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3D Printing:
Applications for Space Exploration

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3D Printing or Additive Manufacturing (AM) was first tested in 1983 by inventor Chuck Hull. Conventional "subtractive manufacturing" involves carving out items from a single block of material, whereas AM involves adding plastic or metal, layer by layer, according to specifications generated through Computer-Aided Design (CAD) software to manufacture a product. While, a number of processes that differ in the method of depositing of layers and their binding have been developed over the years, the technology has not evolved enough to find mainstream support. Its use was restricted to production of CAD models for use in various evaluation processes and for prototype research. Advances in metallurgy, miniaturisation and processing have now made it a viable competitor to conventional manufacturing in producing end products. It is even being called the third industrial revolution.

Key Points

1. Conventional "subtractive manufacturing" involves carving out items from a single block of material, whereas Additive Manufacturing, also called 3D Printing involves adding plastic or metal layer by layer according to specifications generated through a computer-aided design (CAD) software to manufacture a product.
2. This provides a number of benefits over the conventional manufacturing processes but its ability to replace mass production is still questionable. However, it holds transformative potential in designing and fabrication for a niche domain such as space.
3. Advanced space faring nations, along with some private players are investing in the technology and its diverse applications. NASA's 3D printer that was installed aboard the International Space Station and has subsequently produced a number of parts has brought these efforts to the forefront.
4. Success of these experiments would enable revolutionary changes in space exploration infrastructure and operations. All space faring nations, including India, would benefit from investing in this futuristic technology.

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3D Printing...

Commercial enterprises, having recognised the transformative potential of AM, in both designing and manufacturing, are increasingly investing in it. In designing, it allows faster iterations, providing flexibility for refinements and variations and produces more accurate 3D scaled models for testing. This helps in accelerating product development and manufacturing, with corresponding cost benefits. Conventional manufacturing involves production of a number of parts that are then brought together to form a functional structure or component. Limitations of these processes have constrained the design potential from turning into reality. While evolution in technology helped gradually address these limits, AM, with its ability to construct integrated structures with very high precision, can potentially revolutionise this 'design to manufacturing' process. The process would allow integrating many of the system's geometries into structural elements during production, reducing the number of parts and interfaces, eliminating most joints or welds, thereby making the system more efficient, lighter, sturdier and safer. At the same time, it would enable production of highly complex parts. Existing proven parts could be replicated with these benefits or even redesigned for greater benefits, while, at the same time, reducing human involvement and the associated risk of human errors. Designers can be more audacious in their pursuits, stepping beyond the constraints of conventional design and manufacturing, while seeking innovative solutions or entirely new capabilities. The manufacturing process requires less material, reduces wastage during production and is more energy efficient, making it potentially more environment friendly. Objects can be created on demand, thereby eliminating costs, logistical complexities and wastages related to surplus inventories. Initial printers were capable of handling single materials only but the multi-jet technology is allowing combining of materials to produce gradient alloys with varied material properties: mechanical, thermal and chemical. Structural problems such as those related to welding together of sub-components made of different metals, especially with different sets of mechanical and physical properties, can be overcome by allowing mixing of materials at the printing stage itself. Better control would allow the option of changing the alloy proportions depending on the strength needed in each section of a component allowing savings in weight and costs. Embedded 3D printed electronics are also being researched for aerospace, automotive, and industrial applications. Nanotechnology coupled with 3D printing promises exciting opportunities in the future. Proponents of the technology even forecast that it will enable large factories with their assembly lines to be done away with.

Already, expiration of patents and opening up of proprietary controls to allow access to technology is allowing availability of cheaper printers that has made the power of designing and producing publicly available. In a similar fashion more materials are also being made available. This democratising of manufacturing has the potential to revolutionise innovation. Applications are being developed for a host of high technology sectors that include medical, automotive and aerospace. Defence research is also looking at the technology to provide innovative solutions for military operations. Market researcher Gartner forecasts that worldwide spending on 3D printing will rise from $1.6 billion in 2015 to around $13.4 billion in 2018. Despite the excitement, there are experts who say that the technology might only evolve to supplement the conventional mass manufacturing methods that will continue to be faster and cheaper. They instead favour its suitability for niche and customised production. However, as has been with most contemporary technologies, developments have taken place at, much faster rate than had previously been estimated by experts.

Space exploration has always been expensive owing to its requirement of low volume, precise, customised and, at times, unique components, and the requirement of highly skilled manpower required for assembling and testing these parts. The benefits provided by 3D printing are seen by the space industry as particularly enabling for the domain. Various Research and Development (R&D) efforts for ground-based as also in-orbit manufacturing are being supported for technology progression with an aim to produce parts that meet the stringent high performance and high reliability criteria required for space operations. These efforts have borne positive results providing encouragement for more interest and investments. In 2013, the National Aeronautical and Space Administration (NASA) successfully tested a rocket engine injector that was 3D printed using copper alloy materials. It claims that 3D technology enabled designers to create more complex injectors while, at the same time, reducing the number of parts from 115 to just two, allowing for more efficient processes and better thermal resilience. Also, engineers have claimed that against traditionally constructed injectors that cost about $10,000 each and took more than six months to build, the 3D printed versions cost less than $5,000 and were produced in weeks. In 2014, NASA, along with US rocket engine maker Aerojet Rocketdyne, followed up with 19 hot-fire tests with different injector and thrust chamber assembly configurations on a rocket engine scaled at about half the size of the RS-25 engine that is slated to power NASA's Space Launch System. The components proved themselves under pressures of up to 1,400 pounds per square inch and temperatures of up to 6,000 degrees Fahrenheit, while producing 20,000 pounds of thrust. These tests have provided confidence in the technology and its potential to replace other complex engine parts. Still, exhaustive testing will have to be done on full scale engines and the components will have to prove their reliability over prolonged operations and with much larger thrusts before they can be employed in actual launches and space flights.

Already, some additively produced structural parts have been utilised as internal components onboard US and European satellites. For example, the KySat-2, a CubeSat class satellite launched by NASA in November 2013, includes nine such parts. NASA has a number of ongoing projects and is also evaluating using the technology for manufacturing composite CubeSats. As part of its human exploration project for Mars, it is testing a Desert RATS (Research and Technology Studies) rover, 70 percent of, whose parts have been additively manufactured. The European Space Agency's (ESA's) and European Commission's Additive

Manufacturing Aiming Towards Zero Waste & Efficient Production of High-Tech Metal Products (AMAZE) project, has 28 European companies as partners that are looking at perfecting 3D printing of high quality metal components for aerospace applications. Chinese investments in this technology are growing and on their last manned space mission in 2013, their *taikonauts* occupied customised 3D printed seats. In December 2014, Chinese scientists claimed to have produced a 3D printing machine, which could be used during space missions. Private companies the world over are involving themselves in the pursuit of aerospace applications. The Japanese Space Agency (JAXA), along with Mitsubishi, is working at producing 3D components for a new large-scale rocket that the two are expected to develop by 2020. The Swiss company RUAG Space has built an antenna support for an Earth Observation (EO) satellite that will replace a conventionally manufactured one after tests. Similar development is being undertaken by NASA to develop 3D printed space-worthy support structures for satellite antenna arrays. These would be the first 3D printed components used on the outside of a spacecraft, exposed to radiation and temperature extremes of outer space, whose success will pave the way for more AM involvement in spacecraft production. Space X, in January 2014, successfully launched its Falcon 9 rocket with its first operational 3D-printed part, a Main Oxidizer Valve (MOV) body in one of the nine Merlin 1D engines. The company claimed that the MOV body was printed in less than two days, compared with a typical castings cycle measured in months. The engine chamber of the SuperDraco thruster to be used on the crew version of SpaceX's Dragon spacecraft, capable of producing 16,000 pounds of thrust, is manufactured using 3D printing and is presently undergoing tests. Planetary Resources, a private US company, seeking space exploration and asteroid mining, has collaborated with another US AM entity, 3D Systems, for developing and manufacturing components for its ARKYD Series of spacecraft using its advanced 3D printing and digital manufacturing solutions. A team of engineering students from the University of Arizona, with help from 3D printing company Solid Concepts, recently assembled a 3D printed rocket within a day and successfully tested it. Tethers Unlimited, a US company in contract with NASA aims to manufacture large components of kilometre-scale systems for use in space exploration, such as parabolic reflectors, phased array antennas, optical mirrors, solar panels, and trusses. All these efforts are providing solutions that are cheaper, involve smaller number of parts and have comparatively shorter developmental timelines. Future developments might allow constructing integrated spacecraft structures which would better sustain the rigours of launch and space exploration. They would even enable reconceptualising space architectures, impacting on their design, sizes and functionality.

The most exciting opportunity is 3D printing of objects in space – an idea that has the potential to cause a paradigm change in the way we look at space exploration. The concept has been debated for decades and NASA has also conducted some experiments since the Skylab space station of the 1970s. In 2010, it collaborated with a US company, Made in Space, to develop and test a 3D printer that could operate in microgravity aboard the International Space Station (ISS). As part of the "3D Printing in Zero-G Technology Demonstration" experiment, the microwave oven sized printer, previously tested on sub-orbital flights, was installed onboard the station on November 17, 2014. After two calibration tests, on November 24, 2014, on command from the ground controllers, the printer produced the first 3D object in microgravity. The object was a faceplate of the printer itself, demonstrating that the printer could make replacement parts for itself or even whole printers in the future. Until January end, the printer has produced 14 items constructed from 25 pieces, including a ratchet wrench whose design was "emailed" to the ISS. All the other parts made by the printer had come from designs installed on the machine before its launch. These parts will subsequently be returned to Earth where they will be compared with similar samples made by the same printer before launch and also analysed for the effects of microgravity on them. This would help in evaluating the variance and possible advantages of AM in space and in defining the roadmap for future developments. Meanwhile, Europe's POP3D (Portable On-Board Printer), designed and built in Italy, is also scheduled for installation aboard the ISS this year. While the current printers are using plastic, future experiments are expected to involve metals.

Producing parts and structures in space potentially provides a host of benefits. Structures being constructed on Earth have to be built in an environment that is different from where they would operate. These parts also have to survive the vibrations and high 'g' stresses of launch. Freed from these constraints, novel space architectures, more optimised to the microgravity environment, can be imagined and developed. 3D printers in space would enable astronauts to manufacture their own components and tools, undertake repairs, replace broken items and respond to evolving requirements without being dependent on support from Earth. This would bring down logistical requirements related to deployment of structures in space, while improving mission efficiency and reliability. Already, many companies have come with solutions for 3D printing of food and NASA is funding research to achieve this in space. This would overcome the current issues related to food shelf life, variety and nutritional requirements. It would be possible to have human missions of longer duration and venturing much further into space. Made In Space has an ongoing project R3DO that seeks to recycle 3D produced broken or redundant parts to create new ones, thereby helping reduce space waste. The technology in the future could be used for space-based construction of large structures – even entire spacecraft. Meeting the high power requirements related to the technology in space will be a major challenge. Already companies are working at developing low power technologies and also looking at efficiently garnering solar power to address this.

Notwithstanding the benefits, there would still be a requirement to transport large amounts of raw material to space – to cater to all probable requirements. This would require a logistical optimisation to avoid carrying excess raw material that could end up adding on, rather than reducing, the weight. The complexity will only increase when catering to requirements of different materials. On the other hand, solid chunks of material that would mostly be less voluminous than finished parts would provide the benefit of space onboard the constrained environment of the spacecraft. Another concept being envisaged is the use of 3D printing for construction of large housing structures, roads and launch pads using the resources available *in situ* on celestial bodies. Building of housing structures through 3D printing has already been demonstrated in plastic as well as concrete. Both NASA and ESA are exploring printing of objects using Regolith, the powdery substance that covers much of the surface of the moon. Besides the huge savings in cost and time, such habitats would be more suited to the local hazardous environment. The printers could either be controlled from Earth or make use of automated robotic machines. These capabilities would be a great step forward for human interplanetary exploration.

3D printing is making rapid strides and its applications are being recognised by industry. Scientists are working to smoothen out the inefficiencies and shortcomings of the processes as also evaluating potential opportunities. Developments in the space domain are promising but these would have to be put through rigorous testing before being cleared for regular use and this would be a long drawn process taking years. Qualification and verification standards that would eventually be defined for this new industry would have to be more stringent for use in space. More complex printers will have to be devised for construction of larger parts. Currently, most construction is focussed on building frames and structures but in the future would also require manufacturing techniques for producing working electronic components. For production in space, bigger printers would bring forth issues of mass, volume and power requirements, each one of which is critical for space launch and operations. Some methods would also have to be devised to assemble the parts so produced. The new technology provides an avenue for space industries the world over to graduate to common standards of software as well as hardware. This would allow a larger pool of scientists and engineers coming together, learning and benefiting from each other. The existing outer space regime will need to be revisited to address issues related to use of 3D printing in space such as legal status of objects produced in space and their employment, and use of *in situ* resources.

In India, 3D printing technology is still in its infancy, with low penetration in the industry. Some global AM companies have gained a foothold in India through collaborations and there are some indigenous initiatives too. However, current usage is mainly restricted to production of CAD models and testing. Isolated research is being undertaken by some private and public sector entities including the Defence Research and Development Organisation (DRDO). Private companies are collaborating with some engineering institutions like the Indian Institutes of Technology (IITs) to promote research. There is also the Additive Manufacturing Society of India (AMSI) that seeks to promote 3D printing and AM technologies. There is growing recognition of its applications, and defence and aerospace are two important sectors that most AM companies want to focus on. The chairman, of the Indian Space Research Organisation (ISRO), after the successful Mars orbiter mission, mentioned 3D printing as one of the technologies that he wishes to see Indian engineers build upon in the future.

India has lagged behind in conventional manufacturing and metallurgy. It now has the opportunity to leverage its advances in software technology and collaborate with international experts to initiate activities in this sunshine sector. The 'Make In India' programme that seeks to transform India into a global manufacturing hub would do well to pursue such futuristic technologies besides trying to improve on the conventional ones. India is one of the leading space-faring nations of the world and its successes in recent times has reaffirmed this position. A more confident ISRO is now seeking bigger launch vehicles, exploration missions to the Moon and Mars, and human exploration endeavours. All these would benefit from this promising technology. While increased awareness and commercial benefits will drive industry to invest in the sector, defence and aerospace initiatives would require the government to play the vital supporting role while seeking participation from industry and academia. Investments would be required in planning and executing the supporting infrastructure required to enable fabrication processes, in creating knowledge and capabilities through education and training and for provision of adequate R&D facilities.

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