ADDITIVE MANUFACTURE OF PROPULSION SYSTEMS IN LOW EARTH ORBIT

Kristen C. Castonguay, Major, USAF

WRIGHT FLYER PAPERS

Please send inquiries or comments to
Editor
The Wright Flyer Papers
Department of Research and Publications (ACSC/DER)
Air Command and Staff College
225 Chennault Circle, Bldg. 1402
Maxwell AFB AL 36112-6426
Tel: (334) 953-3558
Fax: (334) 953-2269
E-mail: acsc.der.researchorgmailbox@us.af.mil

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KRISTEN C. CASTONGUAY, MAJOR, USAF

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Director, Air University Press
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Air University Press
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Foreword

It is my great pleasure to present another issue of the *Wright Flyer Papers*. Through this series, Air Command and Staff College presents a sampling of exemplary research produced by our residence and distance-learning students. This series has long showcased the kind of visionary thinking that drove the aspirations and activities of the earliest aviation pioneers. This year's selection of essays admirably extends that tradition. As the series title indicates, these papers aim to present cutting-edge, actionable knowledge—research that addresses some of the most complex security and defense challenges facing us today.

Recently, the *Wright Flyer Papers* transitioned to an exclusively electronic publication format. It is our hope that our migration from print editions to an electronic-only format will fire even greater intellectual debate among Airmen and fellow members of the profession of arms as the series reaches a growing global audience. By publishing these papers via the Air University Press website, ACSC hopes not only to reach more readers, but also to support Air Force–wide efforts to conserve resources. In this spirit, we invite you to peruse past and current issues of the *Wright Flyer Papers* at https://www.airuniversity.af.edu/AUPress/.

Thank you for supporting the *Wright Flyer Papers* and our efforts to disseminate outstanding ACSC student research for the benefit of our Air Force and war fighters everywhere. We trust that what follows will stimulate thinking; invite debate; and further encourage today's air, space, and cyber war fighters in their continuing search for innovative and improved ways to defend our nation and way of life.

JAMES D. DRYJANSKI
Colonel, USAF
Commandant

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I thank Lt Col Peter Garretson, USAF; Dr. M. V. "Coyote" Smith, colonel, USAF, retired; and Dr. Brent Ziarnick for giving me the opportunity to write this paper in the Space Horizons Task Force, as well as our funders for the opportunity to travel and meet with some of the truly great minds in propulsion.* Thank you to Dr. Shawn Phillips, Dr. Ingrid Wysong, Dr. Justin Koo, and Dr. Marcus Young, as well as to Jamie Malek, for their expertise and contributions to this paper and spending time explaining the future of propulsion at the RQ-West Propulsion Lab. Also, thanks to the Detachment 7 commander, Col Anne Clark, a great mentor and facilitator of this research. Thanks also go to Dr. Robert Hoyt of Tethers Unlimited and Dr. Bahn at TGV for insights into the work at their companies. It was truly amazing how far this field has grown and advanced in a matter of a few years. I hope this research will further help that growth and reach beyond our earthly bounds!

*I wish to thank Dr. Barbara Clark; Dr. James Campbell, brigadier general, USAF, retired; and Maj Douglas Castonguay and Maj Kiel Martin, PhD, for their thoughtful comments and suggestions. All errors found herein are my own.

Abstract

Lifting mass to orbit is one of the most challenging concepts of space travel. This paper proposes a concept of a hub at low Earth orbit (LEO) that additively manufactures or more colloquially 3-D prints components of the boost and satellite systems to reduce weight to orbit. A hub at LEO with three component modules will accomplish this, and estimates put the cost for this effort around that of one government satellite launch. This concept proposes a receive/assemble/deploy module to capture a satellite as it boosts from Earth and then attaches additively manufactured parts to the satellite for redeployment, a print module to print RL-10-like boost phase engines and multimode propulsion systems, and a storage facility for materials and propellants. This hub will enable making parts through additive manufacturing in space and lead to the printing of more complex systems in the future, thereby promoting the development of space exploration.

Revolutionary Aspects of In-Orbit Additive Manufacturing

Enabling Capabilities

The future of launch is ever developing. Commercial companies are charging ahead to reduce the costs of mass to orbit. This paper discusses the proposal that printing a boost phase engine and satellite propulsion system on orbit would allow for great mass to orbit via a hub in a low Earth orbit (LEO) with an additive manufacturing (AM) printing capability. Second stage boost engines would be printed, as well as the tanks and propulsion system for the satellite. Robotic technology with optional "human-in-the-loop" access would assemble any large parts. These are the parts outside the on-orbit printer capacity or complex parts that require welds due to material or stress requirements.

Printing an Upper-Stage Boost and Satellite Propulsion System

The ideal propulsion system to boost a satellite to operational orbit would be an engine with performance similar to the RL-10 due to its reliability since the 1960s and its high thrust levels. The RL-10 is an example of an operational upper-stage engine that is most mature in AM parts and hot-fired tests by NASA's Marshall Space Flight Center (fig. 1).[1] SpaceX has recently revealed that 40 percent of its Raptor 2 next-generation engine has been printed.[2] Blue Origin has shown a print of its oxidizer turbopump for its BE-4.[3] Additionally, US contractor Aerojet Rocketdyne has shown multiple parts of its liquid engine fleet to be printed, including a pogo accumulator and a turbopump.[4] Printing turbopumps shows some of the most advanced AM so far due to the complex nature of the machinery. Applying this technology to future rocket propulsion solutions on orbit is critical to our next step into outer space.

Figure 1. RL-10 upper-stage booster. (Courtesy of SpaceFlight Insider.)

The satellite propulsion system would also be printed on orbit. This proposed multimode propulsion (MMP) system is a concept being supported and fleshed out by the Air Force Research Laboratory (AFRL). It involves sharing a fuel and oxidizer system over multiple types of propulsion. The most commonly shared propulsion systems are chemical and electric (EP). Despite the proof-of-concept hot-fire tests done in 2009, funding was cut in 2010.[5] This proposal calls for an AM version of the multimode propulsion system. An AM version of the MMP would create the capability of a chemical and electronic propulsion system printed on orbit. Experts in the field believe a pulsed plasma, Hall thruster, or catalyst bed system would be the most likely type of electric propulsion system to be printed.

Technical Requirements / Build Time

The nominal schedule for a hub on orbit would be 10 years. This timeline involves the parallel aspects of research being done to mature the printing technology for AM of propulsion systems in LEO, the development and design of robotics to assemble hardware on orbit alongside the hub design, and launch mission planning to get all the needed materials into the proper orbit. Figure 2 depicts an initial concept of a three-module hub.[6] More details of the layout and components of each module are presented later in this paper.

Figure 2. Projected three-module AM hub. (Courtesy of Bigelow.)

A fully AM printed upper-stage liquid propulsion system could be a reality in as soon as five years on Earth.[7] This forecast assumes development occurs at its present rate with no injection of USAF funding or research. Projection-wise, it should take another five years to shift this technology to orbit. The MMP system has a longer design time. If research was fully funded, the system could be operational in an on-orbit prototype phase in the next 10 years. Nominal timelines for this research and operations are outlined in figures 3 and 4. Remote robotics will have to develop as well to allow for the remote control of robotic arms from Earth for assembly of the propulsion system as well as attachment of the propulsion systems to the satellites after their delivery into orbit.

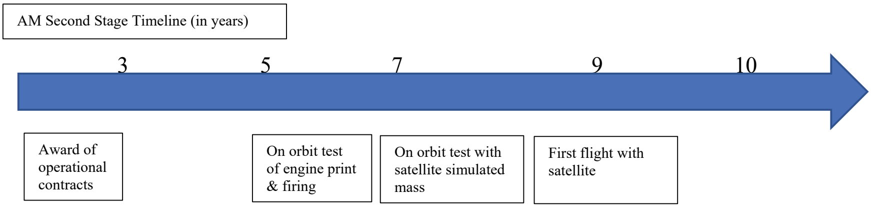

Figure 3. AM booster stage timeline

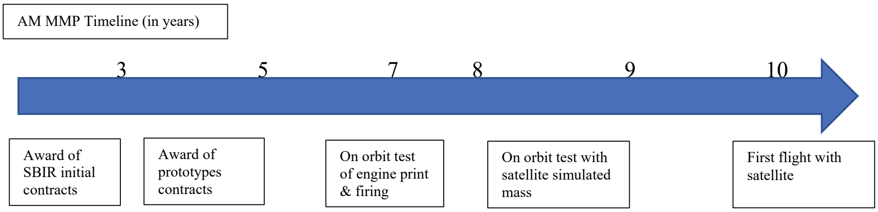

Figure 4. AM MMP timeline

A hub design is critical to the development of printed systems on orbit. Without it, parts could be printed but potentially never attached to operational hardware. The design would have to include a receiving area to capture the satellite from the booster. The same receiving area would be used to collect raw materials from either Earth or, in the future, the Moon. The hub would also have to have a build area for the second-stage boost engine and another for the multimode propulsion systems. A tank building area would be required to print all of the tanks for the propulsion systems, and space would be needed to build electronics for the propulsion systems. Figure 5 shows a nominal timeline for the hub's research and deployment.

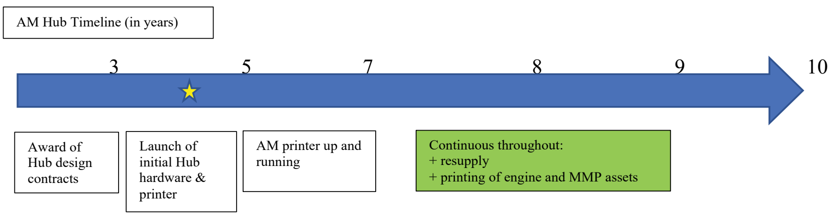

Figure 5. AM hub timeline

Activities to Make AM in LEO a Reality

On-orbit AM requires the completion of several key steps before it becomes a reality. First, the plans must be laid for the AM MMP system. The relative immaturity of this system necessitates further development and testing in the university setting or government lab. While traditional MMP has been demonstrated, research related to printing small components such as pumps and valves is still necessary. These parts are the most challenging to print due to their small size and multiple rotating parts as well as the high standards for surface finishes on these rotating parts. This research is envisioned to take five to seven years. In parallel with this research would be an examination of how to print the full MMP system. At the five- to seven-year point, a prototype should be ready for vacuum chamber testing. After one to two years of vacuum testing, an on-orbital system will be deployed. This research effort is estimated at $20 million over a 10-year period.[8]

The other option for the MMP is to allow the technology to develop, and then leverage that technology when it is more mature. This option is cheaper, with a longer lead time and minimal level of effort on the DOD's part. This lead time is about 30 years and would most likely have a $5 million price tag at the 30-year point. There is danger here as our adversaries could take advantage of the technology or mature it faster, leaving the United States out of this technology business.

The technology for printing an upper- or second-stage boost engine is much more developed. NASA, SpaceX, Blue Origin, and Aerojet RocketDyne have all printed full engines or components of engines and had full hot-fires. A few examples include NASA's RS-25, a Space Launch System (SLS) propulsion system pogo accumulator that has shown a 35 percent reduction in cost and 80 percent reduction in build time versus the known Space Shuttle engines.[9] NASA has also printed and hot-fired an RL-10 thrust chamber with a reduction in part number of 90 percent from the original subtractive or standard engine build.[10] Aerojet RocketDyne has printed and hot-fired a Bantam rocket with a thrust level comparable to one of SpaceX's reported upper-stage engine.[11] Blue Origin and SpaceX have both printed components of their upper-stage engines and are moving toward further printing due to the reduction in cost and parts. The company Relativity Space has made great strides in AM of rocket engines. It hot-fired its 100 percent AM Aeon engine 100 times at NASA Stennis. An example of its hot-fire test is in figure 6. This engine has a thrust of 19,500 pounds- force, which is in the same order of magnitude as the RL-10 thrust of 24,700 pounds-force. The Aeon engine has a specific impulse of approximately 360 seconds. A print of this engine takes

15 days, and a standard rocket build is 180 days. The Aeon has 100 components while other rockets have 2,700 components.[12] With this maturity, it is projected that full-boost engines will be entirely printed and tested on Earth in five years. The next step would be moving the printing process to orbit and testing prototypes there. If funded properly, this step could be done in five years. Currently, SpaceX is running contracts in this vein of research at the cost of $67.3 million for the SpaceX Raptor 2.[13]

Figure 6. Aeon hot-fire. (Courtesy of Relativity Space.)

Robotics is another essential piece of technology required for on-orbit AM. The aerospace company Made in Space already has the concepts in place to build with robotics in space via its Archinaut system. Made in Space is also developing the External Augmentation of Generic Launch Elements (EAGLE). The EAGLE system is a recycling concept aimed at building new assemblies from old rocket parts.[14] These two concepts are critical to developing ways to print in space without a human in the loop and to tackling the challenging concept of debris removal.

Relativity Space also has advanced robotics AM. Its Stargate system is a set of three robotic arms designed to print a full rocket, including the propulsion system (fig. 7). This robotics system has AM metal capabilities and machine learning to improve designs as propulsion or other rocket systems mature. This is just one type of robotic system being developed for AM. Robotics is growing at a tremendous rate not only for assembly but also as an actual printing system. These robotic systems will allow for automated print and assembly of rocket engines on orbit.

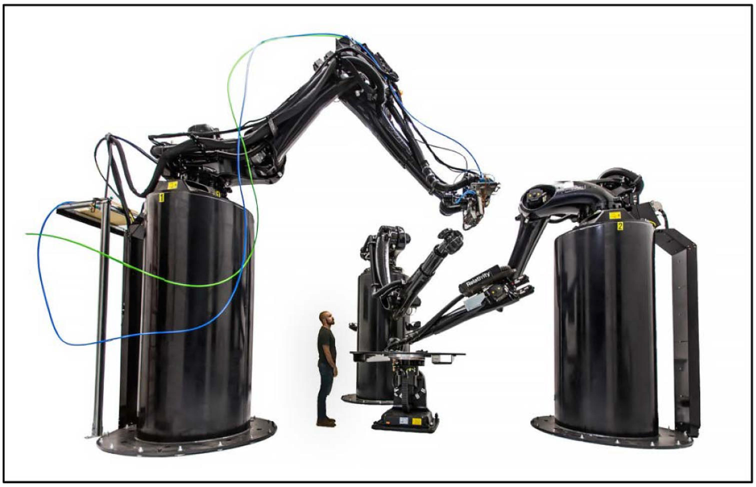

Figure 7. Robotic AM system. (Reproduced from Relativity Space, accessed 20 April 2018, https://www.relativityspace.com/stargate.)

Policy/Requirements for AM Hub

The first step in building the LEO AM hub is demonstrating its benefits for both government and commercial use in a way that inspires public/private partnership. Showing the benefits of such a partnership can cut the cost of launch and satellite deployment with an upfront investment is key. Also, these systems allow for larger payloads to be placed in orbit. Next, money must be put against the plan for a nominal 10-year schedule for the upper stage and MMP as well as robotics development. Material selections must be made for the propulsion systems makeup and limits set for the acceptable level of divergence for in-space operations. The hub must be designed. Partners are needed for this project. Whether they come from private industry or are foreign friendly nations, due to the cost of this endeavor, it is critical that many space players see the value added of printing in space and move toward similar goals. Once propulsion systems are printed, there is no upper limit to what might be printed next on orbit. This capability could easily be adapted to print full satellites or even man-rated spaceships as time and technology evolve.

Projected Cost

Presently, communication satellites cost in the $300–$500 million range. An operational launch vehicle ranges from $300 to $400 million for large payloads. Best estimates put the efforts for an AM LEO hub at $50 million in research and development and approximately $400 million for the on-orbit components, with current modules in the $125 million range. This estimate is based on the BA-330 Bigelow module.[15] The projected cost breakdown is $375 million for hardware modules and $25 million for robotics, with the assumption that robotics is a mature technology. Launch vehicles would have to be assessed on a case-by-case basis; the current cost is $90 million for SpaceX Heavy to $350 million for the Delta IV. If done correctly, future launches should cost approximately $270 million to get all hub materials to orbit; this estimate correlates to roughly $90 million per launch using SpaceX Heavy with its reusable option.[16] AM metal printer development is developing at a rapid rate. Estimates to increase printer size are $10 million, as General Electric, Stratasys, and NASA are already printing large components. Assuming these estimates, the total cost of the AM hub at LEO is $730 million. Even with inflation and program creep costs, this cost is below that of one standard large satellite launch and gives the United States the capability to print parts on orbit. Resupply costs for propellant and print stock are estimated to be between $80 and $90 million a year. These numbers do not consider any type of international cooperation or industry money placed toward research.

Current Concepts of Additive Manufacturing Current State and Vectors

Metals Printing

Current on-Earth technology. The existing technology on Earth for AM is quite extensive and diverse. There are two main types of metal printing: metal powder and wire feed. Due to the nature of microgravity in LEO, or at least until *technology* develops to the extent of keeping powder safe from electrostatic discharge in the hub, wire feed printing is the best option for on-orbit printing. Figure 8 shows an AM wire feed system as well as photos from production runs. The metal feedstock is fed through a tight orifice and deposited on the desired print location. Depending on the style of AM, a laser, an arc welder, or an electron beam then heats the feed wire. The metal feed wire then melts into the rest of the AM form and is bonded together.

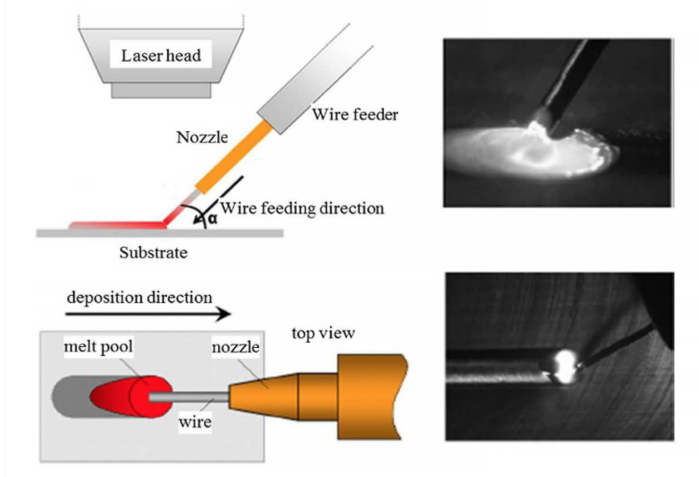

Figure 8. Wire feed AM. (Reproduced from Hannah Rose Mendoza, "Wire-Feed Additive Manufacturing Holds Great Potential for 3D Printing," 3DPrint.com, 29 May 2015, https://3dprint.com/66185/wire-feed-additive-manufacture/.)

Current technical challenges. Issues to be resolved for printing metal for engine systems on Earth include electrostatic discharge concerns, powder removal from interior geometries, and material standards development. Due to microgravity, powder printing systems will not be used on orbit. Therefore, material standards and void mitigation would be the focus of much of the research for in-space printing. There is a large thermal variation in space orbit. It is unknown at this time how AM parts will hold up to this sun cycling. More research into the effects of sun-cycling on AM printed metal in orbit and how to mitigate them will help reduce the impact of this risk.

Another big question at the moment is the material behavior of AM parts in space. Materials act differently in the ultrahigh vacuum of space due to high pressures and strains on the metal material lattices and bonds. We are unsure how the voids in the metal lattices of AM parts will react to this vacuum. The danger with these voids is similar to outgassing with plastics. A void can build pressure with heating or large rapid pressure changes as seen in space. If the fluid trapped in these voids expands too much, the material could be blown apart and cause part failure. This line of investigation is integral to realizing AM in space and for space rating of materials.

Beyond the material science and material standards, developing system designs for printing on orbit will be critical and challenging. Tanks will be printed first to allow initial systematic errors to be worked out, followed by the printing of more intricate parts of propulsion systems.

Demonstration of Metal Printing on Orbit

Currently, there is no known demonstration of metal printing on orbit. However, there are contracts let to industry partners moving in that direction. One such contract is a $10 million effort NASA awarded in late 2017 to Tethers Unlimited, Techshot, and Interlog Corporation involving ground-based prototypes for machines capable of printing metal on orbit.[17]

Future Tech on Orbit

Many of the needed metals for rocket engine and the MMP systems have already been developed on Earth. Various alloys such as Mondaloy 500, Inconel 625, and Ti-64 have been proven in print capacities on Earth for rocket components such as pogo accumulators and power pumps.[18] This print capacity will have to be transferred to orbit.

Another interesting line of research regarding printing on orbit is electronics. Made in Space has an initial printing system called Satellite Manufacturing Machine (SMM). This system's goal is to print electronics in space. This technology and others like it should be leveraged to the fullest extent possible in order to print as many elements of a propulsion system in space to reduce the cost of lift.

Current Launch Capabilities

The current launch capabilities will be evaluated for the launch of material and as a comparison for the benefits of AM print on orbit. The investigated systems are United States platforms only that will be available in the near term for space lift.

Table 1 shows the launch vehicles in current space lift capability for the United States. These two platforms were chosen as they are the top class of lift for their platforms and have both launched. The Delta IV Heavy brings a tremendous launch capability of payload to the pad, but with a hefty price tag. Assessments have been done for the larger boost phase engine, as the MMP is much smaller with less mass. The dry weight of an RL-10 is approximately 277 kg or 611 pounds dry, so the Delta IV Heavy could lift enough material for 103 engines.[19] Assuming a 3 percent loss of material during the printing process, this is still enough material to make at least 100 upper-stage engines—plenty to boost satellites to higher orbits for years to come.

Table 1. Current US lift capability

Lift vehicle	Payload mass to LEO	Cost	Booster thrust	Booster Specific Impulse	2nd-stage thrust	2nd-stage ISP
Delta IV Heavy	62,540 lb.	$350 million	9.3 meganewton	414 secs.	110 kilonewton	464 secs.
Falcon Heavy	140,660 lb.	$90 million - reusable $150 million - expendable	7.6 meganewton	282 secs.	9.3 kilonewton	348 secs.

The Falcon Heavy launch on 6 February 2018 demonstrated its reusable mode. It will cost approximately 25 percent of the Delta IV and could lift enough material for 230 second-stage engines. Again, accounting for 3 percent losses, at least 223 upper-stage engines could be printed on orbit These engines could be printed and left in orbit as is the standard today, or they could be printed and returned to the hub. The latter is preferable since reusability and not increasing the space debris in orbit are favorable in today's planning climate. Of course, engines and their tank systems would have a life cycle when being reused. This factor would have to be taken into account. Current life cycles on the large boost engines are five tests before they are considered not operationally sound. Therefore, it is proposed that on-orbit boost engines will have at least five reusable boost-to-orbit operations before they will be brought back and evaluated for a recycle option for another engine build or a less sensitive build such as a tank.

Key Metrics of Value

Cost Analysis

The initial upfront cost for the hub would be a substantial $730 million. However, once on orbit, propulsion systems could be printed for second-stage boost and MMP leading to a reduction in mass on satellite payloads and a reduction in mass of the second stage by all the weight of the tanks and propulsion system. As an example, the RL-10 weighs 611 pounds dry. According to recent NASA estimates, every pound sent to space costs $10,000. Therefore, with dry mass alone, it is a $6.11 million savings per launch for printing a second-stage engine on orbit.[20] This is the engine itself, not even mentioning tanks or other support equipment.

Customers

The service of printing these engines would provide a much-needed reduction in cost of launch for all of US launch providers. By printing propulsion systems on orbit, the lift capability to orbit will be greatly increased. This is because the whole second stage with its tanks and propulsion systems will be eliminated. Also eliminated would be the tanks and propulsion system and accompanying weight for the satellite propulsion system.

Volume and Mass

Considering the current size of upper-stage engines, a print size needs to be targeted. The RL-10 is 13.6 feet in length and seven feet in diameter with a dry weight of 611 pounds.[21] This information is the most defined in open nonproprietary information for propulsion systems. The Raptor 2 has been released as having a diameter of four feet.[22] The MMP system will be smaller as the EP and smaller five-pound chemical systems needed for delta-v corrections are much smaller than boost-sized engines. Also, the tubing can be printed in sections and joined via robotics. Taking these sizes into consideration and adding the size for robotic arms to move around the hardware, the printer size should be 15 feet by 10 feet by 10 feet—equaling 1,500 cubic feet or 42.5 cubic meters. Considering the current print time of rocket components, the print and assembly time for one engine will most likely be around 24–48 hours.

Proposal for In-Space AM LEO Printer Hub

AM LEO Printer Hub Build

The build of the hub shall be done in a few different stages. Its nominal orbital altitude would be LEO. First, two Bigelow or Bigelow-like modules will be brought up along with the robotics needed to assemble different components. Also, in the payload will be an initial metal printer and printer material for prototype testing. Robotic arms will deploy first and then the modules, which will then be attached together by the robotic system. From there, the rest of the modules and materials will be delivered in one more launch.[23] Propellant tanks will be printed first for simplicity. Materials and more printers will be brought up in an additional launch, and restocking launches will have to occur once a year.

Figure 9 shows a nominal design of the hub printing center. Module 1 will receive the payload from launch, attach the engine and MMP systems, and then release the satellite into it proper orientation to initiate its first delta-V burn. Module 2 is the printing area where engines will be printed and stored. Module 3 is where the raw materials and propellants will be placed for storage until needed.

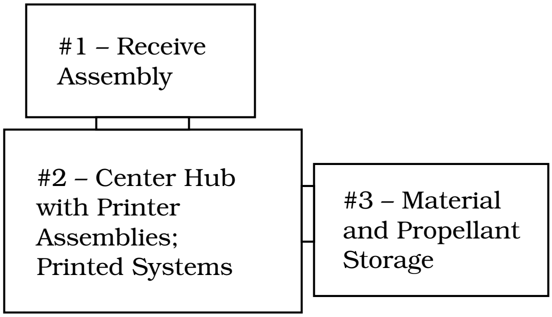

Figure 9. Hub diagram

Discussion of Different Models

Alternative models of development must be explored to develop this technology so that the best route to follow can be determined.

Commercial off-the-shelf (COTS) model. Using a readily available or COTS model would be easiest and will push development for the hub concept into the next decade. However, the COTS world of AM is still developing. While an AM upper-stage engine will be a reality in the near future and robotics capability is improving every day, the technology is not currently available off the shelf for this type of LEO AM system. If allowed to develop and mature, COTS could be used in about 25 to 30 years to build the proposed system on orbit. This method would involve the USAF and commercial partners taking the lead and has an estimated bill of $10 million.

AFRL model. The AFRL model would involve letting SIBR contracts to universities and other businesses in the first one to three years of development to start the research on AM and robotics. This would then move into small-scale parallel prototyping and develop into the TRL 4-6 level over the next five years. Finally, the program would move into operational test and have a prototype on orbit in the final two to three years. This research program would most likely run in the $50 million range.

Defense Advanced Research Projects Agency (DARPA) model. The DARPA model would be a fast-paced, expensive development program. Technology will be developed rapidly. It is thought that a functional hub system would be possible in seven years from the start of the program. Costs for research would run higher than the other models at $100–$200 million.

Commercial model. While not within the control of the USAF, commercial entities might decide to pursue this AM capability. This would not be ideal for the USAF as it would not have a say in many factors and interoperability of the hub and its facilities without a cost. If done by commercial entities, the DOD and other interested parties would perhaps rent space or buy parts from the commercial vendors as they print and store them on orbit. While not inherently negative, it must be remembered that these services would be for sale for all parties. The United States could be made to wait for parts or could have secrets divulged while sharing print facilities with potential adversarial nations.

Limitations of Printing on Orbit

Experts from industry and government labs say that the most difficult pieces of technology to print are pumps and valves. Particular challenges are the closed nature of the parts, which restricts AM by-product removal, as well as the microlevel precision needed for the rotating parts to operate correctly. Therefore, to speed up the process of printing on orbit, experts recommend removing the printing of high-speed pumps and the main propulsion valves. While this technology will be developed on Earth in time, it could take longer than other technology to mature.

Evolution of the Design

Technology design is generally an iterative process, and AM is no exception. It will evolve and take on new roles on orbit as it has on Earth. Printing in microgravity will be a unique technical challenge with benefits. Designs for the new boost engines and MMP systems constructed in space will vary from those on Earth because researchers will not have to consider launch payloads for these new propulsion systems. They will have to factor in only the stresses of operating in space, not the constraints of multiple gravitational forces placed on a rocket during launch. Thus, the generative design process will move further as the rocket engines can move toward lower weight and higher efficiencies.

Assembly

In many discussions, the overwhelming thought from the technical community concerning assembly on orbit for more complex parts of known propulsion systems was robotic, with the potential for "human in the loop" guidance from Earth.[24] The reason for the interest in robotic arms and assembly was that the lack of humans would allow for a much cheaper hub. Robotics are much easier to keep functioning in space than humans. Also, recent tests on orbit in the ISS have shown that the humid environment required to keep humans comfortable can cause clumping with the AM feedstock as well as problems with metal deposition in the desired positions.[25] The vents and pumps required to allow for the exchange of air cause vibrations that would have to be dampened out as well. The most plausible idea is remotely controlled robotic arms by technicians on the ground. This concept is similar to the robotic arm on the ISS or the former Canada Arm on the STS. Robotic arms in the form of computer numerical control (CNC) machines have been proven time and time again to be precise on Earth. This process would involve taking Earth-bound technology and applying it to a manufacturing process on orbit.

Propellants *from the Moon*

Initially, all propellants will come from Earth. These can be brought up in increments according to launch supply schedules. Also, any excess fuel can be drained from the first stage if needed or if the vehicle is expendable. In time, as the technology develops for farming of Moon elements, the hub would benefit greatly from receiving hydrogen and oxygen from the Moon for the engine systems. The MMP chemical system would also benefit, while the rarer EP propellant requirement might be fulfilled as we learn more about the elements available in the lunar regolith.

Printing Materials

There are two options for mining and procurement of print materials for AM on orbit. One is Earth and the other is the Moon. Payloads of materials from Earth are immediately available since feedstock and powder are already being used for terrestrial AM. According to currently published lift assets and assuming a LEO hub location, the Delta IV Heavy can lift 62,540 pounds of payload into orbit while the Falcon Heavy can lift 140,660 pounds to orbit.[26] Another Earth-based possibility is to use the in-place International Space Station supply route with the Antares system out of the Virginia spaceport. This lift capability supplies 14,300 pounds of material to orbit and costs $80 million per launch. While the Antares rocket has less capacity than a Falcon Heavy, the launch infrastructure is already in place for LEO launch in Virginia and is driven by the use of surplus DOD motors for launch instead of disposal. Further, the resupply mission from the Virginia coast is mature, making this alternative viable.[27]

The second Moon-based option is a more futuristic look. It involves the mining and receiving of lunar material in the form of oxygen and hydrogen. It also would involve receiving metals from the lunar regolith. This technology would require purified liquid oxygen as well as purified liquid hydrogen. These propellants would have to be filtered to the required level acceptable, removing any dangerous propellant tube line- blocking material. Metals from the Moon would need to be in micron powder form and then compressed into wire form for the necessary printing.

Launch/On-Orbit Capabilities Improved with AM on Orbit

The idea driving the AM LEO hub design is that second-stage boost and MMP systems (tanks, avionics, etc.) will be printed on orbit. Before a system is attached to an operational satellite, the prototype will be tested on a satellite mass simulator. After successful testing, operational satellites will be flown up from Earth's surface, and the propulsion system will be attached and fueled. Then the fully integrated system will propel to its final destination. This new configuration will enable more latitude for lift and mass components. Beyond this concept, one can envision fully printed satellite systems. The AM LEO hub is a goal for 25–50 years in the future.

Conclusion

The development of an on-orbit hub for AM of propulsion systems is a technology that would change the face of space lift and propulsion development. AM on orbit will drop the cost of launch substantially by cutting the weight of launch vehicles' second stage and payloads. I propose that the United States take the lead in research and execution of an AM hub for printing in LEO. Starting with printing simple items like propellant tanks and then evolving to second-stage engines and MMP systems will allow a technology base to be developed on orbit. The second-stage engines will be attached to satellites coming up from Earth and used for a final boost. The MMP system will be connected and used for final maneuvering and station keeping.

The cost for the AM hub proposal is in the range of $500 million for the hub and another $270 million for the launch systems to deliver the hardware into orbit. Development projects will run in parallel on three tracks. These are development and operation of the (1) second-stage propulsion system, (2) MMP system, and (3) AM hub in LEO. Restock will cost between $80 and $90 million a year. In the long term, development and printing of satellites or even spacecraft will be the goal for technologically advanced countries.

Notes

1. Saunders, "Aerojet Rocketdyne."
2. Winick, "Additive Manufacturing."
3. Saunders, "Blue Origin's Liquid-Fueled BE-4."
4. National Aeronautics and Space Administration, "Methane-Powered 3-D Printed Turbopump."
5. Justin Koo, PhD (technical advisor to the Electric Propulsion Branch, AFRL-RQ West, Edwards AFB, CA), interview by the author, 15 March 2018.
6. Thompson, "Bigelow's Inflatable Space Stations."
7. Jamie Malek (program manager, Liquid Propulsion Branch, AFRL-RQ West, Edwards AFB, CA), interview by the author, 15 March 2018.
8. Marcus Young, PhD (program manager, Electric Propulsion Program, AFRL-RQ West, Edwards AFB, CA), interview by the author, 15 March 2018.
9. Harbaugh, "NASA Tests 3-D Printed Rocket."
10. Saunders, "Aerojet Rocketdyne."
11. "Aerojet Rocketdyne Increases Thrust Level," Aerojet RocketDyne.
12. "Aeon 1," Relativity Space Company.
13. Foust, "$40 million to SpaceX."
14. "Archinaut," Made in Space.
15. Maness and Holtzin, "City in the Sky."
16. "Falcon Heavy," SpaceX.
17. Robert Hoyt, PhD (cofounder, Tethers Unlimited, Bothell, WA), interview by the author, 22 February 2018.
18. Malek, interview.
19. "RL10 Engine," Aerojet RocketDyne.
20. Drachlis, "Advanced Space Transportation Program."
21. "R-10 Engine," Aerojet RocketDyne.
22. Belluscio, "ITS Propulsion."
23. For specifications on the Bigelow Expandable Activity Module size, see "BEAM," Bigelow Aerospace.
24. Koo, interview.
25. Hoyt, interview.
26. ULA, "Delta IV"; and "Falcon Heavy," SpaceX.
27. Government Accountability Office, *Surplus Missile Motors*, 1–12.

Appendix A
Requirements/Policy/Initial Capabilities Document

- The Joint Force Space Component Commander (JFSCC) has a requirement for on-orbit reusable propulsion systems for the upper-stage boost and satellite that can be fabricated and serviced on orbit.
- JFSCC has a requirement to be able to additively manufacture rocket engines on orbit using terrestrial and lunar/asteroid feedstocks.
- JSFCC has a requirement for these engines to be able to use terrestrial and lunar propellants.
- JFSCC has a requirement for reusable launch to lift the hub components into space. Resupply launches will be evaluated fiscal year to fiscal year.

Abbreviations

AFRL	Air Force Research Laboratory
AM	additive manufacturing
CNC	computer numerical control
COTS	commercial off-the-shelf
DARPA	Defense Advanced Research Projects Agency
EAGLE	External Augmentation of Generic Launch Elements
EP	electric propulsion
JFSCC	Joint Force Space Component Commander
LEO	low Earth orbit
MMP	multimode propulsion
SLS	Space Launch System
SMM	Satellite Manufacturing Machine

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