manufacturing also enables satellites to be repairable and reconfigurable, making both civil and military spacecraft more resilient to changing threats in space.

Technological innovation is the engine which will keep us ahead of China and other nations. Space is acknowledged as integral to the current national economy, an area of high economic growth over the next decade, and, increasingly, as formally recognized by the Department of Defense in 2017, a warfighting domain. Because of these factors, it is imperative that active measures be increased to develop new technologies and business models which utilize space for commerce, science, and defense.

In order to maintain and grow America's space-based edge over China and others, Made In Space strongly encourages continued support of programs which enable the step-by-step development of new commercial space capabilities, including the SBIR program, NASA's IRMA program, DARPA's support of in-space manufacturing and assembly development, and the International Space Station.

Made In Space, Inc. and the Emerging Cislunar Economy

Made In Space is a small business with offices in California, Florida, Alabama, and Ohio.

Made In Space was founded in 2010 with the goal of enabling people to sustainably live and work in space.

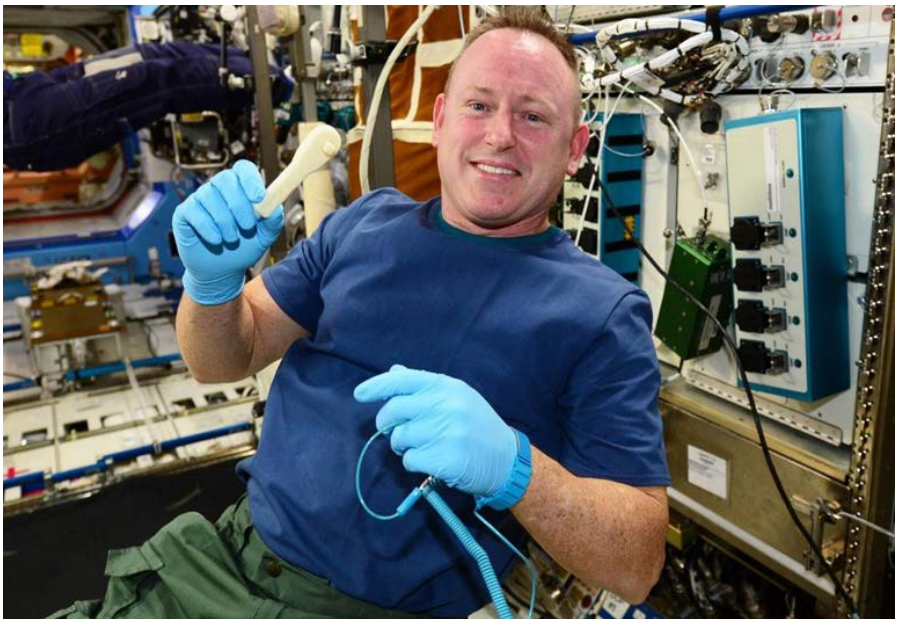

Figure 1. ISS Commander Barry "Butch" Wilmore holding a 3D printed ratchet manufactured in space. The ratchet was designed on the ground and manufactured in space one week later, making it potentially the fastest delivery to space ever. Image credit: NASA

This goal is shared by many in the space industry who believe in the economic promise the final frontier holds. Companies like SpaceX and Blue Origin are focused on building low cost launch vehicles, 21st century versions of the covered wagon. We at Made In Space are focused on developing the tools and manufacturing facilities that will fill those wagons to the stars, enabling growth portions of American industry in a regime where China and others are increasingly competitive with U.S. offerings.

We focus on two types of space-based manufacturing: manufacturing technologies that enable new missions in space; and manufacturing technologies which leverage the space environment to create high value goods for use on Earth. We believe these areas will drive significant growth of American industry over the next decade. Furthermore, they represent technical advantages the U.S. possesses over China and others which should be developed and implemented in operational civil and defense space applications as quickly as possible before they are duplicated or surpassed.

NASA and OGA Support Enables Manufacturing In Space For Use In Space and the Future of American Industry In Space

In-space manufacturing and assembly dramatically reduces spacecraft cost, reduces the limitations rocket launch places on spacecraft design, and removes astronauts from harm's way. Traditionally, satellite design has been constrained by launch-shroud size and launch load/environment survivability requirements. Similarly, due to lift capacity limits and the high risk and low availability of astronaut EVA for assembly, creating large space-based structures such as space stations has been a once-in-a-generation endeavor. Archinaut minimizes or removes these and other design limitations.

In-space manufacturing and assembly enables a wide variety of desirable missions. These include largescale telescopes for astrophysics missions, increased power production for small satellites, and future space station backbones. In-space manufacturing and assembly is also transformational for defense applications, enabling largescale reflectors, long baseline structures for civil and defense SAR applications, and space-based solar power stations. Additionally, these technologies enable satellites to be modified, repaired, or reconfigured on orbit, thereby enabling these assets to be more resilient and durable in a manner that does not exist in the current “fire and forget” approach to satellite design, manufacture, and deployment.

Working closely with NASA, DARPA, and others and utilizing multiple pieces of the space infrastructure described above, Made In Space has made significant progress in developing and demonstrating in-space manufacturing technologies for both satellite applications and human spaceflight missions. MIS engineers initially internally developed a prototype gravity-independent 3D printer. Through a grant from the NASA Flight Opportunities Program, that prototype was tested and successfully operated on board a parabolic flight aircraft in 2011.

Based on this success, Made In Space was awarded SBIR contracts to develop the technology for demonstration aboard the ISS. Via an SBIR Phase III contract with NASA run out of the In-Space Manufacturing group at NASA Marshall Space Flight Center, Made In Space built and operated the first 3D printer to operate in space. In late 2014, via the 3D Printing In Zero-G Technology Demonstration experiment, this space-capable 3D printer was installed on the ISS and manufactured the first functional objects ever made off the planet Earth (see Figure 1).

Thereafter, Made In Space built the Additive Manufacturing Facility (AMF, see Figure 2), a second-generation more capable 3D printer. The AMF was launched to the ISS in March 2016. Via agreements with NASA and the Center for the Advancement of Science In

Figure 2. The Additive Manufacturing Facility (left) is the first ever commercial manufacturing facility deployed to space. The first commercially manufactured part in space was a space optimized hand tool (right). Image credits: NASA/Made In Space.

Space (CASIS), the managers of the ISS National Lab, Made In Space owns and operates the AMF, routinely sending print jobs to the ISS and manufacturing them on a

weekly basis. The AMF print services business is profitable and has produced parts for NASA, the U.S. Navy, Lowe's, universities such as Texas A&M University, student groups, and even individuals. Parts manufactured include space optimized structures, hand tools for the ISS crew, prototype medical splints and ventilators, and adaptors for ISS equipment. This commercial service is one of several pioneering commercial uses of low Earth orbit. These uses represent pathfinders for future commercial space station-based businesses, a future cornerstone of American industry's utilization of space.

The capability to manufacture parts on demand during a space mission is paradigm shifting. 3D printing serves as a fast and inexpensive way to manufacture parts on-site and on-demand, reducing the need for costly spares on the ISS and other spacecraft. Long-term missions would benefit greatly from having onboard manufacturing capabilities. New parts may be manufactured to enable new scientific experiments or augment existing ones.

Further building on this success and internal research and development into manufacturing very large, space-optimized structures in space, Made In Space was selected to participate in the two phase NASA Space Technology Mission Directorate In-Space Robotic Manufacturing and Assembly Tipping Point program (IRMA) program. The IRMA program seeks "to transform the way we manufacture, assemble and repair large structures in space, leading us closer to a robust space infrastructure freed from launch window scheduling, launch vehicle mass limitations and astronaut safety concerns. Ultimately, [IRMA] will enable more frequent science and discovery missions in Earth orbit, across the solar system and beyond."[1] Furthermore, IRMA operates via "public-private partnerships to deliver technologies and capabilities needed for future NASA, other government agency, and commercial missions."[2] Tipping point technologies were sought. That is, technologies and capabilities which, if investment was made in a flight demonstration, there would be "significant advancement of the technology's maturation, a high likelihood for utilization of the technology in a commercially fielded space application, and a significant improvement in the offerors' ability to successfully bring the space technology to market" thereby enabling the capability to be available to NASA and OGA's but sustained by the commercial market, resulting in more cost effective and better technological outcomes for the government.[3]

Phase I of the IRMA program focused on ground demonstrations of in-space manufacturing and assembly technologies, maturing these technologies for flight demonstrations in Phase II where properly planned definitive demonstrations in space will push these technologies past the tipping point and raise their technology readiness level to the point that civil, defense, and commercial customers will utilize the technologies for

[1] See: https://www.nasa.gov/mission_pages/tdm/irma/index.html
[2] See NASA Solicitation UTILIZING PUBLIC - PRIVATE PARTNERSHIPS TO ADVANCE TIPPING POINT TECHNOLOGIES appendix number NNH15ZOA001N-15STMD-001 to NASA Research Announcement (NRA): Space Technology - Research, Development, Demonstration, and Infusion – 2015 (SpaceTech–REDDI–2015), NNH15ZOA001N released May 21, 2015.
[3] *Id.*

operational missions. This programmatic structure and focus is enabling American industry to develop and implement technologies which will improve satellite design, operation in the future, providing significant advantages over the U.S.'s competitors.

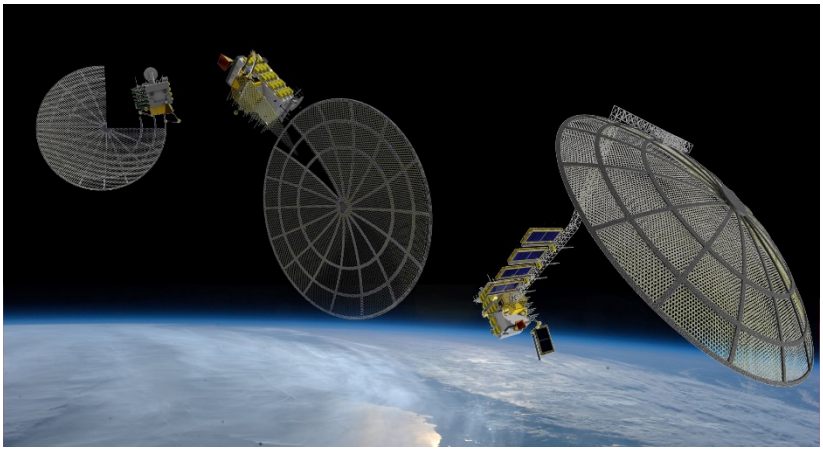

Figure 3. This artist's rendering depicts the Archinaut payload during its deployment in space. Via additive manufacturing and assembly, a large reflector is manufactured and integrated over time. Image credit: Made In Space

Under a Phase I contract begun in late 2016, Made In Space led a team including Northrop Grumman to develop its Archinaut in-space manufacturing and assembly technology (see Figure 3). During rocket launch, spacecraft are subjected to high g forces and large vibrational forces. Further, the entire spacecraft must fit within the limited volume of the launch fairing. Surviving this launch environment requires wasting mass to over engineer components to survive launch and engineering deployables which unfurl once the satellite reaches orbit, creating points of failure. Archinaut technology will enable optimization of spacecraft structures for their operational environment, rather than launch. Additionally, repair and reconfiguration of assets once they are on orbit will be possible. Further, this technology enables providing large structures at lower cost and enabling robotic manufacture and assembly of large reflectors, space stations, and other applications for civil, defense, and commercial space customers. Before operating in space, this technology was demonstrated in NASA environmental testing facilities and aboard ISS via AMF, including manufacturing space-optimized structures in space.

The Archinaut Development Program is a private-public partnership designed to develop a technological capability that is useful to both government and commercial customers. As part of its effort, the Made In Space-led team is contributing over 25% of the program cost. Made In Space believes that space technologies should be developed into products which are useful and sold to both government and commercial space customers. This expands their utilization and lowers costs for all customers.

The Future of American Industry Depends on Unrestricted Access to Space, China's Investments in the Space Sector Are Part of a Larger Space Strategy that Threatens This Access

The American space economy is expanding and innovating at a faster rate than any time since the Apollo program. Thanks to public-private partnerships such as the IRMA program and commercially oriented NASA programs like the Commercial Resupply Services program, the ISS Crew Transportation Services program, and their

predecessors, commercial activity in space has never been stronger. Investments in certain aspects of the space economy, such as orbital launch and remote sensing, have also reached record highs.

However, it is critical to note that private sector investment is not driving expansion of the utilization of space across the board. Areas crucial to maintaining America's edge, such as defense, research and development, and technology demonstration, are often too niche or too early stage for significant private sector investment. An array of government-driven efforts help develop, test, and implement new technological innovations for civil and defense space applications. Many of these efforts also emphasize commercialization of technologies as they are developed, enabling the private sector to benefit from capabilities developed for civil or defense space needs.

Despite these triumphs, space is becoming an increasingly contested environment. Mere years after Made In Space initially demonstrated the ability to 3D print in microgravity, Chinese researchers conducted a very similar experiment aboard a parabolic aircraft, duplicating the technological feats of 3D printing in microgravity.[4] Much like Made In Space and NASA first demonstrated microgravity-capable 3D printing and then progressed to developing in-space manufacturing and assembly technologies and missions, it appears that China is following up on its initial demonstrations in a similar fashion. The China Academy of Space Technology Corporation, a major Chinese aerospace contractor, has recently announced plans to develop and deploy a large scale space-based solar power station. By 2025, using in-space manufacturing and assembly, they plan to construct a megawatt space solar power station which will be utilized to beam power to ground stations in China.[5] The technologies used to construct such power stations could also be used to create next generation military and civil space assets as described herein at a pace which is potentially faster than current space technology development investments permit.

Conclusion

Made In Space has benefited enormously from a virtuous cycle of technology development and operation enabled by the Small Business Administration, NASA, and OGA's. Made In Space is grateful to all those that have helped along the way and proud to continue working with NASA and other government agencies. Over the next decade, the space economy will grow due to this support. Competitors such as China have taken note of the progress on made in space technology development. While the U.S. currently has an edge in high impact areas such as in-space manufacturing and assembly of satellites, this capability advantage is eroding. Additional investment is required and operational mission infusion should be accelerated in order to maintain America's edge

[4] See http://english.cctv.com/2016/04/20/VIDE7CXvsIir229CK0YHJkni160420.shtml detailing Chinese demonstration of 3D printing aboard parabolic flight test aircraft in April 2016. In the US, this was first successfully demonstrated by Made In Space via NASA's flight opportunities program in 2011.

[5] See https://3dprint.com/236795/chinese-scientists-building-solar-space-station-projecting-that-3d-printing-robotics-will-assist-future/

in these important areas or else risk losing the ultimate high ground of space. This represents an existential threat to the U.S., both militarily and economically, in a wide array of known, and more worryingly, unknown arenas. If ceded this advantage may never be won back.