One of NASA's Missions: Taking 3D Printing to New Heights

In-space manufacturing, despite many challenges, offers the potential to enhance astronaut safety, lighten payloads & extend missions

By Robert Grace

In-space manufacturing has become a priority at NASA. Here, a student-designed device – dubbed the Multipurpose Precision Maintenance Tool (see Page 17 sidebar) – floats in microgravity. Courtesy of Made In Space Inc.

Manufacturing high-precision components is challenging under any circumstances. Now consider doing so in the following conditions: zero gravity, with limited supplies, in the area roughly the size of a refrigerator, and with virtually no margin for error. Oh, and succeeding *may* be a life or death proposition or, at least, help determine whether a multimillion-dollar mission meets all its goals or not.

Other than that, no pressure.

NASA – the U.S. government's National Aeronautics & Space Administration – has been keenly interested in finding a way to manufacture items in space for nearly two decades. The reasons for wanting to achieve this are manifold:

- Being able to manufacture and replace broken components can keep vital gear functioning;
- Doing so also lightens the payload of a spacecraft by minimizing the number of spare parts that must be carried up to space;
- Medical devices may be needed to help keep astronauts healthy, especially on extended trips such as the three-year mission to visit Mars.

Now, with rapid technological advances in 3D printing – also known as additive manufacturing – NASA is getting closer to turning this dream into a reality.

The agency began testing 3D printing technology in space back in 1999, when it first conducted experiments on so-called parabolic flights – in which a fixed-wing aircraft is used to train astronauts in zero-gravity maneuvers, giving them about 25 seconds of weightlessness out of 65 seconds of flight in each parabola. That effort was headed up by Raymond "Corky" Clinton, Jr., who is associate director of the Science & Technology Office at NASA's Marshall Space Flight Center (MSFC) in Huntsville, Ala.

It was a start, but obviously there are limits to what one can 3D print in spurts of less than 30 seconds. NASA began a more ambitious 3D printing project in 2012, starting with testing various polymers, and launched the first 3D printer into space on Sept. 21, 2014.

The woman heading the initiative, both then and now, is Niki Werkheiser, NASA's project manager for In-Space Manufacturing (ISM). Also based at MSFC in Huntsville, Werkheiser – a mother to two daughters – dreamt of working for NASA since she was a child. She earned degrees from the University of Alabama in Huntsville in Russian studies (B.A.), biology (B.A.), and gravitational biology (M.S.), and has focused on 3D printing in space for the past five years. A December

Niki Werkheiser, based at the Marshall Space Flight Center in Huntsville, Ala., has headed NASA's In-Space Manufacturing program for the past five years.
Courtesy of NASA

2014 *Forbes* magazine feature labeled her a "phenomenal NASA pioneer."

Seeking self-sufficiency

The goal of her team is to make astronauts more self-sufficient in space, by enabling them to make useful objects, landing pads, radiation protection and even entire habitats (see sidebar, Page 16). Doing so would enhance their safety, and allow them to travel much further and stay in space longer.

A recent article on Mashable.com noted that astronauts, for example, run a high risk of developing cardiovascular disease from weightlessness and space radiation, making the idea of being able to manufacture medical equipment in space even more important for long-term missions.

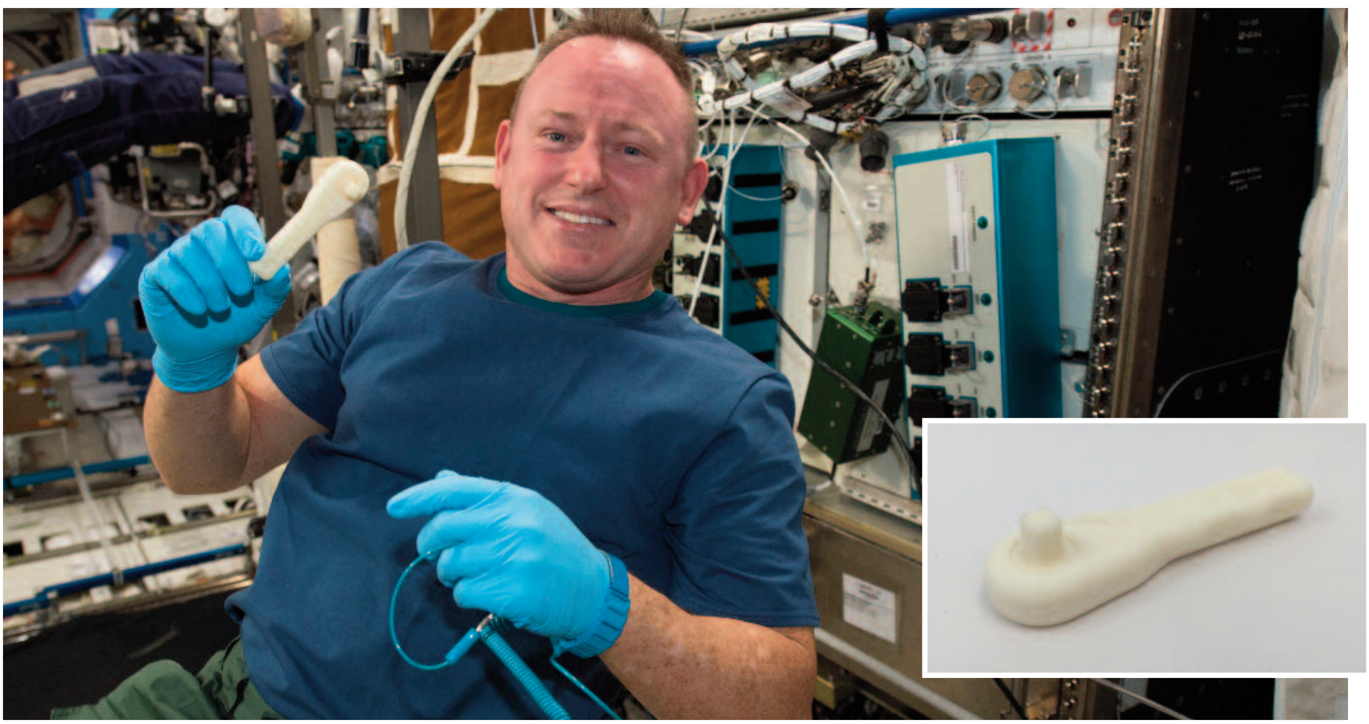
In late 2014 NASA's in-space manufacturing initiative involved sending a small, custom-made Fused Deposition Modeling (FDM) machine to the International Space Station (ISS), where it conducted more than 1,600 3D printing experiments. Scientists used the results to try to learn as much as possible about the challenges of printing in zero gravity.

The whole purpose of that payload, Werkheiser said, was to compare ground samples and flight samples and see if microgravity might have introduced any meaningful differences in the functionality for the characteristics of the part. Such research continues today.

One much-celebrated object that the ISS 3D printed is space in 2014 was an all-white, unremarkable-looking ratchet wrench that measured 4.48 in. long by 1.29 in. wide. The wrench was designed by Noah Paul-Gin, an engineer at Made In Space Inc. (www.madeinspace.us). NASA had issued a Small Business Innovation Research (SBIR) contract to the Silicon Valley-area company to design, build and operate the printer. Paul-Gin created a 3D model of the ratchet and made several wrenches.

"In less than a week," Werkheiser said at the time, "the ratchet was designed, approved by safety and other NASA reviewers, and the file was sent to space where the printer made the wrench in four hours."

It can take months or even years, depending on the launch resupply schedule, to get equipment to space, and for exploration missions, resupply from Earth may be impossible, NASA has noted. This technology may change how NASA completes exploration missions and even the way science



Pictured here in December 2014, NASA astronaut Barry (Butch) Wilmore holds a 3D printed ratchet wrench from the new 3D printer aboard the International Space Station. The printer completed the first phase of a NASA technology demonstration by printing a tool with a design file that was transmitted from the ground to the printer. (Inset) Ratchet print for NASA made as a demonstration of a tool. Images courtesy of NASA is conducted on the station.

Almost three years ago, Werkheiser was already speculating on the promise of this technology when she stated the following: "If you can transmit a file to the station as quickly as you can send an email, it opens up endless possibilities for all the types of things that you can make. We even may be able to make objects that previously couldn't even be launched to space."

The International Space Station's 3D printer is shown configured in the Microgravity Science Glovebox. Testing this on the station was the first step toward creating a working machine shop in space. This capability may decrease cost and risk on the station, and will be critical when space explorers venture far from Earth and will create an on-demand supply chain for needed tools and parts. Courtesy of NASA

In a recent telephone interview, Werkheiser recounted how the U.S. government's Office for Management & Budget gave guidance in NASA's budget in 2015 to create this In-Space Manufacturing Initiative, with the objective being to identify and develop new technologies, processes and capabilities needed for on-demand manufacturing, repair and recycling during space missions.

"The space station is a huge test bed for us," she said, "but where this really becomes a critical paradigm shift is our longer exploration missions, to destinations such as Mars," which is a three-year mission.

"The ISS (International Space Station) has been there 15 years, been an amazing process, and we've learned quite a bit, but we're still very earth-dependent. It's a very different operating model than the one we will be employing for our longer missions."

Quoting Corky Clinton, Werkheiser said the aim is that "we will take this from being a novel capability or a lab curiosity to an institutionalized capability that we're using."

There's a 3D printing machine on the ISS now that NASA calls the Additive Manufacturing Facility. This is a commercial printer made by the company Made In Space. It currently can run three thermoplastic resins – ABS, HDPE and Ultem 9085, a specific grade of SABIC's polyetherimide material.

A focus on materials

"The machines get a lot of attention," Werkheiser said, "but behind the scenes we're really working hard on material development and characterization, our verification and validation on how we create a consistent, uniform process that's repeatable, and things like our design database."

One of the keys now is for NASA to figure out exactly *what* it needs to make in space, and that's not a task it can outsource to anyone else, she noted. "So we're working with our exploration system designers who are working today on systems such as environmental control and life support, tools, habitant, structure — because it really starts in the design process.

"To create the 'how' we will make it, we're working very closely with industry and academia," Werkheiser said. "We want to leverage what's being done in that disruptive field. We're not trying to reinvent the wheel, but we want to be partners with them."

One of the many challenges in this project involves figuring out how to adapt the methodology to allow for having only small statistical samples, and to focus on functionality.

"There's a fine line between trying to be academic and then ensuring that the parts that we make work," Werkheiser said, "because for the crew members on orbit, there's obviously no WalMart."

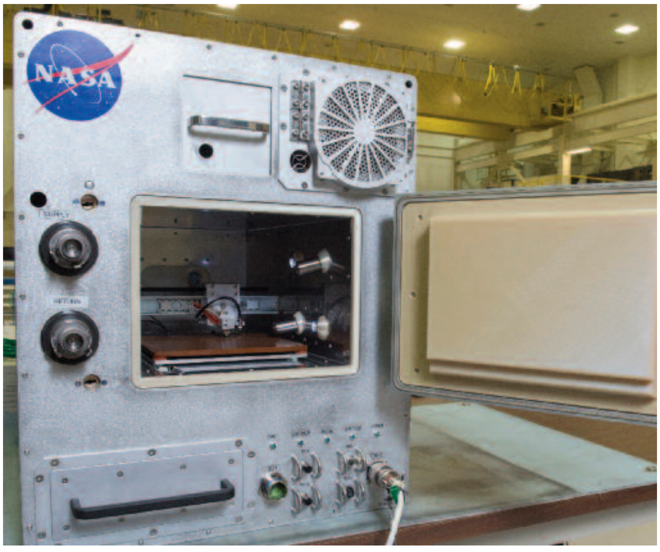
Aerospace engineer Dr. Tracie Prater is materials design lead on the ISM project. The team also has a design optimization additive manufacturing expert, another lead to stay on top of all technology development, and a materials lead.

"Any part that we end up making," Werkheiser explained, "we turn those knobs differently between the material, the machine we're using, and how you can optimize the design. Each one of those parts have a different formula, with them working very integrated and closely together.

Scientists at Marshall continue to study sample parts that have been 3D printed in space, focusing mostly on gathering and analyzing additional statistical data, measuring process variables, and the like, Prater said.

"That data," Werkheiser said, "has reinforced that we did not really see any variables we could pinpoint that were microgravity-based, but we do definitely realize how important the integration and understanding [is] of the printer process characterization for that printer itself, and the design approach."

NASA has taken the initial lessons learned and commissioned Made In Space to build the second-generation, commercial printer that's on orbit now on the space station.



Developed by Tethers Unlimited Inc., this novel machine serves as an integrated 3D printer and recycler, able to turn used parts back into high-quality 3D printing filament.
Courtesy of NASA

That's the so-called Additive Manufacturing Facility, or AMF. It's a bit larger than the first printer, which was very small so it could fit into the Microgravity Science Glovebox.

Closing the loop in space

The agency continues to work with outside partners to push the envelope on this initiative. It awarded another SBIR contract to a Seattle-area firm called Tethers Unlimited Inc. (www.tethers.com). Tethers is developing 3D-printing-related recycling capabilities for use in space. It has created a machine called the Refabricator – an integrated 3D printer and recycler – that Werkheiser says is "the first of its kind that I'm aware of. We're currently focusing on Ultem for this one. You can feed a 3D-printed part back into it, and it will recycle it back into Ultem filament, so we can print new parts."

Tethers has patented a new approach that does not involve the grinding of pellets that most recyclers today use. Instead, they use an extrusion process, called the Positrusion filament recycler.

The Bothell, Wash.-based company says the Positrusion recycler "implements a novel method for processing plastic parts into 3D printer filament, resulting in an order of magnitude improvement in dimensional quality over conventional extrusion, improving print quality." The machine "is as easy to use as a microwave," it claims. "Scrap parts are inserted into the machine, the user presses a button, and superior filament is produced. In addition to recycling scrap materials, Positrusion can also be used to rapidly (and affordably) produce small-batch filaments for development and qualification of new filament materials."

Though it originally developed the Positrusion process for use on the space station, Tethers says it currently is developing commercial versions of it, for potential use by industry.

Werkheiser said her team conducted a Critical Design Review for the ISS Refabricator at Marshall in June and that the design "passed with flying colors.

"Tethers Unlimited Inc. is now busily working in Seattle to build the flight unit," she said in a recent email update. "They will bring it to MSFC late this year for final flight certification testing and checkout, and it will ship for flight integration early in 2018 with a spring launch anticipated."

The potential cross-over of innovation from space research to real-world commercial applications also excites Werkheiser.

"That's what I love about working at NASA – in addition to what we do in space, there are also applications for here on the ground, to benefit terrestrial advancement. This [the Refabricator] is probably one of the most promising I've ever seen."

NASA has yet another SBIR agreement with Tethers, plus one with a Dayton, Ohio-based company called Cornerstone Research Group Inc. (www.crgrp.com). They are jointly working on recycling what the space agency calls "common-use materials" such as packaging foam, which consumes a lot of volume, as well as food containers and zip-lock bags, etc. NASA wants to be able to recycle and reuse such items on orbit.

"Both Tethers and Cornerstone finished a Phase 2 SBIR recently, with some marvelous outcomes," Werkheiser said. "They are taking different approaches. Cornerstone is working more on the material side, with a 'reversible thermoset,' and Tethers is focusing more on the design and how they actually lay the material."

She said that Tethers 3D printed a packaging material that attenuates the vibration of launch two times better, under testing, than NASA's current foam. She noted that Tethers and Cornerstone are discussing submitting an SBIR proposal for a Phase 2 Enhancement for another joint effort, but she did not have further details at this time. Cornerstone, meantime, has a spin-off company that takes the technology it has developed and adapts it for use terrestrially.

The heartbeat of space

Another company that has an SBIR contract with NASA is Techshot Inc. (www.techshot.com) of Greenville, Ind. Techshot is collaborating with Orlando, Fla.-based nScrypt Inc. (www.nscrypt.com), which manufactures micro-dispensing and 3D printing systems. nScrypt – headed by CEO Dr. Kenneth Church – is very active in the area of printable electronics and multimaterial printing.

The firms have jointly developed what Werkheiser calls a "bio-fabricator." She said they created the first 3D printed cardiac structure done in microgravity and it flew on a parabolic flight last year. "Next year on the space station, they'll be launching the bio-fabricator, which incorporates a bio-reactor and a bio-printer. We see big things coming out of that pretty soon," she predicted.

A story this past April in *Popular Science* featured the work in a story titled "The factories of the future could float in space." That article described the plane on the parabolic flight in summer 2016 as going into a "a stomach-churning ascent and plunge 30,000 feet over the Gulf of Mexico" that yielded about 25 seconds of simulated weightlessness. It was this brief span of microgravity that "allowed a high-tech printer to spit out cardiac stem cells into a two-chambered, simplified structure of an infant's heart."

"Impressive though this may be," the article continued, "it's just a brick in the road toward an even bolder goal. Executives at nScrypt (the makers of the stem cell printer), Bioficial Organs (the ink provider), and Techshot (who thought up the heart experiment) are planning to print beating heart patches aboard the International Space Station by 2019. The printer will fly up on a commercial rocket."

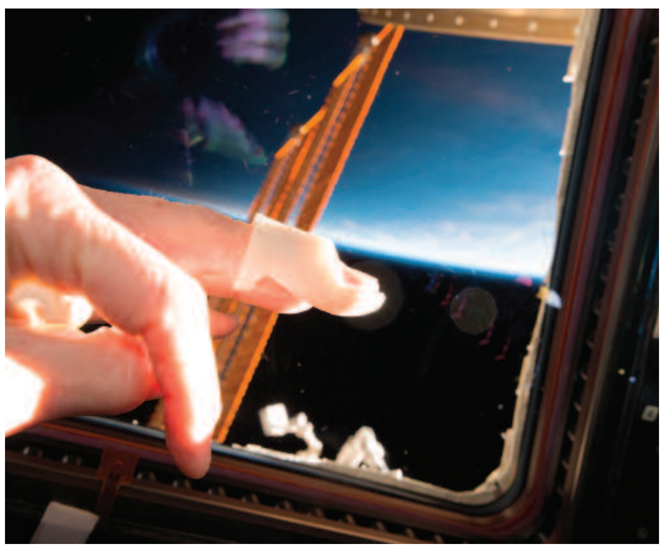
It's clear that NASA and its partners are pushing some incredible boundaries. Certain tasks are more challenging than others. Tracie Prater explained, for example, why it's more difficult to 3D print metal in space than plastics.

"Most of the metal systems that we use at NASA for 3D printing are mostly for propulsion applications – usually PBF, or powder bed fusion, processes," she said. "Those machines require a high power environment, and are in powder form, which is difficult to safely manage in microgravity. And they are highly combustible powders, so there are a lot of challenges in material management [for metal 3DP], and then in miniaturizing that for space flight.

"Wire-fed extrusion processes that are metal-based hold more potential in terms of working in a microgravity environment, but those have high power consumption, as well. And the resulting parts would require some kind of post-process machining such as CNC. So metal is taller challenge than polymers."

Introducing the FabLab

Werkheiser notes that it's critical for NASA to find a way to expand its portfolio of materials and processes for on-demand



The potential medical uses of 3D printing in space range from the exotic (bio-printing stem cells in a cardiac structure) to the more basic (such as making finger splints such as the one shown above). Courtesy of NASA

Where Design & Engineering Converge

Michael Snyder, co-founder and chief engineer of Made In Space, will be one of 20+ presenters at the Design in Plastics conference in Detroit Nov. 6-8. He'll be joined by NASA's Corky Clinton, one of NASA's In-Space Manufacturing leaders. This SPE event focuses on how to hone interdisciplinary collaboration to yield better product development outcomes. Learn more at www.4spe.org/designinplastics.

Snyder

manufacturing on orbit. To that end, she said she was thrilled that NASA put out a public call in May seeking proposals for development of a first-generation, in-space, multimaterial fabrication laboratory, dubbed the FabLab, for space missions. She noted that anyone in industry or academia was eligible to apply to partner with NASA on this effort.

The FabLab development path is to be implemented in three phases, with the objective of the final phase to demonstrate a commercially developed FabLab on the ISS. The agency's solicitation last spring was seeking responses only to Phase A, in which private industry partners would "produce ground-based prototypes with a measurable ability to mature into flight demonstrations on the space station within three years."

Werkheiser noted that this initiative does not explicitly focus on additive manufacturing, but rather sought innovations related to "any on-demand manufacturing process that would work in microgravity, and within the operational constraints we have."

Those constraints are considerable. For starters, any proposed solution needs to fit on one of NASA's EXPRESS Racks. (EXPRESS is an acronym for "EXpedite the PRocessing of Experiments for Space Station" and these are multipurpose payload rack systems that store and support research aboard the space station). She said that each rack is about the size of a double refrigerator. "And we're limited to 2 kW of power per rack. So the volume and power constraints make for the more significant challenges. We also need as much remote command and autonomy as possible."

Werkheiser said recently that the Phase A proposals were originally due on Aug. 2, but based on requests from several proposers, NASA extended the submission date to Aug. 30. "We received a robust number of responses from the Notices of Intent (NOIs), which are encouraged, but not required, so we are very optimistic about the proposals we will receive." She expects the selection announcements to be made in November.

What about industrial design?

NASA obviously works closely with large numbers of scientists, engineers, doctors, materials experts, biologists and other specialists, but what about industrial designers – those creative types known for bringing a "what if?" spirit to product development, while also helping to make products and processes user-friendly?

"That's one of the areas that has come to the table late," admitted Corky Clinton. "What we're trying to do is to institutionalize this capability, and in order to do that, you really need to begin in the design phase.

"We've talked to some of the major implementers like GE that are successful with 3D manufacturing. They'll tell you the same thing," Clinton said: "It's the paradigm shift away from the standard operating procedure," where design, engineering, manufacturing and other disciplines often are kept apart and siloed.

"It's about breaking that structure and integrating these activities and disciplines, and starting from a clean sheet of paper."

What we're trying to do is to institutionalize this capability, and in order to do that, you really need to begin in the design phase.

–Corky Clinton

Werkheiser recognizes this challenge, as well. "I don't lose sleep at night over whether or not these technologies are going to get where we need them," she said. "It's going to take work, and we have to stay with that, but I think we're going to get there.

"What I worry more about is having the engineering team and our designers and what I'm calling now for now our design optimization folks" all collaborating effectively. "That socialization and that dialogue is always the hardest part."

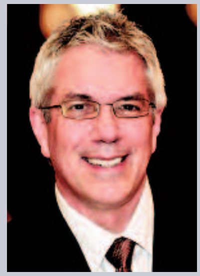
She reinforced Clinton's point, stressing how it's vital to approach every challenge with a fresh set of eyes, to assess the functionality needed and explore how best to consolidate or create an entirely new design that might be more efficient, or have more to offer, or decrease mass, or increase reliability.

"It's all about opening up and getting away from that groupthink," and avoiding foregone conclusions, she said.

NASA, its partners and literally thousands of talented minds continue to work to redefine manufacturing as we know it. Meantime, industry leaders and politicians sometimes refer to amazing stretch goals as "moonshots."

For Niki Werkheiser and her team, however, a moonshot is just another day at the office.

ABOUT THE AUTHOR



Robert Grace began his business journalism career with Crain Communications Inc. in 1980 in Akron, Ohio, and worked for Crain for seven years in London, England, before returning to Akron in 1989 as the founding editor of *Plastics News*. He also served as *PN*'s associate publisher, conference director and business development director. In May 2014 he launched RC Grace LLC, and in July 2016 became managing editor of *Plastics Engineering*. Contact him at bob@rcgrace.com.

Habitats for Humanity – Potentially 3D Printed on Mars

NASA contest finds that recycled thermoplastics could yield a concrete material viable for 3D-printing habitats on the Red Planet

By Robert Grace

NASA wants to find a way to 3D-print habitation structures using recyclables and simulated Martian soil, with the aim of supporting deep space exploration and advancing construction capabilities on Earth.

So it threw down a challenge. This summer the U.S. government agency awarded more than $200,000 in prize money to teams of citizen inventors that have reached the latest milestone of the contest, completing Level 2 of Phase 2, which involved 3D-printing a beam for bend testing. NASA calculated the scores based on the material composition and the maximum load of the beam at failure.

A South Korean team, Moon X Construction, won this stage of the competition (but was not eligible for prize money, since it was an international team). Form Forge of Oregon State University in Corvallis, Ore., took second place (and $67,465), while Foster + Partners California and Branch Technology of Chattanooga, Tenn., jointly earned third place (and $63,783) in this Phase 2, Level 2, after winning top honors (and $85,930) in Phase 2, Level 1.

"This competition is highly dependent on advanced materials design solutions," said Melody Rees, project lead for Branch Technology. Commenting on the efforts of project partner Techmer PM of Clinton, Tenn., Rees said, "Techmer PM's materials design expertise has been vital to our success during each phase of the project."

"Recyclable plastics were used in the top three scoring teams, indicating that a thermoplastic concrete material may be viable for 3D-printing habitats on Mars," said Rob Meuller, senior technologist for advanced projects development at the Swamp Works laboratory at NASA's Kennedy Space Center in Cape Canaveral, Fla., and a subject matter expert for the competition. Thermoplastics "could be obtained from discarded packaging material or even created on Mars using the carbon dioxide atmosphere and hydrogen from water found in the soil. Such concrete materials could also have applications on Earth while using discarded plastic trash."

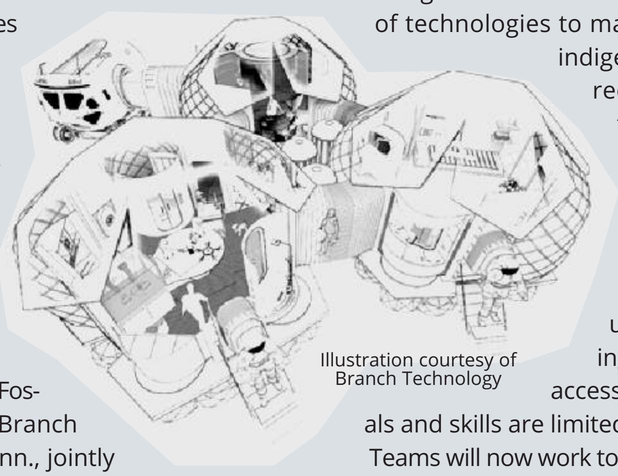


Illustration courtesy of Branch Technology

The goal of the challenge is to foster the development of technologies to manufacture a habitat using local indigenous materials with or without recyclable materials. The vision is that autonomous machines will someday be deployed in deep space destinations, including Mars, to construct shelters for human habitation. On Earth, these same capabilities could be used to produce affordable housing wherever it is needed or where access to conventional building materials and skills are limited.

Teams will now work toward Phase 2: Level 3, where they will be required to 3D-print a dome structure and provide samples for crush testing. Phase 3 of the On-Site Habitat Competition has a $1.5 million prize purse, and will focus on automated 3D-print systems to autonomously construct a complete habitat.

The 3D-Printed Habitat Challenge is run through a partnership with NASA's Centennial Challenges Program and Bradley University in Peoria, Ill. Bradley has partnered with sponsors Caterpillar, Bechtel, and Brick & Mortar Ventures to run the contest.

See more information about the competition at: www.nasa.gov/3DPHab.

NASA Challenges Future Engineers to Think Big, and Out of This World

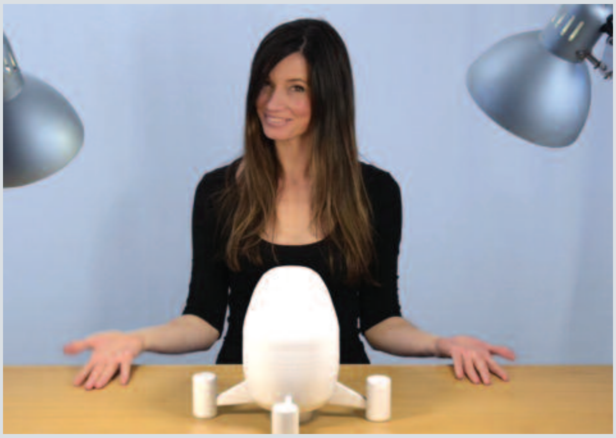
A series of design challenges is helping to engage today's youth and public to create innovative solutions for various in-space issues

By Robert Grace

NASA understands that engaging the public, and firing the imaginations of tomorrow's scientists and engineers is not only good public relations, it's good business.

As a result, the space agency has actively promoted a number of challenges and competitions – some targeting students and others aimed at engaging the general public or innovative companies that could become future partners. And it has had some good results.

In January 2015, for example, NASA and the American Society of Mechanical Engineers Foundation named Robert Hillan, a high school senior in Enterprise, Ala., winner of its Future Engineers Space Tool design competition. The contest launched in fall 2014 and challenged students to create a device that astronauts could use in space. The catch was that it must upload electronically and print on the new 3D printer that was soon to be installed on the orbiting laboratory.



Deanne Bell founded Future Engineers as an online education platform to host national innovation challenges for K-12 students.

Hillan's design – dubbed the Multipurpose Precision Maintenance Tool (http://bit.ly/NASAToolChallenge) – won the teen group (ages 13-19) and was selected out of hundreds of entries to be printed on the space station.

Deanne Bell founded Future Engineers (www.FutureEngineers.org) as an online education platform to host national innovation challenges for K-12 students. Bell, Los Angeles-based CEO of the program, has said: "Our challenges invite students to invent objects for astronauts, which can be both inspiring and incredibly tough."

Hillan's design features multiple tools on one compact unit, including different sized wrenches, drives to attach sockets, a precision measuring tool for wire gauges, and a single-edged wire stripper. NASA installed the new 3D printing machine on the station in March 2015.

Three months later, Hillan was invited to NASA's Marshall Space Flight Center in Huntsville, Ala., and got to watch his design, which had been uploaded to the space station, get printed live. He looked on as NASA astronaut Jeff Williams displayed the finished tool from the station's new Additive Manufacturing Facility. Hillan at the time was a sophomore engineering student at the University of Alabama in Huntsville, just a few miles from MSFC.

More recently, in October 2016, NASA issued a new challenge – its fifth in a series of Future Engineers Challenges – to students in grades K-12 to design an object that could be used by an astronaut to maintain physical health on a 3-year mission to Mars. The Mars Medical Challenge (www.futureengineers.org/marsmedical).

Nearly 750 students from 34 states submitted entries for the Mars Medical challenge in either the Teen Category, for students aged 13 to 19, or the Junior Category, for students aged 5 to 12. This past April, Lewis Greenstein of Seattle was named winner of the teen group for that challenge, for designing an innovative, 3D-printable Dual IV/Syringe Pump.

Greenstein described his product as follows: "IV therapy is crucial because it provides an easy pathway to quickly administer fluids. However, IVs rely on gravity to maintain flow, a luxury not afforded in space. There is only one device able to produce a flow of IV fluid on the ISS: a pressure infuser. Unfortunately, they can only hold one bag, meaning that if more than one infusion was needed, the crew would have to improvise.

"Because of weight limits, I designed my device to use materials already on the ship. A blood pressure cuff is put into one side of the frame (ABS or PLA), and an IV bag is placed in the other. When inflated, the cuff forces the wall to slide, and the spring keeps pressure on the bag. The grid on the front panel allows the bag's label to be read easily. Some medicines must be pushed slowly. In hospitals, this is done with a syringe pump, but there is no such device currently in space. My submission can also be used to slowly administer precise amounts of medicine from up to three syringes simultaneously."

Alabama high school sophomore engineering student Rober Hillan won the 2014 Future Engineers challenge by designing the Multipurpose Precision Maintenance Tool (seen floating above, in front of the space station's 3D printing machine). And Lewis Greenstein of Seattle (right) placed first in the 2016 Mars Medical challenge's teen category with his entry, the Dual IV/Syringe Pump.

Photos courtesy of Made In Space and Future Engineers

For his efforts, Greenstein earned a trip to Houston to tour NASA's Johnson Space Center.

Future Engineers is planning to launch another challenge this fall, and Bell noted: "I am happy that our platform continues to challenge students to dream big and think off-planet."

NASA is not seeking only to engage students. "We're also trying to employ crowdsourcing," said Niki Werkheiser, the agency's project manager for In-Space Manufacturing.

"We did a challenge with a very small prize, like $500, for a part that we could use on orbit, to see if we could design a 3D-printed version of it. Within a few weeks, we had 700 or so entries.

Not only did the entrants design their sample parts, she noted, but "they had done finite element models, and printed and tested them. We brought them in to the team. Never in a million years could our team have come up with that many approaches that rapidly. So we're really trying to do more of that."