3D Printing Applications for Space Missions

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This column is coordinated and edited by William D. Fraser, M.Sc. These articles are not peer-reviewed. The AsMA Science and Technology Committee provides the Watch as a forum to introduce and discuss a variety of topics involving all aspects of civil and military aerospace medicine. Please send your submissions and comments via email to: fraserwdf@gmail.com. Watch columns are available at www.asma.org through the "Read the Journal" link.

Space mission architecture constraints on mass, power, volume, and crew training time limit in-flight medical capabilities, which could result in unacceptable health and mission outcomes.[8] Human space exploration could be revolutionized with 3D printing technology by shifting the current resupply model toward a localized manufacturing approach. For exploration class space missions, 3D printing offers many benefits for autonomous, crew-administered medical care.[20-23] This printing technology facilitates the on-site production of personalized medical resources on demand. An onboard digital catalog of crowd-sourced 3D printable files could minimize spare medical consumables and substantially expand in-flight medical capabilities. The flexibility of 3D printing technology permits the creation of medical equipment components or consumables to address multiple medical scenarios for the same amount of mass in the form of printer material. Fused deposition modeling (FDM) 3D printing technology offers potential auto-repair, recycling, and intrinsic sterilization capabilities.[23] These features of 3D printing could substantially reduce mission costs and optimize crew health outcomes. NASA and ESA are exploring the application of 3D printers for manufacturing food, tools, International Space Station (ISS) replacement parts, next generation advanced prototype space suit customized components, and habitats on-site for long-duration space missions.[18,21]

Types of 3D Printers

Different 3D printing processes vary in the printer material used and how the layers are printed.[24] FDM printers work by heating a solid thermoplastic filament inside a printer extruder which deposits the liquefied plastic in a digitally controlled manner, layer by layer, on a horizontal platform. Selective laser sintering (SLS) printers use a laser to fuse metal, ceramic, or plastic powders on a platform, layer by layer, into digitally specified shapes. Electron beam freeform fabrication (EBF3) printing uses an electron beam gun that melts a dual wire feed inside a vacuum chamber and deposits the molten metal in a digitally controlled fashion on a rotating platform to manufacture structural metal parts layer-by-layer.[6]

FDM printers are being deployed for ISS missions, but are limited to printing thermoplastic materials.[4,9] A portable EBF3 metal printer has undergone parabolic flight testing.[6] Industrial-size SLS printers for manufacturing metal, composites, and other materials are challenging to operate in a microgravity environment, but could be deployed on a lunar, Martian, or asteroid surface.

Off-Earth Fused Deposition Modeling 3D Printing

A gravity-independent, single-extruder FDM acrylonitrile butadiene styrene (ABS) thermoplastic 3D printer was launched to the ISS in September 2014.[13] This 3D printer is sealed to prevent off-gassing into the closed environmental system of the ISS.[23] The first functional object printed in space was an access panel to the printer extruder, which demonstrates that the printer is capable of printing part of itself.[9] With 3D printing technology, it is possible to uplink hardware to space. During ISS Expedition 42, a ratchet wrench was custom designed on the ground, qualified, tested, uplinked to the ISS, and 3D printed in space in less than 1 wk.[13] Onboard the ISS, 25 test prints of 14 designs were printed and are now undergoing structural and mechanical analysis at the NASA Marshall Flight Center.

The next generation FDM 3D printer in space is scheduled for deployment in 2016 and will offer a larger print platform (14 cm in width × 18 cm in length × 10 cm in vertical height) and a wider selection of printer materials, including ABS, high

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density polyethylene, and polyetherimide/polycarbonate.[12] The Italian Space Agency is planning to launch a FDM polylactic acid thermoplastic 3D printer to the ISS.[4] A reclamation device to recycle scrap or waste plastic into ABS or polyetherimide/polycarbonate thermoplastic FDM printer filament is also being developed for the ISS.[14]

Crowd-Sourcing 3D Printable Medical Designs

Interdisciplinary, global collaboration to generate novel solutions is fostered by 3D printing. With 3D printing technology, it is possible to crowd-source innovative, cost-optimized designs of medical resources to treat an ill or injured crewmember on a long-duration space mission. In 2015, the International Space Apps Challenge launched a project challenge entitled "3D AstroMed Devices." The goal was to design 3D printable medical resources for the ISS. Participating in this design challenge were 17 multidisciplinary teams from various countries, including Australia, Cyprus, Ecuador, Finland, France, Japan, Macedonia, Mexico, Morocco, Peru, United Kingdom, and United States. 3D4MD (www.3d4md.com), a global health program that creates 3D printable medical supplies, is working with these teams to advance their prototypes.

Applying 3D Printing to Operational Space Medicine

3D printing technology could be applied to potentially address a number of risks in the NASA Human Research Roadmap, including, but not limited to:[9]

- ExMC 3.03: We do not know which emerging technologies are suitable for in-flight screening, diagnosis, and treatment during exploration missions.
- ExMC 4.06: We do not have the capability to stabilize bone fractures and accelerate fracture healing during exploration missions.
- ExMC 4.08: We do not have the capability to optimally treat musculoskeletal injuries during exploration missions.
- ExMC 4.11: Limited dental care capabilities.
- ExMC 4.23: We do not have the capability to auscultate, transmit, and record body sounds during exploration missions.
- ExMC 4.27: We do not have the capability to sterilize medical equipment during exploration missions.

To date, studies have described the feasibility and cost-benefits of FDM 3D printing thermoplastic surgical instruments, mallet splints, and dental tools for Mars analogue mission crewmembers (**Fig. 1**).[20-23] The ideal 3D printable design for off-world medical resources would: 1) be manufactured entirely out of onboard printer filament; 2) use printer feedstock composed of recycled materials or locally available resources; 3) consume minimal power and printer material; 4) be printable with onboard 3D printers which are used for nonmedical purposes; 5) require no post-processing and little to no assembly by minimally trained personnel; 6) be functional, robust, reliable, and customizable; and 7) be hygienic or sterilization capable, depending on its clinical use.

FDM 3D printers can take minutes to hours to print a surgical instrument.[23] Thus, the printing speed of 3D printers must

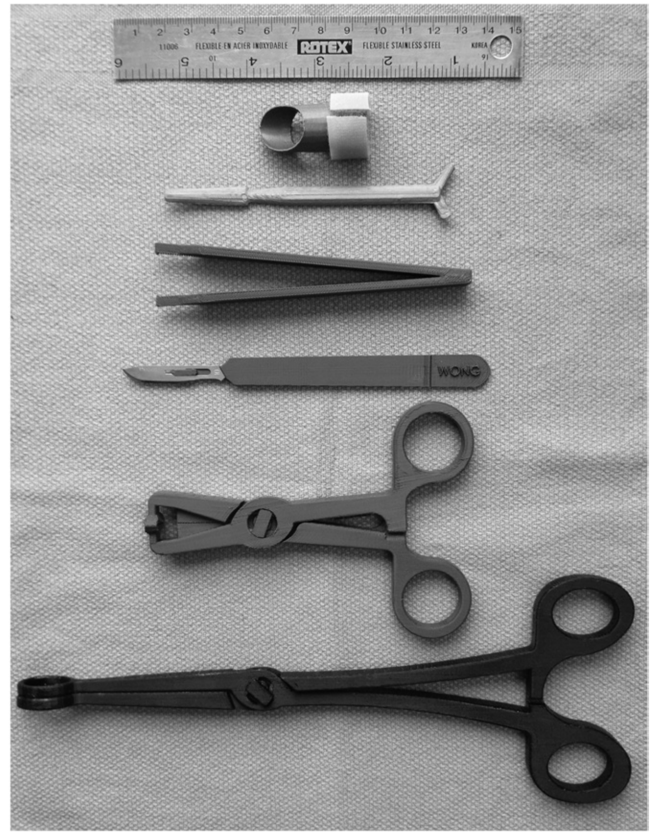

Fig. 1. 3D printed ABS thermoplastic medical resources (from top to bottom): custom mallet splint with hook and loop strap, two-in-one dental filling replacement instrument, toothed forceps, scalpel handle with #10 surgical blade, towel clamp, and sponge stick.

be increased substantially before 3D printers should be used to produce resources on demand for surgical emergencies. However, 3D printers could potentially: 1) manufacture surgical instruments during the 8-h preoperative fasting period; 2) create medical resources customized for a crew medical officer or patient; 3) restock surgical consumables postoperatively; and 4) make dental instruments preoperatively.

Preliminary studies show that the FDM printing process sterilizes ABS and polylactic acid thermoplastic filaments.[10,15,16] Investigations on low temperature sterilization methods show that ABS-M30i, an ISO 10,993 Class VI biocompatible thermoplastic, can be sterilized by ethylene oxide gas and gamma radiation and that hydrogen peroxide gas plasma or nuclear decontaminant gel could potentially be used to sterilize FDM printed ABS thermoplastic.[2,17] However, more work is needed to select and validate appropriate sterilization processes for space missions.

Off-World Metal 3D Printing

Off-Earth 3D printing may not be limited to thermoplastic materials in the future. NASA's Langley Research Center is developing EBF3 technology to 3D print aluminum, copper, titanium, and weldable alloys for the aerospace industry.[19] The theoretical advantages of EBF3 are less wasted material, shorter fabrication times, efficient power usage, reduced costs, secondary processing capability, and localized manufacturing capabilities for space missions.[6,11] In 2013, ESA launched the Additive Manufacturing Aiming Toward Zero Waste & Efficient Production of High-Tech Metal Products (AMAZE) Project, which seeks to create a metal 3D printer for the ISS.[5] The project is currently investigating five metal 3D printing processes, including SLS and EBF3.

3D Printing and In Situ Resource Utilization

Using in situ resources as printer material, 3D printing technology could be applied to construct off-world habitat structures. A 2013 study demonstrated the feasibility of using a SLS 3D printer to manufacture habitat structural parts using simulated lunar regolith.[1] In 2013, Monolite UK Ltd. demonstrated to ESA that their D-Shape 3D printer could use simulated lunar soil to manufacture a 1.5-ton building block for a hollow dome structure.[3] First, magnesium oxide was mixed with the simulated lunar regolith to make it suitable for printing. Then a mobile printing array with nozzles on a 6-m frame sprayed a binding salt to convert the sand-like material layer-by-layer into solid marble. In 2015, NASA's Centennial Challenges Program launched the "3-D Printed Habitat Challenge," a $2.25-million prize competition to design a 3D printed habitat using in situ or recycled resources for Mars and other deep space missions. The top three winning entries proposed using subsurface ice and Martian regolith as printer feedstock for building off-world habitats.[7]

Conclusions

For supporting autonomous, crew-administered healthcare on long-duration space missions, 3D printing appears to be a promising technology. It offers localized, on-demand, customized, and flexible manufacturing capabilities which could lower costs, improve crew health outcomes, and enhance the self-sufficiency of deep space missions. Future work could include crowd-sourcing and obtaining FDA approval for lower cost 3D printable designs of: 1) in-flight medical consumables and equipment components; 2) medical devices undergoing technology readiness level testing for space missions; and 3) medical equipment or consumables that are not currently flown on space missions, but could be potentially life-saving or used to treat an injured or ill crewmember. Further development is also required to validate and certify sterilization and recycling protocols for human exploration missions.

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