AU/ACSC/STOOR, B/AY18

AIR COMMAND AND STAFF COLLEGE

AIR UNIVERSITY

In-Space Manufacturing: A Roadmap to the Future

by

Bradley J. Stoor, Major, USAF
Master of Science, Electrical Engineering

A Research Report Submitted to the Faculty

In Partial Fulfillment of the Graduation Requirements for the Degree of

MASTER OF OPERATIONAL ARTS AND SCIENCES

Advisor: Lt Col Peter A. Garretson

Maxwell Air Force Base, Alabama

April 2018

Disclaimer

The views expressed in this academic research paper are those of the author and do not reflect the official policy or position of the US government or the Department of Defense. In accordance with Air Force Instruction 51-303, it is not copyrighted, but is the property of the United States government.

Abstract

Manufacturing in space can produce satellites, starships, and habitats at a lower cost than launching them to space. Additionally, manufacturing of spare parts can greatly reduce the risk of human exploration of space. This paper examines the technology development path towards in-space manufacturing, and uses the uncovered trends to support recommendations on the next steps. The previous efforts include developments in in-space servicing as many of the same technologies and processes are common to in-space manufacturing. The Hubble telescope validated the utility of servicing by extending the satellite's lifespan and increasing its performance. Efforts to create a market for servicing will help generate interest in manufacturing in space. Towards manufacturing, the government is actively developing foundational technologies, such as the demonstration of a three dimensional printer on the International Space Station. Ground demonstrations show the promise in assembling large structures. Overall, there is sufficient evidence for the utility of in-space manufacturing. The government should use this to modify their acquisition policies to include serviceability and manufacturing on-orbit. This can reduce the cost and risk associated with modern satellite acquisitions, and move further down the path towards human exploration of space.

Contents

Section 1: <u>Introduction</u>

The current paradigm for using machines in space is to manufacture the machines on earth and then launch them into space. These machines include vehicles for human or robotic exploration, and satellites for communication, navigation, and data-collection. This approach takes full advantage of the advancements in precision manufacturing on earth, however, it is limited to the capabilities of the launch vehicle. The launch vehicle's payload fairing limits the machines in size, shape, and mass. The extreme vibrations of the rocket engines requires the machines to have extra structural supports and electronic redundancies. Today, machines are not built to maximize performance in the operational environment, but to survive the delivery mechanism. In other words, machines need to first survive launch rather than operate in space. This paper seeks to change this paradigm to create machines that are optimized for space, rather than launch. In doing so, this will allow the manufacturing of larger structures with lower mass at cheaper cost and greater utility. By focusing on this future, the autonomous, in-space manufacturing of machines can be just as precise as the processes used on earth. The next section provides a vision of this future with a fully-developed capability for in-space manufacturing.

1.1. A Vision of the Future: How In-Space Manufacturing Enables Human Exploration

The following is a fictional mission that describes how manufacturing can enable human's exploration of space and eventually interstellar exploration. While some of this may seem impossible with today's technology, the intent of this paper is to show the technology-development path that will turn this fictional mission into reality.

Prospector II is an autonomous manufacturing spacecraft that NASA launched from earth only five months ago towards the near-earth asteroid named 3554 Amun. Its mission is to establish a base for human occupancy in five years. Alone, *Prospector II* is not able to achieve this mission, so it will need to create more machines. These machines include diggers to core out the asteroid, processors to turn the raw material into usable material, manufacturers to convert the material into parts, and finally, assemblers to combine the parts into machines. However, all of these new machines require energy, so *Prospector II*'s first mission is to expand the available energy resources so that it can support more machines.

On its journey from earth to the asteroid belt, *Prospector II* used its time wisely to create solar arrays with the materials in its storage compartments. This will allow the creation of a handful more machines. *Prospector II* will control an iterative process of expanding the energy resources to support more machines which will allow it do more work. The ever-expanding army of specialized machines enables the exponential growth in productive work, if it is provided sufficient resources and energy. These resources come from an asteroid selected to be a space base for humans. The mining machines dig out tunnels for hallways and carve out large expanses that will become rooms. The mined material is fed into the manufacturing process to become more machines.

The asteroid selected, 3554 Amun, is one of the smaller known M-class asteroids which provides a good starting point for exploration. As an M-class asteroid, 3554 Amun's composition is made of iron, nickel, cobalt, and platinum-group metals.[1] As a concentrated, metallic source, this asteroid provides easy access to more metal than humans have mined on earth. An additional benefit to 3554 Amun is its orbit which is close to the earth which will allow easier transport back and forth from the earth. Moreover, since it is close to the sun, the solar panels will produce more energy than if located at asteroids further out in the asteroid belt. Finally, since the asteroid is not in a gravity well, such as might be found on the moon, once the army of machines is finished converting 3554 Amun, they can travel on to more asteroids where the process can repeat. However, the next mission is more ambitious and they will not just create a base, but they will manufacture an interstellar spaceship.

This army of machines is a significant strategic force and only took the investment in a small autonomous system, *Prospector II*. Self-replicating machines with sufficient resources could turn the asteroid belt into habitats, power stations, and spaceships. This would relieve the stress that human development has placed on the earth's ecosystem. This mission is not purely science fiction, as it can become reality with the focused development and investment in the requisite manufacturing and autonomous capabilities.

1.2. Turning Vision into Reality

The mission in the previous section may seem too far from reality, however, the technology may be closer than it appears. Government and commercial entities are already exploring technologies that can enable this vision. This paper explores these efforts, both in the past and current efforts, to recommend the next steps in the journey to in-space manufacturing.

Section 2 examines a close cousin to in-space manufacturing which is in-space servicing of satellites. There are many overlapping technologies and processes between the two including the handling of materials, and rendezvous and close-proximity operations. Additionally, learning how to service a satellite can expose better design methodologies such as modular designs and designing for serviceability. As such, in-space servicing is a stepping stone towards in-space manufacturing. This section first includes a study of a successful in-space servicing mission found in the National Aeronautics and Space Administration's (NASA) Hubble space telescope. Several servicing missions extended the life of the Hubble telescope past its 15-year lifespan, and provides a framework for developing autonomous servicing missions. Next is a description of the government and commercial efforts to create an economy for in-space servicing, and the missions scheduled for the near future. The final part of this section ties these efforts to in-space manufacturing and describes how a viable economy for servicing can further a push towards manufacturing.

Section 3 examines the current efforts towards in-space manufacturing. NASA's technology demonstration program has several manufacturing projects. These include the development of machines for the fabrication of parts and structures, the assembly of these parts into larger structures, and the autonomous software and hardware to manipulate material. In addition to NASA's technology demonstration program, several government and commercial entities are pursuing their own efforts towards in-space manufacturing. These include the in-space manufacturing of solar cells, systems that can recycle plastic and metal into satellites, and the deployment and manufacturing of habitats for deep space. Finally, to support the operational utility of in-space manufacturing, the last part provides a summary of how the US military is using three-dimensional printing in operational settings. This provides logistical freedom to manufacture parts on-demand. It is also a blueprint for how in-space manufacturing can better support human exploration of the solar system and beyond.

Section 4 provides a summary of the journey to date, and recommendations for the future. The US Air Force, as the lead for space acquisition for the US military, can lower the lifecycle costs of satellites by including serviceability in the requirements baseline for satellites. Second, the US Air Force should support the efforts to create standards for in-space servicing, so that they can be customers of the servicing economy, and ensure that the standards meet government requirements. Finally, US Air Force should release requests for proposals (RFP) for satellites that include in-space manufacturing which will lower launch and lifecycle costs, and increase mission performance.

Section 2: Past and Current Efforts in In-Space Servicing of Satellites

In-space servicing of satellites provides many useful skills and technologies that are applicable to in-space manufacturing. These include handling material in micro-gravity environments, proximity operations with cooperative and non-cooperative satellites, and assembling or repairing man-made machines or satellites. Therefore, further developments towards autonomous in-space servicing of satellites will help build part of the foundational technologies for in-space manufacturing.

This section will look at past in-space servicing efforts with the development and deployment of the Hubble space telescope which was the first satellite designed for in-space servicing. Second is a description of current government and commercial efforts to develop autonomous in-space servicing. Last is a summary of the benefits of in-space servicing and how investment in the technologies for in-space servicing will help the development of in-space manufacturing.

2.1. The Hubble Telescope – A Success Story for In-Space Servicing Requirements

When NASA developed the original acquisition plan for the Hubble telescope, they included in-space servicing as a key aspect of the mission. They planned for in-space servicing as a way to reduce costs over the life of the mission.[2] At the time, the space shuttle was also in development, and provided the means to service the telescope. Astronauts would access panels to replace sensors or bus components. Replacing sensors would allow the inclusion of either new means to conduct science experiments, such as expanding or shifting the observable electromagnetic spectrum, or by replacing failed sensors that were still scientifically useful. Replacing bus components, similarly, could add new capabilities or maintain the previously established baseline. NASA planned for Hubble to have a 15-year lifespan and with most satellite components failing after three to five years, the astronauts would need to perform several trips to keep Hubble functional.[3] The plans in 1979 included returning the telescope to Earth to perform a full refurbishment every five years and an in-space servicing visit at the mid-point, or about two-and-a-half years. However, the engineers were concerned about potential contamination and the additional structural stresses, so cancelled the return to earth trips in 1985, and they settled on an on-orbit servicing visit every three years to reach the 15 years of life.[4] This was a solid plan until the initial checkout of the telescope showed two critical flaws in the telescope.

Shortly after launch, the satellite checkout uncovered two critical flaws in the Hubble telescope that could have caused the loss of scientific value, however, the inclusion of the requirements for in-space servicing allowed NASA to save the Hubble mission. Space shuttle mission STS-31 deployed Hubble on 25 April 1990.[5] On 25 June 1990, engineers discovered a spherical aberration in the primary mirror that prevented clear imaging with the primary payloads.[6] Luckily, since the aberration was spherical in nature, the engineers were able to design a solution that changed the light path with additional mirrors and optics.[7] Additionally, they discovered a problem with the solar arrays that caused jitter in the imagery. As the satellite orbited the earth, it rapidly passed through day and night which impacted the temperature of the vehicle.[8] To solve this problem, the engineers designed different support structures and joints that would isolate and minimize the jitter.

These two problems, if uncorrected would have impacted the quality of collected imagery, and could have prevented scientific discovery. However, since NASA included in-space servicing as a core requirement of the Hubble mission, they were able to provide solutions that would permanently solve the issues. The spherical aberration could have been solved with post-processing, but the additional processing would decrease the resolution or quality of the image. The jitter could have been solved by decreasing the rate of imaging to allow the satellite to stabilize before imaging. This would have limited the amount of collected imagery, but still allow some collection. These solutions would allow the continuation of limited mission capabilities, but with the capability to service the satellite, and with missions already planned to do so, NASA was able to pull the first servicing mission forward in time to save the full mission capability of the telescope.

The in-space servicing missions saved the Hubble telescope's full mission capability and has extended the satellite lifespan well past the initial 15-year lifespan. All five servicing missions have used astronauts and the space shuttle. The first servicing missions occurred in early December 1993 with the primary goal of correcting the spherical aberration and solar array jitter. The Corrective Optics Space Telescope Axial Replacement (COSTAR) installed five pairs of corrective mirrors in front of the three primary payloads.[9] Additionally, the astronauts replaced the solar arrays with re-designed joints and support structures to repair the jitter, and they replaced the gyros that failed after launch.[10] In addition to repairing these items, they added new mission capability with new instruments that increased sensitivity in the ultraviolet wavelengths. This

Figure 1: The Hubble space telescope docked with the space shuttle Endeavour for the first servicing mission.

Photo from: https://www.nasa.gov/mission_pages/hubble/servicing/index.html pattern of repairing failed or end-of-life components and adding new capabilities continued into the second servicing mission.[11] The third servicing mission was interesting because it started off as a routine mission, but turned into a life-saving mission.

NASA split the third mission into two missions to return the telescope to fully mission capable. In early 1999, four of the six gyros failed and the satellite entered a dormant stage.[12] A servicing mission was on the schedule for 2000, but NASA needed to take action earlier to return the satellite to mission. So they split the third servicing mission into two, and completed the first half of the mission seven months earlier than scheduled. They repaired the gyros and other bus components in December 1999 to save the satellite.[13] Later, in 2002, they completed the planned servicing mission to add improved scientific capabilities in the ultraviolet range, and to replace the solar arrays that had degraded from radiation and space debris.[14] These missions again showed how NASA was able to extend the life of the Hubble, and save the initial development and production costs that produced the satellite and telescope body. Without servicing, the Hubble mission would have prematurely ended.

The loss of the Columbia space shuttle in 2003 almost put a halt to additional servicing missions, but it did highlight a weakness in the plan to rely on manned missions for servicing. After the Columbia shuttle had a mission failure during re-entry, NASA placed a hold on future manned missions which included the planned Hubble servicing missions. NASA's administration considered using autonomous, robotic missions, but the technology was not ready and it was deemed too risky and costly.[15] Luckily, NASA was able to correct the problems that lead to the Columbia loss and allowed the final shuttle mission to proceed in 2009.

The final mission accomplished the now routine replacement of bus and payload components, but it also accomplished the first-ever repair of two instruments. NASA designed

Hubble to provide access to remove and replace components, but they did not anticipate repairing or opening any of the payloads or bus components. During the last mission, the astronauts opened the Space Telescope Imaging Spectrograph (STIS) and Advanced Camera for Surveys (ACS). They removed failed electronic cards from the STIS and ACS and replaced them with new cards.[16] The mission was successful and the components returned to full mission capability. This scenario is an important lesson for developing an acquisition strategy with servicing requirements. The servicing requirements should be applied to the maximum extent possible. NASA designed Hubble with easy access to bus and payload components, but did not provide the tools and training for accessing the interiors of satellite components. The astronauts and engineers had to rely on the previous servicing experiences to develop procedures and tools to perform the repairs. The astronauts completed the repair mission, but with higher risk than previous servicing missions. Hubble is still providing scientific value because of the five servicing missions, and is well past the planned 15-year lifespan.[17]

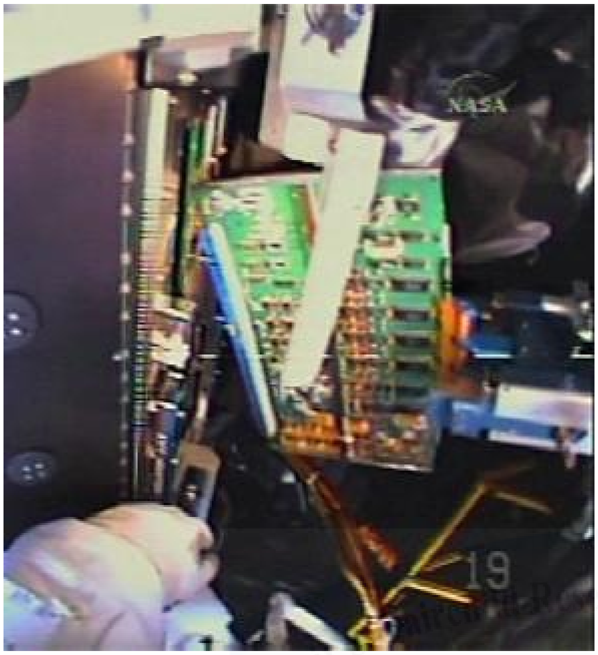

Figure 2: Astronaut John Grunsfeld removes an electronic card from the Advanced Camera for surveys.

Photo from: https://asd.gsfc.nasa.gov/archive/hubble/missions/sm4.html

The fifth servicing mission was the last planned mission, but there are two proposals from commercial companies that could further extend Hubble’s lifespan. NASA removed the space shuttle from service and, with that action, removed the ability to service Hubble. Both Sierra Nevada and SpaceX proposed servicing missions using the Dream Chaser and Dragon capsule, respectively.[18] NASA's administration is considering the missions since they would provide a hedge against continuing delays in Hubble's replacement, the James Webb telescope. Additionally, the missions would correct the orbit decay that will soon allow Hubble to enter the earth's atmosphere. NASA will need to make an assessment as to whether the cost of the servicing mission will have benefit with the limited funds that NASA receives in the federal budget. Regardless of whether NASA proceeds with another servicing mission, the Hubble experience has proven several benefits by including an in-space servicing requirement.

The Hubble mission validated the original goals of reducing costs and maximizing return on investment, and serves as an important lesson for the in-space manufacturing mission. Without in-space servicing, the Hubble mission would have been short-lived with the latent spherical aberration and solar array jitter. Component failures would have ended the mission well short of the 15-year lifespan. Additionally, the requirement for servicing should apply to the maximum extent possible to include the interior of satellite components. Interestingly, NASA did not initially include any serviceability requirements for the James Webb telescope, since the planned orbit is too far from earth at the L2 Lagrangian point.[19] However, recently, they added a docking capability for a servicing vehicle. With further enhancements in autonomous servicing vehicles, this may prove to be a prudent inclusion. The next section will examine the efforts to produce such autonomous in-space servicing vehicles that could potentially service the James Webb telescope and other satellites.

2.2. Current Efforts to Develop Autonomous In-Space Servicing Vehicles

There are several government and commercial efforts to develop the necessary technologies that will create the commercial environment for autonomous in-space servicing. First, NASA's technology transfer program provides useful technologies to the commercial environment for docking and refueling that will set standards and reduce risk for the servicing market. Second, NASA's Satellite Servicing Projects Division (SSPD) and the Defense Advanced Research Projects Agency (DARPA) have missions to demonstrate autonomous servicing in an attempt to create a commercial market. Finally, Orbital ATK's contracts with two companies for in-space servicing demonstrate the viability of the commercial servicing market, and will provide a foundation for the manufacturing market.

NASA's technology transfer program is a key element to reducing the research and development necessary to create a commercial market by providing standards and space-tested products. Two of NASA's technologies offered to commercial entities include a robotic gripper and the Cooperative Service Valve.

The robotic gripper is an essential technology for autonomous rendezvous and satellite capture.[20] As the servicing vehicle approaches the spacecraft targeted for servicing, the robotic gripper allows both vehicles to remain in contact, and provides a stable platform for the servicing satellite to operate on the target vehicle. Importantly, the gripper can autonomously grasp and control the target satellite. Once attached, the gripper is strong enough to allow the servicing satellite to perform all attitude control for both vehicles. In other words, if the target satellite's thrusters are inoperable, the servicing vehicle can stay attached and provide the forces needed for station-keeping. However, a current limitation of the

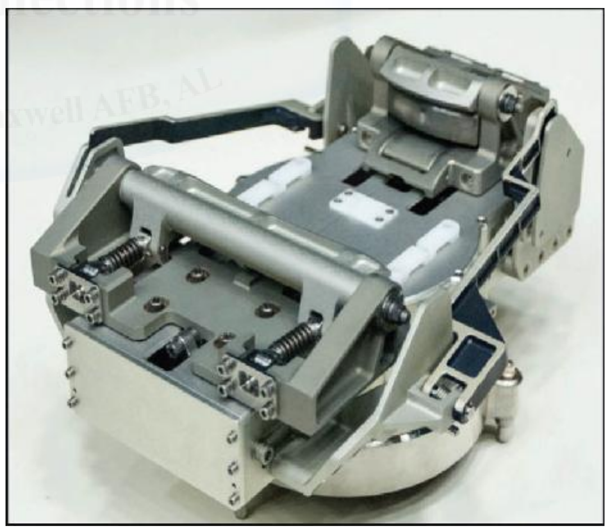

Figure 3: NASA's robotic gripper for servicing satellites.

Photo from: https://www.techbriefs.com/component/content/article/tb/techbriefs/machinery-and-automation/28726 robotic gripper is that NASA optimized the gripper to grasp the separation ring used on the Atlas V and Delta IV rockets, but it should be flexible enough to work with foreign launch vehicles. Finally, the gripper is important for manufacturing since the satellites will need the means to manipulate and move parts and materials in micro-gravity environments. This robotic gripper can help lay the groundwork for grippers on manufacturing satellites.

The Cooperative Service Valve, similar to the robotic gripper, is an essential technology for the servicing mission.[21] One life-limiting factor of many satellites is running out of fuel before the terminal failure of the payload and bus components. In other words, the satellite may be relatively healthy otherwise, but does not have enough fuel to continue the mission. Redundancy helps to maintain mission availability for the components, but fuel is a limited resource. To reduce risk, the Cooperative Service Valve provides a standard interface to fuel the spacecraft both on the ground and in space, and can be used for propellants and pressurants. This is an important technology for manufacturing because the final product will need fuel in order to function.

These two technologies are just examples of the technologies that NASA is providing to the commercial market in an attempt to create and grow the market. Standards like these will help increase the viability of the space servicing industry by saving companies the development costs that would go into developing their own solutions. As an example of the savings, land vehicles, such as cars and trucks, can refuel at any gas station, since the vehicles have standard receptacles and gas stations have standard nozzles. Additionally, standards will prevent a segregated market that Tesla created by producing vehicles that are chargeable at any charging station, but Tesla charging stations can only charge their own vehicles.[22] Standards for service valves and grippers will allow the creation of markets more akin to refueling at a gas station, rather than the segregated market of electric vehicles. This example extends to the in-space manufacturing market, since parts will need standards to ensure interoperability. Standard parts will also increase competition and produce healthy markets since the parts are producible by anyone that can meet the standards. Thus, NASA's technology transfer program is important to creating markets for in-space servicing, as well as, manufacturing. DARPA is also helping to set the standards for in-space servicing with their creation of a consortium, called CONFERS, to develop the "rules of the road" for activities such as rendezvous and proximity operations.[23] Other important government efforts are the missions to demonstrate servicing capabilities.

One such government office, NASA's SSPD, has efforts with the ultimate goal of creating a servicing economy. SSPD's mission is to manage and lead servicing missions for the government.[24] While NASA designed the Hubble telescope with servicing in mind, SSPD intends to extend servicing to satellites without servicing as part of their original designs. Also, NASA used manned-missions to service Hubble, but SSPD aims to use autonomous means in an effort to make servicing a routine effort. Importantly, SSPD does not want these efforts to only benefit the government, since SSPD wants to transfer the technology to other government and commercial stakeholders. This will help create a servicing economy and set the standards for satellite developers. Additionally, since this is an effort by the US government, it allows the United States to have the dominant role in the servicing economy. The path to the dominant role begins with SSPD's Restore-L mission.

The Restore-L mission is a robotic servicing mission that will develop tools and techniques to help spark the commercial market. The mission goals include a rendezvous with a target vehicle so that the servicing vehicle can grasp, control, and stabilize the target vehicle to service and refuel it. Before releasing the target vehicle, the servicing vehicle will relocate the

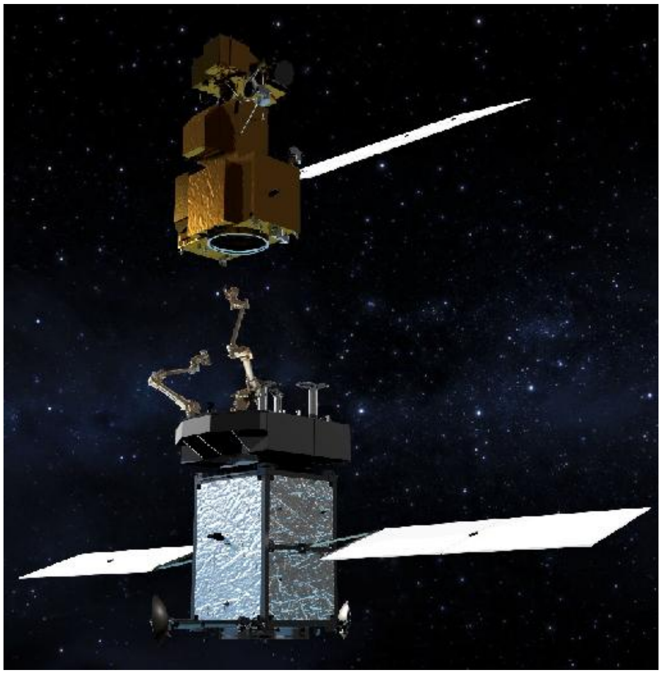

Figure 4: The arms of the Restore-L satellite reaching for a client satellite.

Photo from: https://www.nasa.gov/feature/nasa-s-restore-l-mission-to-refuel-landsat-7-demonstrate-crosscutting-technologies

target vehicle to a different orbit.[25] The mission is currently set for mid-2020 with the Landsat-7 as the target vehicle.[26] Landsat-7 is an interesting choice, because it's design did not include an capability to receive servicing, so Restore-L will have to cut open the gold-foil, protective shield to access the propellant fill line.[27] Following fueling Landsat-7, the servicing vehicle will have to patch the line. It is an ambitious mission, but a successful mission will help spark the commercial market for servicing other satellites, especially since most satellites in orbit do not have easy access to repair or replace internal components. This will help extend the life of the satellites and maximize the return on investments. Similar to how it is cheaper to repair and refuel a car rather than getting a whole new car, repairing satellites will ultimately save companies money. Companies will be eager to sign up for servicing missions if Restore-L is successful. Another demonstration that could spark investment is DARPA's efforts for in-space servicing missions.

DARPA has two programs aimed at sparking the commercial servicing markets with one program aimed at developing foundational technologies, and another for an in-space demonstration. The first program, DARPA's Front End Robotics Enabling Near-Term Demonstration (FREND), developed foundational technology for autonomous servicing.[28] In this effort, DARPA sponsored the US Naval Research Laboratory (NRL) to develop the capability to autonomously rendezvous and dock with a satellite that was not pre-designed for servicing. Additionally, FREND can use the thrusters and fuel on the servicing satellite to re-position the satellite to help with better ground coverage. If the satellite is not worth saving, FREND can help mitigate space debris by removing the malfunctioning or broken satellite from orbit. DARPA and NRL successfully demonstrated, in a ground test environment, the rendezvous and docking steps which proved the functionality of the robotics and spaceflight software. These were useful capabilities that fed into their next demonstration of an actual on-orbit servicing mission.

DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) program seeks to spark an enduring commercial market for servicing satellites.[29] Both RSGS and the previously mentioned Restore-L mission have similar projected operations of inspection, grappling, repositioning, repairing, and upgrading. However, an important difference between them is that RSGS will service a satellite in geosynchronous orbit (GEO). Failed satellites in GEO are usually left in orbit or parking orbits, since they are harder to repair than the satellites that Restore-L is aiming for in low-earth orbit (LEO). This makes the RSGS mission a great trailblazer in creating the commercial market, since the GEO satellites are an untapped market for servicing. However, a limitation, as with all government programs, is the federal budget process. Since, the differences between NASA's Restore-L and DARPA's RSGS missions may not be appreciated by lawmakers, future budgets may seek to save money on the seemingly duplicative projects by combing the programs.[30] This may delay the creation of the commercial market, but it should not prevent its formation due to the obvious demand in the market. As evidence of the demand, Orbital ATK is, thus far, one company that is continuing with commercial ventures for servicing satellites.

Orbital ATK is the only company that has commercial contracts to provide servicing of a satellite, and their success is important in the enduring success of the market. Another company, Space Systems Loral (SSL) is also active in the market, but is support by the government since they are the prime contractor for NASA's Restore-L and DARPA's RSGS missions.[31] Without government support, Orbital's effort to develop the commercial market is commendable. Orbital has contracts for two of their Mission Extension Vehicles (MEV) to service the Eutelsat 5WB satellite in 2018 and an Intelsat satellite in 2020.[32] The MEV will provide services that are similar to previously mentioned services, such as, docking, refueling, inspection, and relocating to a different orbit. An additional function is that the MEV can act as a substitute for attitude control and use the MEV's propulsion to perform the attitude control functions.[33] This is important for satellites that had catastrophic failures in their propulsion systems. Orbital hopes to expand the service offerings. Orbital's roadmap includes more agile robotics and high power solar electric propulsion capabilities. These technologies will help to support their entry into the market for in-orbit, robotic assembly of large structures. Their long-term goal is to have a fleet of servicing satellites to cover the GEO belt.[34] All of these goals align

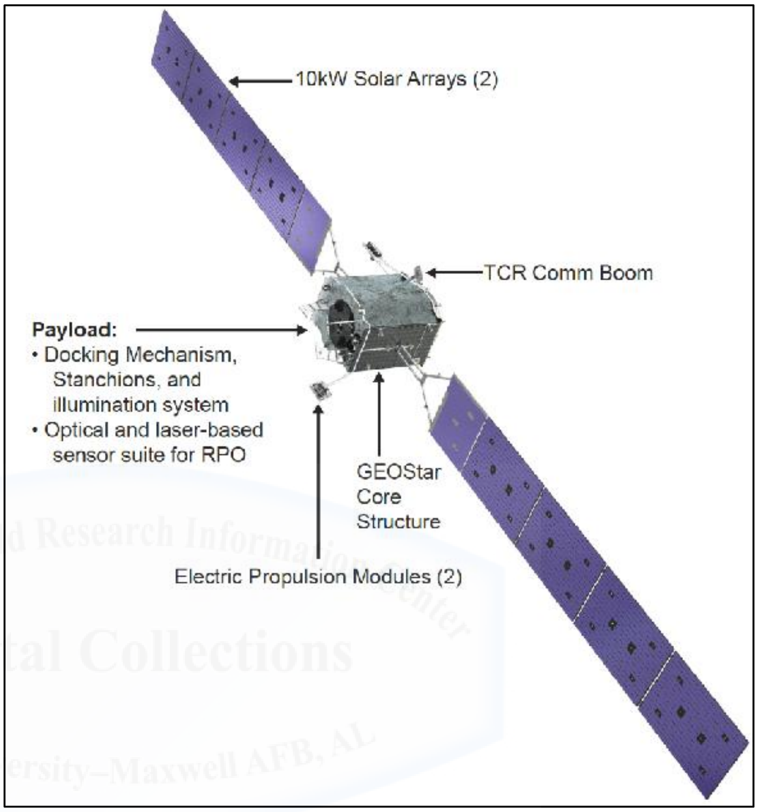

Figure 5: Orbital ATK's Mission Extension Vehicle.

Photo from: https://www.orbitalatk.com/space-systems/spacecraft-buses/docs/MEV_Rev02-17.pdf with the efforts to create a market for in-space manufacturing and assembling. In sum, Orbital's efforts to obtain contracts for servicing commercial satellites will help to create a market for in-space assembly. Both on the business side by getting customers interested in the services, and the technology side by furthering the technologies that can transfer over to manufacturing and assembling.

2.3. Summary of the Benefits of In-Space Servicing as Applied to Manufacturing

A vibrant and successful in-space servicing market will directly impact in-space manufacturing as many of the technologies needed for servicing relate to the manufacturing industry. Both will need autonomous, real-time navigation systems to reach other satellites or supply depots. Additionally, the servicing of avionics in the servicing market will help the understanding of the manufacturing of avionics in space. Furthermore, the dexterous robotic arms to grapple vehicles for servicing will also be useful in manipulating raw materials and parts to produce finished products. Finally, the in-space manufactured satellites require propellant transfer systems, which is a core technology in the servicing market.

In summary, the in-space servicing market is a stepping stone towards in-space manufacturing. Servicing will enable the future applications of on-orbit manufacturing and assembling. Many of the same techniques, tools, and procedures to handle satellites in micro-gravity are the same as handling material or parts to assemble satellites and spaceships in space.

Section 3: Current Efforts in In-Space Manufacturing

In-space, robotic manufacturing and assembly is the final step in producing a usable product, such as a satellite, space station, or spaceship. Although these items are currently produced on the ground, moving them to in-space manufacturing allows the construction of larger structures while saving the costs of designing and testing for the survival through launch.

Satellites need less structural mass to hold a satellite together once it is in orbit. Additionally, the United States was able to assemble the International Space Station (ISS) from modules manufactured on the ground, but in-space manufacturing can create larger living spaces that will improve quality of life of the astronauts. For example, to simulate gravity through centripetal force, the space station would need a diameter much larger than the structures assembled in space thus far. For these reasons, in-space manufacturing and assembling should be a goal for space production.

This section will look at in-space manufacturing and assembly in both government and commercial efforts. First, NASA has several technology development efforts with plans to take the more promising efforts further into development with possible in-space demonstrations. Second, several government and commercial entities have efforts towards in-space manufacturing including fabricating solar panels, three-dimensional (3D) printing and assembly of structures, and the deployment and fabrication of habitats. Next, to prove the utility of in-space manufacturing, a comparison to several ground-based efforts for the military shows the operational utility for future space exploration missions. Finally, space exploration requires in-space manufacturing to reduce risk and is essential for enabling human exploration.

3.1. NASA's Technology Demonstration Missions: In-Space Robotic Manufacturing

NASA's Space Technology Demonstration Mission Directorate (STMD) has a trio of technology demonstration projects that will further in-space robotic manufacturing and assembly.[35] STMD is treating them as "tipping point" projects. If these projects show that the technology is mature, then NASA will move the more promising projects on to flight demonstrations with the ultimate goal of including the technology in exploration missions. The three projects are in the following section. First is the Archinaut technology development project that is exploring additive manufacturing and 3D printing. Second is the Commercial Infrastructure for Robotic Assembly and Servicing (CIRAS) that is researching robotic manipulators and space-based assembly. Last is the Dragonfly project that is investigating self-assembling satellites that allow it to fit within the launch vehicle’s payload fairing by repositioning satellite pieces once the satellite is on orbit.

Archinaut is Made In Space, Inc.’s latest effort to explore additive manufacturing in space to reach a goal of assembling large and complex systems. Previous efforts included the Additive Manufacturing Facility (AMF) that NASA added to the ISS.[36] The AMF provided valuable information on the impacts of micro-gravity on additive manufacturing. So far, the astronauts on the ISS have manufactured parts, tools, devices, and multi-part assemblies. This is a predecessor for long-term missions, and could allow the manufacture of medical parts, and aerospace equipment. The AMF is a smaller-scale version of what Made in Space aims to achieve with Archinaut.

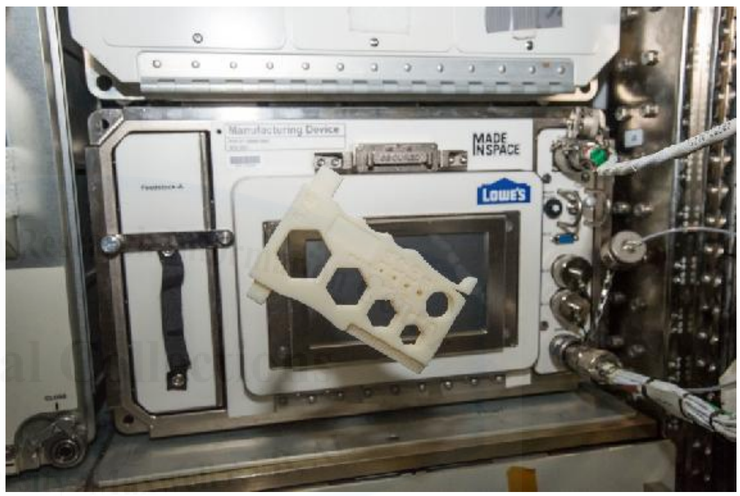

Figure 6: The Additive Manufacturing Facility printed the Future Engineers Multi-tool (in foreground) while installed in the International Space Station.

Photo from: http://madeinspace.us/projects/amf/

The initial Archinaut system will produce beams and struts using additive manufacturing. Future systems will produce and assemble the backbone structures for large telescopes, repair, augment, or repurpose existing spacecraft, and autonomously assemble new space stations.[37] Additionally, 3D printing can produce large communications dishes or the truss structure needed for solar arrays, such as for solar-power satellites that transmit their power to earth.[38] So far,

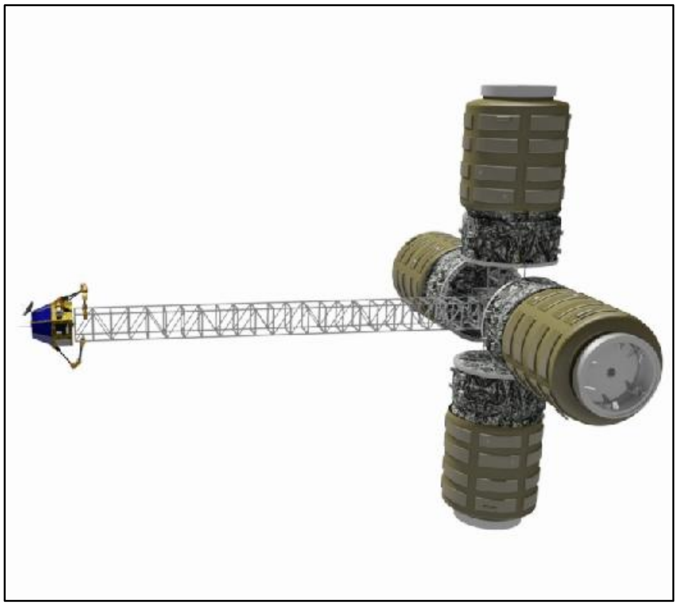

Figure 7: The Archinaut (on the left) builds a long structure that extends from a collection of modules.

Photo from: http://madeinspace.us/archinaut/

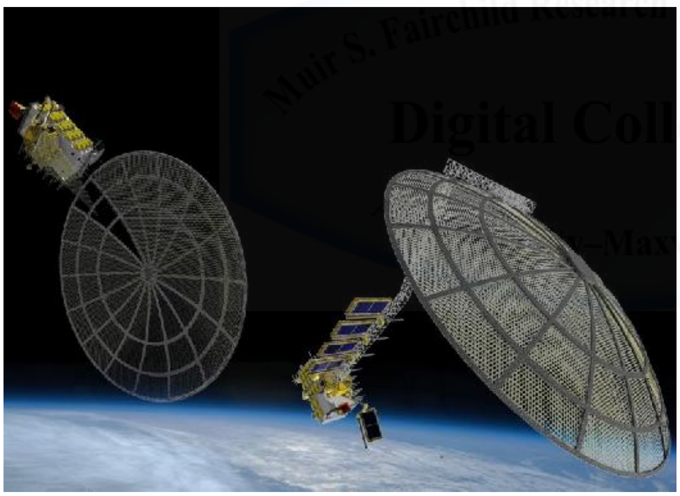

Figure 8: The Archinaut prints an antenna and the support boom for a communications satellite.

Photo from: http://madeinspace.us/archinaut/

Made In Space successfully demonstrated, using the Extended Structure Additive Manufacturing Machine (ESAMM), the printing of large beam segments in the same vacuum and temperature conditions of space.[39] Recently, Made In Space set the world's record for the longest 3D printed beam structure with an overall length of 123 feet 8.25 inches.[40] Their successes with AMF and ESAMM show the potential of their technology which may indicate that it is ready to proceed to in-space demonstrations.

The next project, CIRAS, focuses on not only producing struts, but also assembling those struts into structures.[41] The CIRAS project uses several components to produce and align structures. The NASA Intelligent Jigging and Assembly Robot (NINJAR) positions and holds the struts for alignment and welding. The Strut Assembly, Manufacturing, Utility & Robotic Aid (SAMURAI) will manufacture and pass the struts to NINJAR. With these components, CIRAS had a successful ground demonstration in July 2017 with the assembling of a square bay truss using NINJAR and CIRAS. Future versions of NINJAR will be able to assemble the struts at arbitrary angles, not just the square angles in the test. Additionally, the program will integrate the Tendon-Actuated Lightweight In-Space Manipulator (TALISMAN) robotic arm, originally intended to capture asteroids, but NASA repurposed the arm to demonstrate the installation and repositioning of solar arrays on-orbit.[42] A ground demonstration on 19 January 2018 moved the TALISMAN arm from extended to contracted, and is now ready for more comprehensive testing.[43] In sum, the CIRAS project has

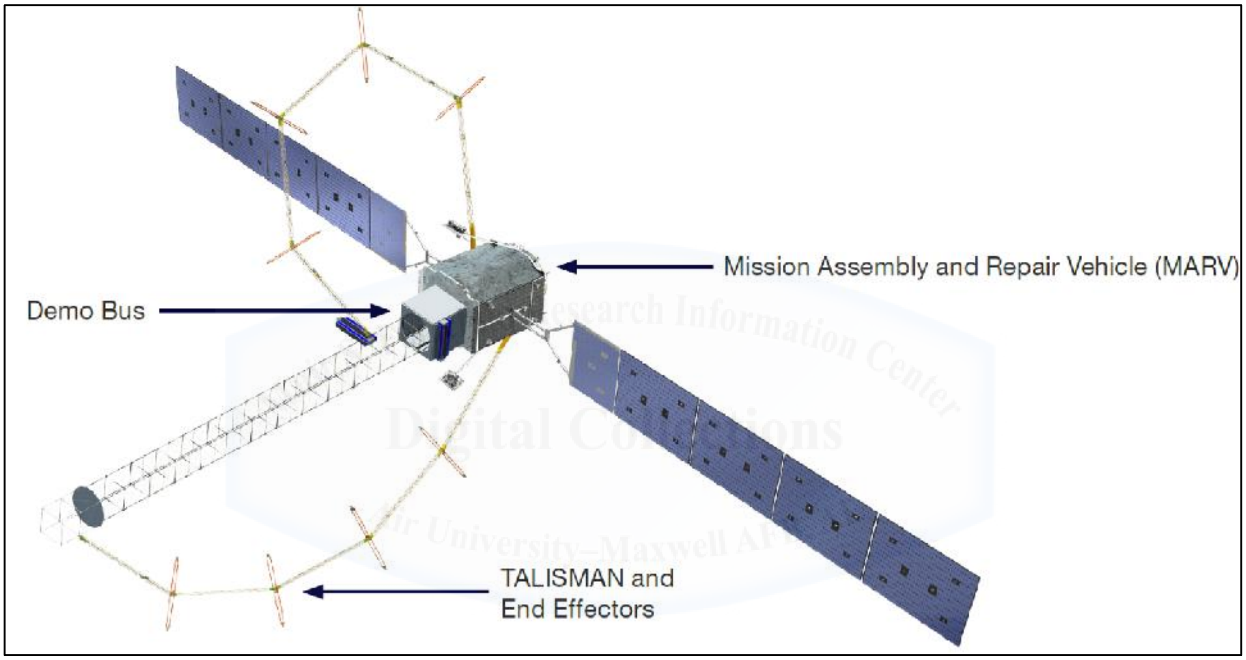

Figure 9: The CIRAS project builds a beam as the TALISMAN attaches struts at the end.

Photo from: https://www.orbitalatk.com/space-systems/human-space-advanced-systems/mission-extension-services/docs/CIRAS_Factsheet.pdf

many interesting features and important aspects for future assembling of large structures. The alignment of struts is important, but the program is not yet working on the welder to secure the joints. Additionally, reusing the TALISMAN saves some development costs, however, in the demonstration video, the arm seemed to lack dexterity which will limit its utility.[44] Future projects should integrate NINJAR's strut alignment technology with Archinaut's strut production capabilities, as these seem to be the more promising technologies.

NASA's final technology demonstration effort is SSL's Dragonfly program which focuses on on-orbit assembly using a robotic arm.[45] Dragonfly consists of a three-and-a-half meter arm that can clamp down with either end of the arm to carry and position items. The utility of the arm comes into play with large satellites or satellite configurations that do not fit well into the space of the launch vehicle's payload fairing.[46] The demonstration video shows, during the initial deployment of a satellite, the Dragonfly moving and attaching antennae near the self-deployed antennae.[47] The idea is that the antennae could not all fit when stowed since they would hit each other on deployment. By moving the antennae after launch, the satellite can be in a smaller configuration during launch. Additionally, using the Dragonfly robot can lower the mass of the satellite by requiring fewer structures or less complex structures to get the antennae into position. SSL plans to demonstrate the arm through 2018 with the goal of producing more fluid arm motions and more precise alignments.[48] Ultimately, this arm will be very useful for in-space manufacturing and assembly since it will allow the autonomous manipulation of materials and the alignment of parts. The arm seems to be more dexterous than the TALISMAN and should move on to the next development stage, if Dragonfly can reach its objectives by the end of the demonstrations.

Figure 10: The Dragonfly moves and attaches an antenna to its operational configuration.

Photo from: https://www.sslmda.com/html/robotics_servicing.php

In summary, the in-space manufacturing and assembly efforts are not as advanced as the servicing effort, but NASA's technology demonstrations should help advance the technology readiness level. Additionally, manufacturing in-space will help move the engineer's mindset from building spacecraft to survive the launch environment to spacecraft more suitable for the space environment. This will reduce the mass requirements and allow for more flexible designs. Moreover, this will remove the launch costs and risks associated with placing heavy materials and structures into space.

3.2. Other Government and Commercial Efforts for In-Space Manufacturing

NASA's technology demonstration program is not the only effort to advance the technology for in-space manufacturing. This next part will examine both government and commercial efforts for various technologies that will help develop capabilities for in-space manufacturing. The first effort is at the University of Houston where they research the production of solar cells from materials found on the lunar surface. Using automation, they have a vision of creating a large solar power facility using lunar material. The next efforts are from a company called Tethers Unlimited, which is looking at additive manufacturing. Their projects include the Refrabicator that recycles materials, the Trusselator to 3D print beams, and the SpiderFab to assemble the printed beams into structures. Last are the efforts from Bigelow Aerospace and NASA to create habitats in space. Bigelow Aerospace uses inflatable habitats, while NASA seeks to manufacture habitats. Both of these efforts will help spur investments in the cis-lunar economy.

At the University of Houston, researchers pursued the manufacturing of solar cells from materials found on the lunar surface. The moon provides all of the required elements to create silicon-based solar cells which includes silicon, iron, titanium oxide, calcium, and aluminum.[49] Additionally, the extreme vacuum of space allows for the use of vacuum evaporation to make thin film solar cells. The researchers estimate that they can theoretically produce cells with an efficiency of five to ten percent.[50] While this is well below the 30 to 40 percent achieved through earth-based production, this is still quite significant when considering the cost savings of launch. Using continuous manufacturing, automated machines could cover a significant portion of the moon with solar cells to produce enough free energy for significant human activity. The researchers successfully demonstrated the fabrication of the substrate material which is the surface on which cells are built, and the solar cells themselves, using the materials that are found in the lunar regolith.[51] In addition to fabricating solar cells, this effort is significant to show the feasibility of fabricating electronics in space. Expanding on this work can lead to methods to fabricate transistors for microprocessors and computer memory. This will help provide the computational power required for the autonomous systems.

Tethers Unlimited has several projects in-work to develop additive manufacturing for large structures using materials from mining or recycling. The first project is called the Refabricator which is an enclosed system that will recycle plastic material and produce new parts.[52] It is a payload intended for the ISS's EXPRESS-Rack system, and has a recycling system and a 3D printer. The cargo that is launched to the ISS often has plastic shipping material which the astronauts consider as waste. However, with the Refabricator, the astronauts can put the plastic shipping material into the recycler, program a model into the 3D printer, and get useable parts. This greatly increases the cost-benefit of supply missions, since the previously unusable packing material is now useable. NASA scheduled the launch on the resupply mission in April 2018, but the promise of the system has garnered interest in systems that use metal.

Tethers Unlimited has two recycling projects that use metal. The first one is similar to the Refabricator. The Metal Advanced Manufacturing Bot-Assisted Assembly system is also intended to be an EXPRESS-Rack payload on the ISS, but will take metal waste as the building

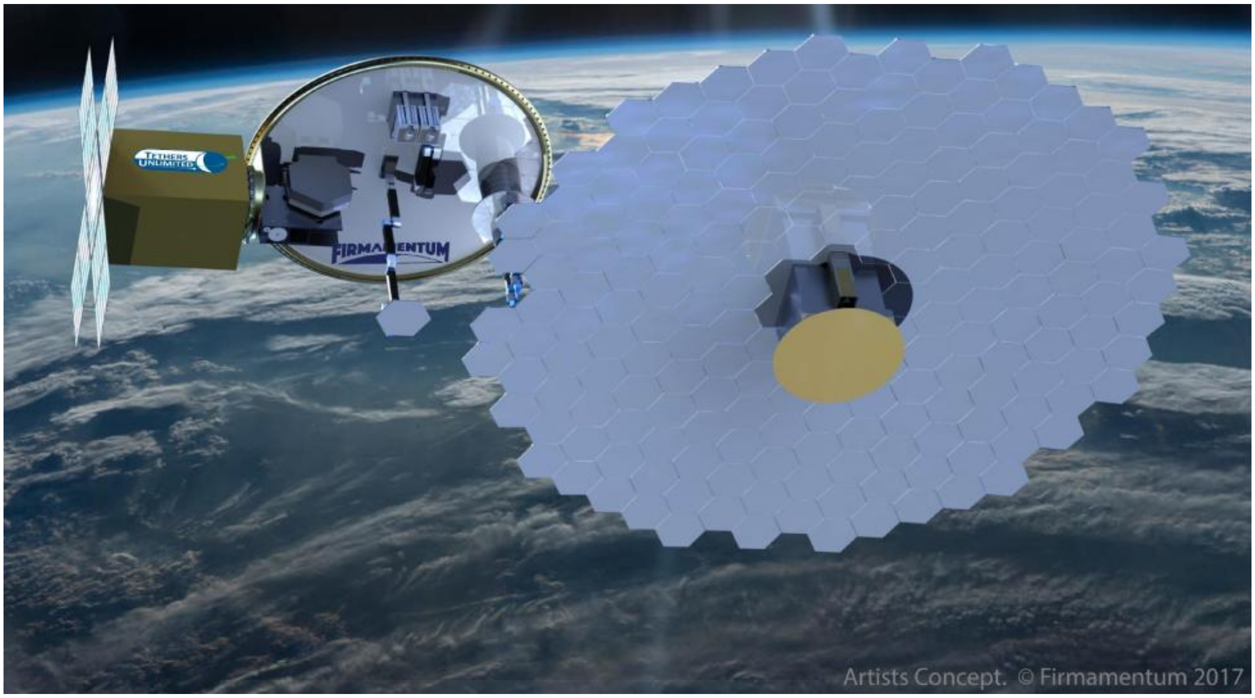

Figure 11: The OrbWeaver produces panels and assembles an antenna.

Photo from: http://www.tethers.com/SpiderFab.html

material.[53] The experience from this program will help Tethers Unlimited develop another metal-recycling program called the OrbWeaver for DARPA.[54] This is an interesting project because the OrbWeaver will launch as a secondary payload on an Evolved Expendable Launch Vehicle (EELV) launch, and once it is on-orbit, it will actually consume the launch vehicle's payload adapter ring.[55] It will convert the ring into an antenna which will be combined with a software defined radio to transmit data at up to 12 gigabits per second. If successful, this will be a huge step for in-space manufacturing. Often times, the upper stage is not reusable after launch. Unlike SpaceX's program that reuses the lower stage of the launch vehicle, the upper stage is too far into orbit and cannot safely return to earth. The OrbWeaver can now reuse the upper stage. Additionally, this increases the value of nonoperational satellites and other space debris as they are now potentially raw material to make other satellites.

In addition to the recycling programs, Tethers Unlimited is working on additive manufacturing systems, such as the Trusselator and SpiderFab, to demonstrate manufacturing large structures in space. The Trusselator can 3D print carbon-fiber struts of arbitrary length. Tethers Unlimited is working with SSL's Dragonfly program, mentioned in the previous section, to validate additive manufacturing by demonstrating on-orbit construction of communication satellites.[56] The SpiderFab integrates the Trusselator with robotic arms to assemble larger structures. In one of their studies, Tethers Unlimited looked at manufacturing in space the starshade for the New Worlds Observer (NWO), rather than launching it from earth. The NWO program uses a star shade to block the light of a star, so that the NWO telescope can gather the light from the planets near that star to see if they have earth-like characteristics. Tethers Unlimited showed that NASA could save over 50 percent of the cost of the starshade by manufacturing it in space, rather than trying to get it to fit in the launch fairing.[57] Additionally, it could improve the science-collection abilities by allowing observations two times closer to the star which could potentially increase the identification of earth-like planets by eight times.[58] This is a promising project in terms of the value for in-space manufacturing.

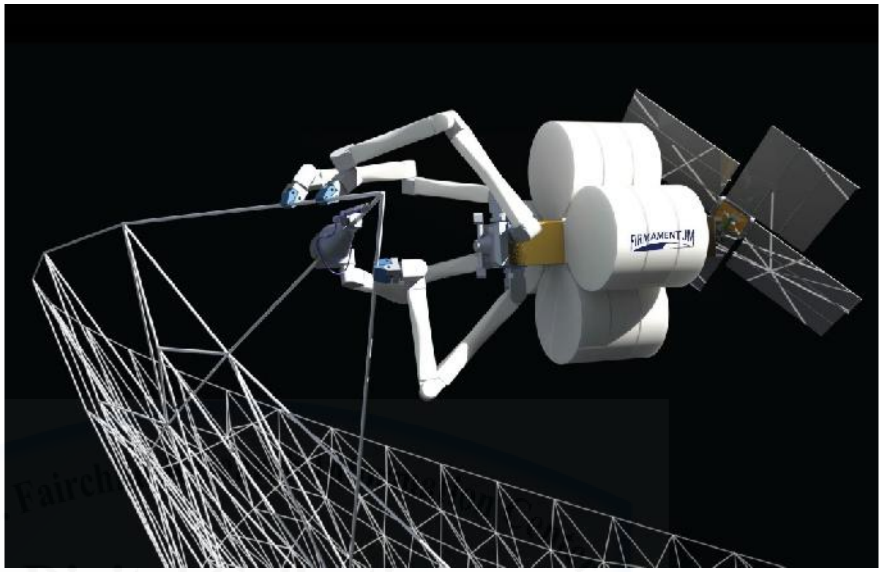

Figure 12: The SpiderFab assembles a curved structure.

Photo from http://www.tethers.com/SpiderFab.html

Tethers Unlimited, overall, has several promising technology demonstrations, but still has work to produce space-worthy systems. They demonstrated the Trusselator in a lab environment by creating the center spline that extends a row of solar panels.[59] Also, they have a demonstration

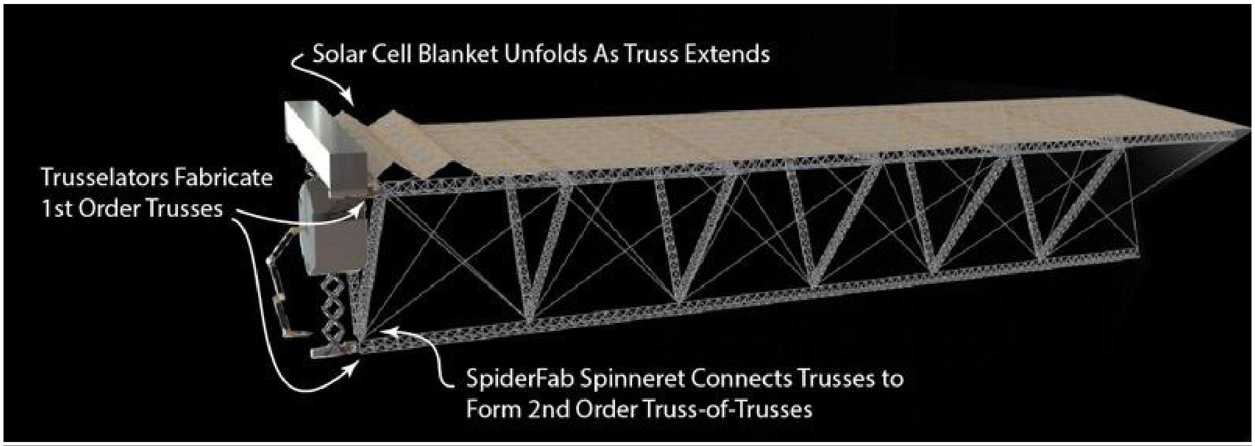

Figure 13: The Trusselator extends the solar panels by manufacturing the support beam.
Photo from: http://www.tethers.com/SpiderFab.html

of the SpiderFab manipulating and moving structures using an autonomous robot and a video feed.[60] However, as these are only lab demonstrations, there is still work to turn them into space-worthy systems. The Refabricator, as a payload on the ISS, should provide insight into manufacturing the struts in micro-gravity environments, but they will still need to research the assembly of these struts using the SpiderFab in the same micro-gravity environment. Tethers Unlimited is on a promising path, and just needs some more time and a steady funding stream to develop the operational systems.

The last area examined is the efforts of Bigelow Aerospace and NASA to create and manufacture habitats in space. Bigelow Aerospace is working towards creating habitats both in-orbit and on the lunar surface. Rather than manufacturing the habitat in space, they are looking at

Figure 14: The Bigelow Expandable Activity Module attached to the International Space Station.
Photo from: https://www.nasa.gov/feature/nasa-extends-beam-s-time-on-the-international-space-station

inflatable habitats. By using inflation, they are able to reduce the size to fit a larger habitat in the payload fairing while avoiding the risk of production in space. They successfully demonstrated their Bigelow Expandable Activity Module (BEAM) with an installation and deployment on to the ISS.[61] The demonstration has been so successful that NASA extended the contract for another three years.[62] The BEAM has shown that soft, expandable materials are just as resistant to space debris as more rigid modules. To further demonstrate the BEAM technology, Bigelow Aerospace has plans with United Launch Alliance (ULA) to place two of the 330-cubic-foot modules into low-lunar orbit.[63] In a step further, they have a concept, but nothing so far concrete, to install three of the modules on the moon's surface.[64] While these projects are only using inflatable habitats, Bigelow's efforts will help to drive the market by pulling interest into the cis-lunar environment. As a stepping stone, inflatable habitats will encourage further development, and show the promise of doing more in space than so far achieved.

Figure 15: Three inflatable habitats form a moon base.

Photo from: https://www.nextbigfuture.com/2017/02/big-permanent-moonbase-by-2021-using.html

NASA's competitions for 3D printed habitats also helps to create a demand for space habitats. The first phase of the habitat challenge, completed in 2015, was only conceptual with architectural drawings of possible habitats.[65] The second phase, completed in 2017, focused on the actual production of structurally sound habitats. The competitors had to 3D print beams, cylinders, and domes that NASA tested through compression until failure.[66] The competition helped to push the boundaries of sustainable habitats with potential use on earth or in deep space.

NASA recently started the third phase of the competition with registration due in February 2018.[67] This phase will produce scale models using only locally-sourced materials for the 3D printers. The results of this competition will provide a strong indication of the feasibility of manufacturing habitats from asteroids or on the lunar surface. However, like the Tethers Unlimited efforts, the competitors will have more work ahead of them to take the processes that they use in a laboratory environment to convert them into space-worthy systems.

3.3. The Operational Utility of 3D Printing

The recent boom in consumer 3D printing has influenced how military technicians think about repairs and logistics. The military experimented with integrating 3D printing into their operations and logistics. This example, as applied to space exploration missions, shows how astronauts might incorporate 3D printing. This section examines how the US Army and Navy experimented with 3D printing and some of the challenges that might apply to space exploration.

The Army and Navy have looked at a wide range of possible applications for 3D printing. First, the Army set up mobile printing laboratories in Afghanistan.[68] In these laboratories, they printed parts to repair ground vehicles and aircraft. Future efforts include 3D printing of electronics, such as printing helmets with antennae or UAV wings with sensors. It is easier to print the parts and electronics at the same time than it is to etch out the material to add the electronics after the fact. Next, the Navy tested 3D printers on the USS Essex, which is an amphibious assault ship.[69] Their tests included producing disposable medical supplies such as plastic syringes, oil tank caps, and model planes. They conducted the tests while the ship was in dry dock, so operational tests will need to identify any impacts from engine vibrations or ship movements. These effects could impact the quality of the parts by displacing the print head which might ruin the part.

Additional limitations to operational 3D printing include the inability to print flight qualified parts, since the consumer-level printers cannot match the strength of machined or cast parts. With calibrated machines in a controlled environment, General Electric printed high-temperature jet engine valves and Lockheed Martin printed 10-foot long parts for the F-35.[70] The harsher environments and conditions of the operational environment requires additional printer development to achieve the same level of quality found in controlled environments.

In order to meet this operational demand, Made In Space developed the Tactical 3D Printer (TAC 3D).[71] Since the TAC 3D does not require a clean environment, it can work in a variety of harsh environments such as ocean platforms, submersibles, arid deserts, remote mountains, arctic research stations, and mobile ground vehicles.[72] It can even use a variety of materials ranging from aerospace grade polymers to composites. Including a capability like the TAC 3D in military units would help alleviate some of the challenges associated with logistics, and create a more effective combat force. Military units could make field repairs without having to wait for supplies to arrive.

Similarly, space exploration benefits from the ability to print-on-demand space-qualified parts. Rather than bringing a full complement of spare parts, astronauts could print any parts they needed for repairs. If they are on Mars, for example, it could take several months to years to get a spare part which could be catastrophic if the failed part is in a life support system. Just as the military found benefit in removing supply chain dependencies to print their own parts, space exploration has the same benefit. If the intention is to reach other planets, the astronauts must able to manufacture parts and systems from local materials. Space exploration should seek to be independent of earth's resources. The next section further explores this concept.

3.4. In-Space Manufacturing and Assembly: Building a Future of Space Exploration

The construction of large structures requires the capability to manufacture and assemble in-space. The counterargument to this claim is that SpaceX is reducing the cost of launch so that it remains cost effective to launch all material, parts, and systems. However, even to build the ISS, NASA required multiple launches over decades to get all of the modules into orbit. Once in orbit, astronauts positioned and attached the modules into their final locations. Pursuing autonomous manufacturing and assembling will reduce the costs associated with assembling the large structures since the manned-missions are much more costly. Even if the material is launched into space rather than manufactured in space, autonomous assembly will be a large cost savings.

Additionally, there are benefits to in-space manufacturing and assembly that apply to exploration and colonization missions. NASA and SpaceX are pursuing missions to Mars. In these pursuits, they have options on how to create habitats for survival. They can either send the habitats with the astronauts at an increased cost. Or they can send manufacturing robots that can turn the Martian materials into habitats. The robotic missions will provide an enduring capability that can expand the colony as more astronauts arrive. Another benefit to developing in-space manufacturing is with repairing the habitats and space vehicles. If a part on the habitat's life support system or on the transport vehicles breaks, the astronauts will have to use spare parts if they cannot produce their own spare parts. They can only use a spare part if they brought a spare part for the particular system that broke. In this manner, they would need fully redundant systems, since every part could potentially break, and the lack of the spare part could result in catastrophic mission failure. Manufacturing provides more options for repairs and helps to reduce risks. The astronauts will feel much safer knowing that they can produce spare parts for anything that breaks, rather than waiting on NASA or SpaceX to send replacement parts. Due to the varying distances between Mars and Earth as they orbit the sun, the parts could arrive well past the need date and jeopardize the mission.

However, in-space manufacturing and assembly is only one part of the equation. Investment and development in the capabilities to identify and turn raw materials into useable material is still required. In this area, NASA has a proposed a mission to redirect an asteroid to the moon. In this mission, NASA plans to select one of the near-earth asteroids, autonomously collect a multi-ton sample from the surface, and send it to an orbit around the moon.[73] In order to do this, NASA used remote sensing instruments to identify the materials in candidate asteroids which allowed them to identify four possible candidates. If NASA receives the funding to complete this mission, they will be able to demonstrate remotely identifying resource-rich asteroids, excavating and collecting material for processing, and operating in micro-gravity environments.[74] All of these are key enablers to the in-space manufacturing efforts, since, lacking these capabilities, useable materials will still need to be launched into space before processing can occur. With an expectation of autonomous manufacturing and assembly, the robotic machines will need organic capabilities to identify the composition of the raw materials before attempting to process and turn it useable materials.

Section 4: Summary and Recommendations

A journey of a thousand miles starts with a single step. In-space manufacturing is at the end of a long journey of technology development and investment, and can only occur through the initial steps described in this paper. One of the first steps, the Hubble telescope provided an example of in-space servicing and the manipulation of satellites. While astronauts performed the servicing missions, it did show that designing satellites for servicing can extend the life of satellites and maximize the return on the investment in the satellite structures and mirrors. NASA, DARPA, and commercial entities currently have efforts to create an in-space servicing economy. In creating this economy, they will further the technology for manufacturing with developments in autonomous rendezvous, material handling in micro-gravity environments, and in-space assembly through the replacement of inoperable components.

The second step in the journey include the initial developments in manufacturing. NASA is taking a lead with their technology development projects to demonstrate producing struts, and assembling them into larger structures. These projects help to support innovative projects that recycle materials into usable parts. As NASA looks to return to the moon or send humans to Mars, manufacturing will greatly reduce risk as seen in the integration of 3D printing with the military's logistical supply chain. Operational printing removes the dependency on supply chains which is a critical enabler for human exploration of space.

The steps into the future should include the continuation of these efforts to fully develop space-qualified systems. To further increase the likelihood of success, the following recommendations will increase the military's support for in-space manufacturing while reducing their acquisition costs.

4.1. Recommendations

1. Add serviceability requirements to future acquisition baselines. Recently, space acquisition has received criticism for the high costs and lengthy timelines that make it hard to rapidly provide capabilities. By borrowing from Hubble's success, including requirements to design for servicing will maximize the investment in the initial costs for the satellite structures and other components. If the satellite has a modular design, accessible panels that are hinged, and standard fasteners and refueling ports, then this will reduce the risk of servicing missions and

allow for the installation of new capabilities. Rather than having to acquire a whole new satellite to rapidly provide capabilities, servicing missions can augment the capabilities of existing satellites.

2. Support the efforts to create standards for in-space servicing and incorporate the recommendations into acquisition baselines. As mentioned earlier, CONFERS is a standards board seeking to establish the norms and standards for in-space servicing. The full participation of the government will ensure that the standards will fully meet the needs of the providers and the receivers. Without the government's support early in the process, future satellite acquisitions will unlikely include the standards. As an example of the benefits, a standard refueling port will ensure that satellites do not meet the fate of the Kepler satellite. Kepler is a fully functioning satellite, but its mission will end within the next several months, once its fuel runs out.[75] Additionally, spacecraft are more resilient with more fuel. If an adversary launches an anti-satellite missile at a friendly satellite, one possible course of action is to maneuver out of the way. However, in doing so, it may expend a majority of its fuel. With the ability to refuel, the satellite would not only survive the attack, but can continue fully operational.

3. Consider allowing in-space manufacturing for new satellite proposals. Often, satellite program offices are too comfortable with the existing spacecraft design, and any follow-on acquisitions have the same design with similar performance at a slighter higher cost. In order to unlock innovation, program offices need to research the risks associated with in-space manufacturing to assess proposals with these innovative approaches. For example, manufacturing struts that hold antennae could significantly increase the separation distance and, thus, increase geolocation accuracy. The launch vehicle influences the satellite design, and allowing for in-space manufacturing will reduce its influence.

End Notes

1. Dennis Wingo, "Asteroidal Resources and the Cis-Lunar Industrial Economy," in *Return to the Moon*, ed. Rick Tumlinson and Erin Medlicott (Ontario, Canada: Apogee Books, 2005), 170.

2. NASA, "NASA Facts: Servicing History and Long-Term Plans", NASA Goddard Space Flight Center, June 1993, 1-2, https://asd.gsfc.nasa.gov/archive/hubble/a_pdf/news/facts/ServicingHistory.pdf.

3. Ibid.

4. Ibid.

5. NASA, "The Hubble Space Telescope: Servicing Mission 1," NASA: Goddard Space Flight Center, https://asd.gsfc.nasa.gov/archive/hubble/missions/sm1.html.

6. NASA, "NASA Facts: Servicing History and Long-Term Plans", NASA Goddard Space Flight Center, June 1993, 1-2, https://asd.gsfc.nasa.gov/archive/hubble/a_pdf/news/facts/ServicingHistory.pdf.

7. Ibid.

8. Ibid.

9. NASA, "The Hubble Space Telescope: Servicing Mission 1," NASA: Goddard Space Flight Center, https://asd.gsfc.nasa.gov/archive/hubble/missions/sm1.html.

10. NASA, "The Hubble Space Telescope: Servicing Mission 1," NASA: Goddard Space Flight Center, https://asd.gsfc.nasa.gov/archive/hubble/missions/sm1.html; NASA, "NASA Facts: Servicing History and Long-Term Plans", NASA Goddard Space Flight Center, June 1993, 1-2, https://asd.gsfc.nasa.gov/archive/hubble/a_pdf/news/facts/ServicingHistory.pdf.

11. NASA, "The Hubble Space Telescope: Servicing Mission 2," NASA: Goddard Space Flight Center, https://asd.gsfc.nasa.gov/archive/hubble/missions/sm2.html.

12. NASA, "The Hubble Space Telescope: Servicing Mission 3A," NASA: Goddard Space Flight Center, https://asd.gsfc.nasa.gov/archive/hubble/missions/sm3A.html.

13. Ibid.

14. NASA, "The Hubble Space Telescope: Servicing Mission 3B," NASA: Goddard Space Flight Center, https://asd.gsfc.nasa.gov/archive/hubble/missions/sm3B.html.

15. Gabriel Okoski, "Chronology of the Hubble Space Telescope," NASA, 18 April 2008, https://history.nasa.gov/hubble/chron.html.

16. NASA, "The Hubble Space Telescope: Servicing Mission 4," NASA: Goddard Space Flight Center, https://asd.gsfc.nasa.gov/archive/hubble/missions/sm4.html.

17. Neill Reid, "This Week on Hubble Space Telescope (HST)," 1 March 2018, http://www.stsci.edu/~inr/thisweek1/thisweekonhst.html.

18. Jay Bennet, "A New Spaceship Could Fly Astronauts to the Hubble Space Telescope for Repairs," *Popular Mechanics*, 14 February 2017, https://www.popularmechanics.com/space/telescopes/a25211/mission-to-service-hubble-space-telescope/; Donald F. Robertson, "A Not-so-final Servicing Mission," Space News, 21 April 2015, http://spacenews.com/op-ed-a-not-so-final-servicing-mission/.

19. Brian Berger, "NASA Adds Docking Capability For Next Space Observatory," Space.com, 23 May 2007, https://www.space.com/3833-nasa-adds-docking-capability-space-observatory.html.

20. NASA Technology Transfer Program, "Robotic Gripper for Satellite Capture and Servicing," NASA: Goddard Space Flight Center, https://technology.nasa.gov/patent/GSC-TOPS-190.

21. NASA Technology Transfer Program, "Cooperative Service Valve for In-orbit Cooperative Satellite Fueling," NASA: Goddard Space Flight Center, https://technology.nasa.gov/patent/GSC-TOPS-170.

22. EV Connect, “Can A Tesla Charge at a Standard Electric Vehicle Charging Station?,” EV Connect: Charging Forward, 28 June 2017, https://www.evconnect.com/blog/can-tesla-charge-standard-electric-vehicle-charging-station/.

23. Sandra Erwin, “On-orbit satellite servicing: The next big thing in space?,” Space News, 17 November 2017, http://spacenews.com/on-orbit-satellite-servicing-the-next-big-thing-in-space/.

24. NASA: Satellite Servicing Projects Division, "About SSPD," NASA: Goddard Space Flight Center, https://sspd.gsfc.nasa.gov/about.html.

25. Adrienne Alessandro, "NASA's Restore-L Mission to Refuel Landsat 7, Demonstrate Crosscutting Technologies," NASA: Goddard Space Flight Center, 6 Aug 2017, https://www.nasa.gov/feature/nasa-s-restore-l-mission-to-refuel-landsat-7-demonstrate-crosscutting-technologies.

26. NASA: Satellite Servicing Projects Division, "Retore-L: Robotic Servicing Mission," NASA: Goddard Space Center, https://sspd.gsfc.nasa.gov/restore-L.html.

27. Frank Morring Jr.,"NASA Plans Satellite-servicing Spinoff To Industry," Aviation Week & Space Technology, 16 May 2016, Academic Search Premier, EBSCOhost (accessed 5 January 2018).

28. B.E. Kelm, J.A. Angielski, S.T. Butcher, N.G. Creamer, K.A. Harris, C.G. Henshaw, J.A. Lennon, W.E. Purdy, F.A. Tasker, W.S. Vincent, and B.P. Whalen, "FREND: Pushing the Envelope of Space Robotics," *2008 NRL Review*, 2009, 239, https://www.nrl.navy.mil/content_images/2008_NRL_Review.revised.pdf.

29. John Keller, "DARPA RSGS program eyes space robot to maintain geosynchronous satellites," *Military & Aerospace Electronics* 27, no. 6 (June 2016): 4, Academic Search Premier, EBSCOhost (accessed 5 January 2018).

30. Frank Morring Jr., “Trump May Be Privatizing Public Space Technology,” Aviation Week & Space Technology, 5 June 2017, Academic Search Premier, EBSCOhost (5 January 2018).

31. Caleb Henry, “NASA’s Restore-L contract nudges SSL closer to in-orbit servicing,” SpaceNews, 6 December 2016, http://spacenews.com/nasas-restore-l-contract-nudges-ssl-closer-to-in-orbit-servicing/; Cliff Drubin, "DARPA Selects SSL for Revolutionary Goal of Servicing Satellites in GEO," *Microwave Journal* 60, no. 4 (April 2017): 47. Academic Search Premier, EBSCOhost (accessed 5 January 2018).

32. Orbital ATK, "Orbital ATK On Track to Launch Industry's First Commercial In-Space Satellite Servicing System in 2018," Orbital ATK News Release, https://www.orbitalatk.com/news-room/feature-stories/MEV/default.aspx?prid=92; Doug Messier, "Orbital ATK Receives Order for Second In-Orbit Satellite Servicing Vehicle," *Parabolic Arc*, 5 January 2018, http://www.parabolicarc.com/2018/01/05/orbital-atk-receives-order-inorbit-satellite-servicing-vehicle/.

33. Orbital ATK, "Orbital ATK On Track to Launch Industry's First Commercial In-Space Satellite Servicing System in 2018," Orbital ATK News Release, https://www.orbitalatk.com/news-room/feature-stories/MEV/default.aspx?prid=92.

34. Ibid.

35. Jennifer Harbaugh, "Technology Demonstration Missions: In-space Robotic Manufacturing and Assembly (IRMA)," NASA, https://www.nasa.gov/mission_pages/tdm/irma/index.html.

36. Made in Space, "Additive Manufacturing Facility: Unprecedented Access to the ISS National Lab for Iterative Design," Made in Space, http://madeinspace.us/projects/amf/.

37. Made in Space, "Archinaut: Large Structure on Demand Manufacturing Capability Available on Orbit for Existing or New Spacecraft and Satellites," Made in Space, http://madeinspace.us/archinaut.

38. Shannon Ridinger, "The Geometry of Success: Archinaut Project Conducts First Large-Scale Additive Manufacturing Build in Space-Like Environment," NASA news release, 10 August 2017, https://www.nasa.gov/mission_pages/tdm/irma/the-geometry-of-success-archinaut-project-conducts-first-large-scale-additive-manufacturing.html.

39. Ibid.

40. Mike Wall, “Made In Space Sets Guinness World Record For Longest 3D-Printed Piece,” Space.com, 22 February 2018, https://www.space.com/39790-made-in-space-3d-printing-guinness-world-records.html.

41. Lee Mohon, "Orbital ATK Supports Ground Testing on CIRAS at NASA's Langley Research Center," NASA, 30 August 2017, https://www.nasa.gov/mission_pages/tdm/irma/orbital-atk-supports-ground-testing-on-ciras-at-nasa-s-langley-research-center.html.

42. Ibid.
43. Kristyn Damadeo, "Robotic Arm Gets a Workout," NASA: Langley Research Center, 6 February 2018, https://www.nasa.gov/feature/langley/robotic-arm-gets-a-workout.
44. Ibid.
45. Shannon Ridinger, "NASA's Dragonfly Project Demonstrates Robotic Satellite Assembly Critical to Future Space Infrastructure Development, " NASA: Marshall Space Flight Center, 13 September 2017, https://www.nasa.gov/mission_pages/tdm/irma/nasas-dragonfly-project-demonstrates-robotic-satellite-assembly-critical-to-future-space.html.
46. Space Systems/Loral, "Robotics and Servicing," SSL, https://www.sslmda.com/html/robotics_servicing.php.
47. Space Systems/Loral, "Dragonfly: Robotic On-Orbit Satellite Assembly," video on Youtube.com, https://www.youtube.com/watch?v=u_gYhG4L4QU.
48. Shannon Ridinger, "NASA's Dragonfly Project Demonstrates Robotic Satellite Assembly Critical to Future Space Infrastructure Development, " NASA: Marshall Space Flight Center, 13 September 2017, https://www.nasa.gov/mission_pages/tdm/irma/nasas-dragonfly-project-demonstrates-robotic-satellite-assembly-critical-to-future-space.html.
49. A. Ignatiev et al., "New Architecture for Space Solar Power Systems: Fabrication of Silicon Solar Cells Using In-Situ Resources," NIAC annual meeting presentation, 6 June 2000, http://www.niac.usra.edu/files/library/meetings/annual/jun00/433Ignatiev.pdf
50. Alex Ignatiev, "Space Materials Science," University of Houston's Center for Advanced Materials, http://www.cam.uh.edu/projects/space-materials.
51. C. Horton et al., "First demonstration of photovoltaic diodes on lunar regolith-based substrate," *Acta Astronautica* 56, no. 5 (March 2005): 537-545; Alexandre Freundlich et al., “Manufacture of Solar Cells on the Moon”, IEEE Photovoltiaic Specialists Conf, 2005, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050110155.pdf.
52. Robert Hoyt, "Refabricator: A Recycling and Manufacturing System for the International Space Station," Tethers Unlimited, http://www.tethers.com/Refabricator.html.
53. "Shifting our Manufacturing Off-World: TUI/Firmamentum Lands 4 NASA Contracts to Develop Orbital Manufacturing and Construction Technologies," Tethers Unlimited press release, 20 April 2017, http://www.tethers.com/PR/NASA_SBIR_P1s_2017_PressRelease.pdf.
54. Debra Werner, "Tethers Unlimited expands to fulfill additive manufacturing orders," Space News, 8 December 2017, http://spacenews.com/tethers-unlimited-expands-to-fulfill-additive-manufacturing-orders/.
55. Dr. Rob Hoyt, "TUI/Firmamentum Lands DARPA Contract to Pursue In-Space Manufacturing of a High-Throughput SATCOM Satellite," Tethers Unlimited news release, 12 June 2017, http://www.tethers.com/PR/OrbWeaver_PressRelease_APPROVED.pdf.
56. "Firmamentum Signs Contract with SSL for In-Space Manufacturing Demo," Tethers Unlimited press release, 26 September 2016, http://www.tethers.com/PR/Dragonfly_PhI_PressRelease.pdf.
57. Dr. Rob Hoyt et al., "SpiderFab: Process for Construction of Kilometer-Scale Apertures," NIAC presentation, 3-6, http://www.tethers.com/papers/SpiderFab_SpringNIAC_v6.pdf.
58. Ibid.
59. Tethers Unlimited, *Trusselator Demo*, YouTube video, 1 min., 25 November 2013, https://www.youtube.com/watch?v=3pYWuypTBOc.
60. Tethers Unlimited, *SpiderFab Demo Video*, YouTube video, 3 min., 10 January 2017, https://www.youtube.com/watch?v=Wg6msu6OUNc.
61. Mark Garcia, "NASA Extends Expandable Habitat's Time on the International Space Station," NASA, 4 December 2017, https://www.nasa.gov/feature/nasa-extends-beam-s-time-on-the-international-space-station.
62. Ibid.

63. "Bigelow Aerospace and United Launch Alliance announce Agreement to Place a B330 Habitat in Low Lunar Orbit," United Launch Alliance press release, 17 October 2017, https://www.ulalaunch.com/about/news/2017/10/17/bigelow-aerospace-and-united-launch-alliance-announce-agreement-to-place-a-b330-habitat-in-low-lunar-orbit.

64. Brian Wang, "Big permanent moonbase by 2021 using SpaceX and Bigelow has been the obvious non-corrupt choice for years," Next Big Future, 26 February 2017, https://www.nextbigfuture.com/2017/02/big-permanent-moonbase-by-2021-using.html.

65. Molly Porter, “NASA Opens $2 Million Third Phase of 3D-Printed Habitat Competition,” NASA Marshall Space Flight Center, 8 November 2017, https://www.nasa.gov/directorates/spacetech/centennial_challenges/3DPHab/nasa-opens-2M-third-phase-of-3d-printed-habitat-competition.

66. Gina Anderson, “NASA Awards $400,000 to Top Teams at Second Phase of 3D-Printing Competition,” NASA Marshall Space Flight Center, 29 August 2017, https://www.nasa.gov/press-release/nasa-awards-400000-to-top-teams-at-second-phase-of-3d-printing-competition.

67. Molly Porter, “NASA Opens $2 Million Third Phase of 3D-Printed Habitat Competition,” NASA Marshall Space Flight Center, 8 November 2017, https://www.nasa.gov/directorates/spacetech/centennial_challenges/3DPHab/nasa-opens-2M-third-phase-of-3d-printed-habitat-competition.

68. Kevin McCaney, "Army Taking 3D Electronic Printing to the Next Level," Defense Systems, 3 December 2013, https://defensesystems.com/articles/2013/12/03/army-3d-electronics-printing.aspx.

69. Sydney J. Freedberg, Jr., "Navy Warship Is Taking 3D Printer to Sea; Don't Expect A Revolution," *Breaking Defense*, 22 April 2014, https://breakingdefense.com/2014/04/navy-carrier-is-taking-3d-printer-to-sea-dont-expect-a-revolution/.

70. Ibid.

71. Made In Space, "TAC 3D: The World's Most Rugged Additive Manufacturing System," Made In Space, http://madeinspace.us/tac3d/.

72. Ibid.

73. Jim Wilson, "What is NASA's Asteroid Redirect Mission?," NASA, 3 August 2017, https://www.nasa.gov/content/what-is-nasa-s-asteroid-redirect-mission.

74. Small Bodies Assessment Group, "ARM Connections to the Priority Small Body Science and Exploration Goals," Universities Space Research Association, 26 September 2016, https://www.lpi.usra.edu/sbag/documents/ARM-SAT-2016-09-26.pdf.

75. Elizabeth Howell, “NASA’s Prolific Planet-Hunting Kepler Spacecraft is Running Out of Fuel,” Space.com, 16 March 2018, https://www.space.com/40008-kepler-planet-hunter-running-out-of-fuel.html.