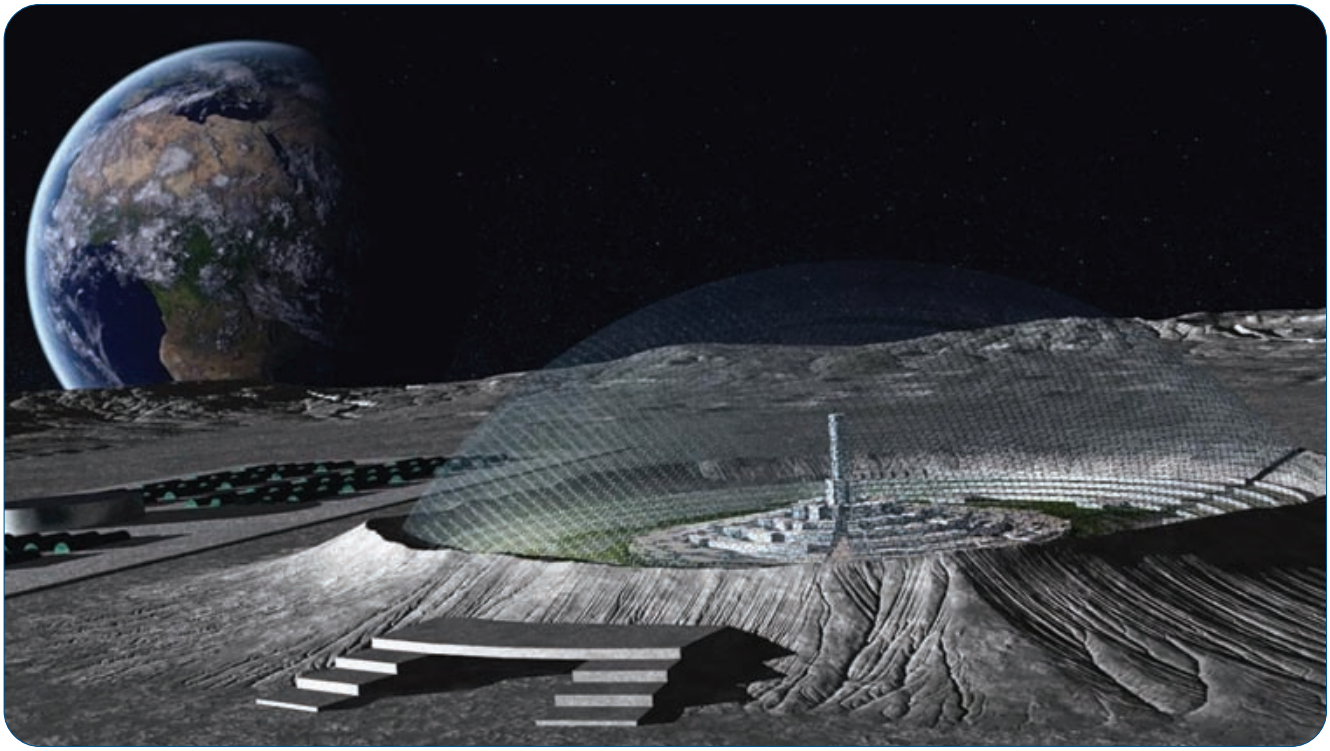


ESA's 3D printed moon base

Advances in 3D printing for the space sector

3D printing has come on in leaps and bounds in recent years, as developments have resulted in technology that is more readily-available, cost-effective, and sophisticated, than ever before. Today, 3D printing is being utilised by industries far and wide, and, naturally, the space sector is not one to be left behind.

3D printing, or additive manufacturing, has been big news in recent years. There's been a flurry of interest in the ability to print anything and everything, from guns to lampshades, that has really captured the imagination of the masses. Essentially, 3D printing enables the production of a 3D object based on a digital model, in a huge variety of materials, including plastic and metals.

The applications of 3D printing are many and varied. Clothes designers are experimenting with 3D printed shoes, dresses ad bikinis, while food companies are using 3D printing to form chocolate and sweets to develop exciting new products. Manufacturers are seeing the benefits of being able to develop prototypes much faster and more cost-efficiently in a whole host of sectors, including the production of land and aerial vehicles. Meanwhile, the medical sector is making great strides in utilising 3D printing to create customised implants, for orthopaedics and splints, for example.

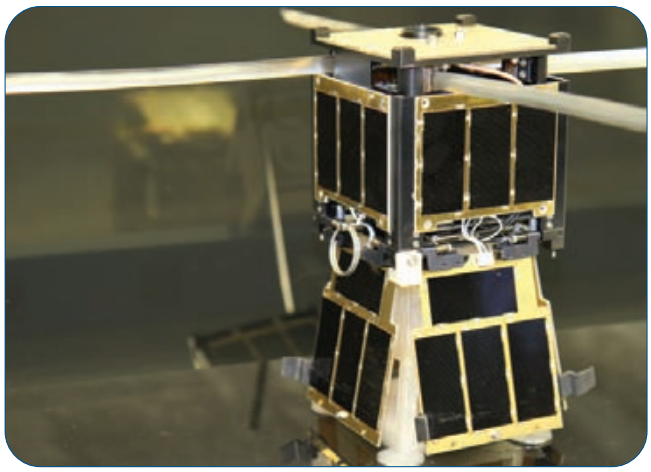
Within the space sector, the possibilities are endless. 3D printing is being used across the world to create CubeSats, ground equipment, launch vehicles and their components. As for other industries, the benefits include rapid lead times, cost-efficient prototyping, and incredible flexibility. As the technology matures, 3D printing is expected to have a significant impact on all aspects of the space sector, including off-world and deep space missions.

Earth-based 3D printing

With the growing popularity of 3D printing in such a vast array of industries, the barriers to entry are falling. Indeed, students at universities across the world have been getting in on the action, developing 3D printed CubeSats for launch on rideshare missions. A variety of traditional and NewSpace sector entities are now seeing the value in utilising 3D printing technology to advance their long-term goals in producing spaceflight technology here on Earth.

Blue Origin

Like SpaceX, Blue Origin is working on providing commercial access to space at much lower costs than are possible today, by developing new launch vehicles technologies, including reusable rockets.



CRP USA's KySat2 in Windform XT2

Blue Origin began working on its fourth rocket engine, the BE-4 engine back in 2011. Designed to reach orbital space and beyond, the BE-4 will be the company's first engine to burn liquid oxygen and methane propellants. In September 2018, United Launch Alliance (ULA) selected the BE-4 engine to power its Vulcan launch vehicle, and according to Blue Origin, the BE-4 engine will be flown on both the Vulcan and its in-house New Glenn orbital vehicle in 2020.

The BE-4 features an Ox Boost Pump (OBP) to enhance performance; it is the component parts of the OBP which Blue Origin has opted to produce using 3D printing. The housing is a single printed aluminium component, while all the stages of the hydraulic turbine are printed from the nickel alloy Monel. According to Blue Origin, this manufacturing approach enables the integration of complex internal flow passages in the housing that would be more difficult to make using traditional methods. The turbine nozzles and rotors are also 3D printed, requiring only minimal machining to achieve the perfect fit.

Relativity Space

A relative newcomer to the space sector, Relativity Space was founded in 2015 with the mission of developing its own launch vehicles and engines for the commercial satellite sector, but utilising 3D printing much more heavily – apparently accounting for 95 percent of its launch vehicle components, engines included - than its competitors. In addition, with a particular focus on future missions to Mars, Relativity Space asserts that intelligent automation and lightweight, compact 3D printing are fundamental technologies required to build a new society with scarce resources.

The company has developed Stargate, reportedly the largest metal 3D printer in the world, to further its goals. Stargate is the backbone of Relativity Space's vertically integrated factory, capable of going from raw materials to flight within 60 days, for new and existing rocket designs alike. According to Relativity Space, Stargate is constantly getting smarter and faster using sensors and reward-based learning.

With Stargate, Relativity Space is developing the Aeon 1 engine, which can be produced within 15 days compared to the industry standard of 180, and featuring just 100

Aeon 1 engine

components, where competitor engines typically have 2,700. The future looks pretty good for Aeon 1, which has completed more than 100 test flights to date. Ten of the liquid oxygen/liquid methane propellant Aeon 1 engines will be used to launch Terran 1, Relativity Space's two-stage 3D printed expendable launch vehicle, which is currently under development. Terran will be produced using a proprietary printable metal alloy and is uniquely designed for satellite constellation deployment and resupply missions. The company's website details launch prices at US$10 million for a dedicated mission, US$11,000/kg for SSO, and US$8,000/kg for LEO, making it one of the most cost-effective launch vehicles yet.

CRP Group

High-technology company CRP Group has spent considerable time developing its 3D printing capabilities for a variety of industries, including the space sector. The company specialises in the production of small satellites and their propulsion systems using 3D printing methods.

At the end of 2017, CRP Group launched the first fully-3D printed satellite from the International Space Station (ISS). The Tubesat-POD (TuPOD), a tube-shaped CubeSat, served as a deployment platform for smaller TubeSats, and was produced in collaboration with Teton Aerospace, Morehead State University and JAXA. The platform deployed TubeSats created by TanCREDO and ONSAT teams. TuPOD was 3D printed using CRP Technology's Windform XT 2.0 material, which is also used for wind tunnel and track testing for Formula One racing. The electrical components were added to the satellite after it was printed. CRP Group has also used Windform XT 2.0 to 3D print the KySat-2 CubeSat in 2013.

The company has been ramping up its presence in the aerospace sector in recent months, so we can expect to hear a great deal more in the years to come.

Aerojet Rocketdyne

Aerojet Rocketdyne is one of those long-standing aerospace and defence companies investing heavily into innovation on all fronts, including 3D printing. Following two decades of investment and research into the production of rocket engine and defence system applications via 3D printing methods, the company is now benefitting from more affordable technologies with significantly reduced lead times.

In recent years, Aerojet Rocketdyne has successfully hot-fire tested engines and propulsion systems made entirely with 3D printing and counts small satellite propulsion systems such as its MPS-120, the small and medium boosters making up its Bantam engine family, and the larger rocket engines like the RL 10 and the upcoming AR1, among its notable achievements. The company highlights the reduced costs, reduced lead times and increased flexibility among the advantages of 3D printed space components.

In October 2018, Aerojet Rocketdyne thrusters with 3D printed components were qualified to fly humans on NASA's Orion spacecraft. The reaction control system (RCS) is the only means of guiding the Orion crew capsule after it separates from its service module in preparation for atmospheric re-entry and splashdown. Aerojet Rocketdyne utilised 3D printing technology to produce the RCS engine nozzle extensions. The year-long qualification test programme saw a single engine subjected to shock and vibration that exceeded the maximum stresses expected during the upcoming Orion launch, wherein the vehicle will be launched around the Moon on NASA's Space Launch System (SLS) rocket.

Lockheed Martin

Lockheed Martin, another satellite industry long-timer company, is pushing the limits of additive manufacturing technology to build space-qualified components that could not previously be built. The company famously launched the first-ever printed parts into deep space on board NASA's Juno spacecraft in 2011 and has made great advancements in technology since then.

In July 2018, Lockheed Martin completed a multi-year development programme resulting in the 3D printing of a 46inch diameter satellite fuel tank made from titanium. The tank consists of two 3D printed domes that serve as caps, produced using Electron Beam Additive Manufacturing, and a variable-length, traditionally-manufactured titanium cylinder that forms the body.

Satellite fuel tanks, which must be both lightweight and strong enough to withstand the vacuum of space for decades, are notoriously hard and expensive to produce; traditional manufacturing methods take around one year per tank, and 80 percent of the material goes to waste. With 3D printing, Lockheed Martin has cut out the waste, and significantly reduced the production timeline.

"Our largest 3D printed parts to date show we're committed to a future where we produce satellites twice as fast and at half the cost," said Rick Ambrose, Lockheed Martin Space Executive Vice President. "And we're pushing forward for even better results. For example, we shaved off 87 percent

of the schedule to build the domes, reducing the total delivery timeline from two years to three months."

Later in October, Lockheed Martin and the Office of Naval Research announced a new two-year US$5.8 million contract to explore how to apply artificial intelligence (AI) to train robots to independently oversee and optimise the 3D printing of complex parts. Technicians currently spend many hours per build testing quality after fabrication; this research will enable robots to make decisions based on previously verified analysis for the production of common types of microstructures much more efficiently than is achieved today.

"When you can trust a robotic system to make a quality part, that opens the door to who can build usable parts and where you build them," said Zach Loftus, Lockheed Martin Fellow for additive manufacturing. "Think about sustainment and how a maintainer can print a replacement part at sea, or a mechanic print a replacement part for a truck deep in the desert. This takes 3-D printing to the next, big step of deployment."

Completed dome exiting printer

Space-based 3D printing

3D printing is also becoming big business in space, with a number of entities, both commercial and association alike, keen to get in on the action. The possibilities of 3D printing in space are incredible; there are significant cost savings to be made by not having to launch tools and equipment from Earth, not to mention the time saved by simply printing whatever is needed, in space. Providing astronauts with the ability to print the things they need, when they need them, makes long-duration space travel, such as missions to the Moon, Mars and beyond, much more viable, not to mention much safer.

Made in Space

Until recently, Made in Space (MIS) was the only commercial company working with 3D printing in space. The MIS Additive Manufacturing Facility (AMF) was launched to the International Space Station (ISS) in 2014, having been developed to operate in a microgravity environment. Since it's installation, the AMF has been utilised by NASA, the US National Laboratory and commercial partners to carry out repairs, upgrades and installations, as well as complete novel experiments.

MIS is also working on some exciting new projects, including the Archinaut Technology Development Project (ATDP), an in-space additive manufacturing and robotic assembly platform. The project was extended by 12 months at the end of 2017 following a successful first year which saw the core technology, Archinaut's Extended Structure Additive Manufacturing Machine (ESAMM), developed and ground tested. The next step in ATDP focused on testing the Ground-Based Manufacturing and Assembly System Hardware (GBMASH), which combines additive manufacturing with robotic assembly. GBMASH paves the way for potential flight demonstrations of Archinaut's additive manufacturing and robotic assembly capabilities in space. Meanwhile, in July 2018 it was reported that MIS is using the Archinaut system to develop high power systems for small satellites, taking them from a typical 1kW power system up to 5kW. Archinaut-based solar array systems utilize space-manufactured structures and robotically-assembled state-of-the-art solar cell blankets to provide up to 20m^2 of solar array

for small satellites that launch from ESPA rings or small launch vehicles. For small satellites, Archinaut's power system is able to provide up to five times the power of state-of-the-art systems by launching the system with raw material and tightly packed solar arrays, rather than folded up booms and complex deployment mechanisms. On orbit, Archinaut manufactures the core array lattice structures and robotically, physically and electrically, integrates solar array blankets, completing the solar array wing.

In other news, May 2018 saw NASA select MIS to develop VULCAN, a next-generation metal space manufacturing system. VULCAN will fabricate precision parts which require the strength and durability of aerospace-grade materials, such as housings for life support systems, that can't be made with current systems, from more than 30 aerospace-grade metals and high-grade polymers, and hybrid components that combine multiple materials. The technology is being developed for a demonstration on the ISS to example its usefulness in future human spaceflight operations, such as on board the Lunar Orbiting Platform Gateway. VULCAN will be the first of its kind to bring machined parts to space, enabling more critical parts to be manufactured off-world. The system's hybrid technique utilizes both additive manufacturing to create the desired near net-shaped part, and traditional manufacturing methods to create the finished product. The system manufactures, refines, and performs quality checks in a streamlined, automated process, eliminating the need for a human in the loop during manufacturing. VULCAN is expected to be ready for launch in the mid-2020s.

The Refabricator experiment

Following on from MIS' world-first foray into space-based 3D printing is the Refabricator experiment, which was developed by Firmamentum, a division of Tethers Unlimited, Inc. (TUI) under a NASA Phase III Small Business Innovation Research (SBIR) contract. The experiment combines a recycling system with a 3D printer, producing a closed-cycle space-based manufacturing process. The Refabricator will accept plastic materials of various shapes and sizes and transform them into feedstock for the 3D printer.

"When we begin launching humans to destinations beyond low-Earth orbit, space will be at a premium," said Niki Werkheiser, Manager of In-Space Manufacturing at NASA's Marshall Space Flight Center in Huntsville, Alabama. "It simply won't be feasible to send along replacement parts or tools for everything on the spacecraft, and resupplying from Earth is cost and time prohibitive. The Refabricator will be key in demonstrating a sustainable logistics model to fabricate, recycle, and reuse parts and waste materials."

Closed-loop materials recycling, enabled by 3D printing, is expected to reduce the cost and risks for NASA and other space exploration missions going forwards. The Refabricator will be the first integrated recycler-manufacturer in orbit and may eventually be able to recycle and print, using metal as well as plastic, with very little monitoring from the station crew members.

By 2020, NASA wants to create a Fabrication Laboratory, 'FabLab,' to test an integrated, multi-material, on-demand system.

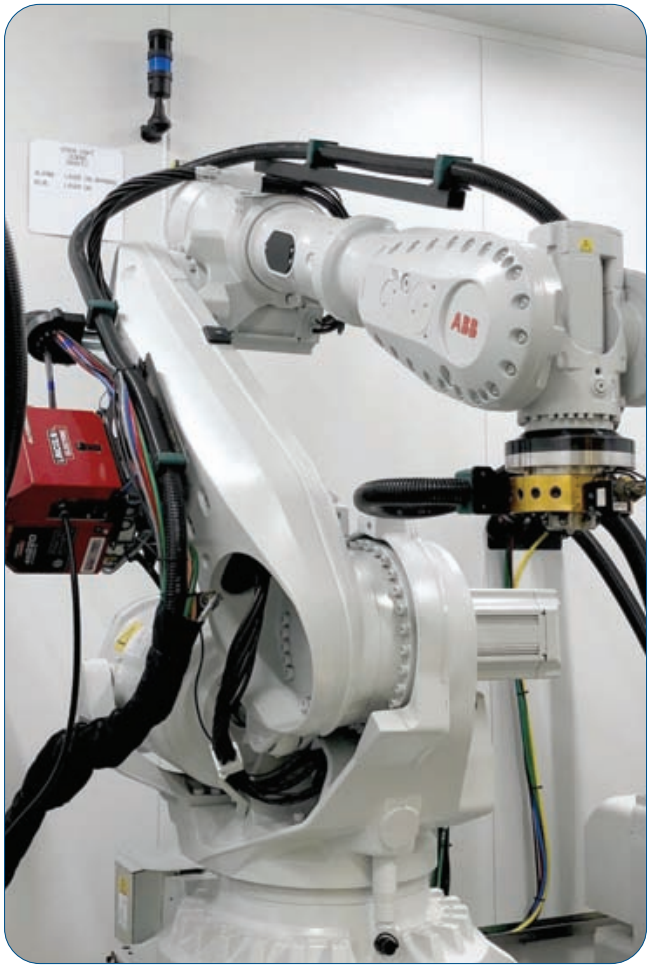
The Refabricator was launched to the ISS in November 2018 on board Northrop Grumman's Cygnus spacecraft's 10th commercial resupply services mission.

Firmamentum is also developing a revolutionary suite of technologies called SpiderFab, which will enable on-orbit fabrication of large spacecraft components like solar panels and antennas, including kilometre-scale antenna reflectors. Under a NASA/LaRC SBIR contract and a follow-on NASA Tipping Point Technologies Public-Private Partnership, TUI is working on the first step in the SpiderFab architecture; the Trusselator uses 3D printing techniques and robotic assembly to create long, high-performance truss structures.

The European Space Agency

The European Space Agency (ESA) is also exploring its 3D printing options. The agency launched an investigation in July 2018 to establish how 3D printing could be used to create and run a habitat on the Moon. The ESA opined that additive manufacturing could be used to create everything from building materials to solar panels, equipment, tools, clothes, and even nutrients and food ingredients.

One of the ESA's greatest priorities for future Moon-settlement missions is that they be self-sufficient, that personnel are able to utilise things that are already there or were brought on the original mission, rather than continually sending back and forth to Earth for more supplies, which would be extremely costly and time-consuming. As such, 3D printing is expected to allow on-demand production of key items and enable the routine recycling of materials available within the base, increasing sustainability. The ESA's research continues, being complemented by various public outreach programmes, including a 2018 call for ideas from the general public on the one item they would like to have 3D printed to keep in a lunar home. ■



Lockheed Martin Metal 3D printer

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