

From 3D-Printing Lunar and Mars Habitats to Affordable Sustainable Housing on Earth

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In 2015, the NASA Centennial Challenges program launched the 3D-Printed Habitat (3DPH) competition to develop housing solutions for extended-duration missions on planetary surfaces using advanced additive construction technology. The challenge was executed in three phases with increasing complexities and requirements. The main goal of the competition was to use of planetary indigenous materials and mission recyclables as feedstock for large-scale, autonomous 3D printers to construct a habitat on the Moon or Mars. Phase 1 challenged teams to develop state-of-the-art architecture concepts that took advantage of unique capabilities offered by 3D-printing. In Phase 2, teams autonomously 3D-printed structural components using terrestrial/space-based materials and recyclables. Phase 3 tasked competitors to fabricate sub-scale habitats using indigenous materials with or without mission-generated recyclables and ended in a head-to-head competition. The developments from this challenge are applicable both to the fulfillment of NASA's Moon to Mars mission and to the creation of affordable and sustainable housing solutions on Earth. This paper will summarize the results of the four-year challenge and provide an overview of team achievements as a result of the

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competition. Results from the competition include humanitarian and business opportunities created/negotiated and the development of 3D-printed housing solutions for people such those in need of shelter in Austin, Texas and 3D-printing houses at the United Nations habitat headquarters in Nairobi, Kenya. The Phase 3: Level 5 winner, AI. SpaceFactory, is currently 3D-printing an ecofriendly house in New York called Terra, a full-size habitat design for Mars and available on Earth.

Nomenclature

<i>3DPH</i>	=	3D-Printed Habitat
USACE	=	United States Army Core of Engineers
ERDC	=	Engineer Research and Development Center
SEArch+	=	Space Exploration Architecture LLC
BIM	=	building information model
ConOps	=	Concept of Operations
GCRs	=	Galactic Cosmic Rays
AO	=	Allied Organization
C-Fab™	=	Cellular Fabrication

I. Introduction

The NASA Centennial Challenge program is part of the NASA portfolio of public-facing prizes and challenges competitions used as to incentivize the generation of ideas and/or products for the agency. In 2003, NASA received legislative authority to use appropriated funds to conduct public prize competitions and consequently established the Centennial Challenges program with prizes for specific achievements in alignment with the Vision for Space Exploration. To this day, Centennial Challenges offers incentive prizes to generate revolutionary solutions to problems of interest to NASA and the nation. In keeping with the spirit of the Wright brothers and other American innovators, Centennial Challenges seeks innovations from diverse, multi-disciplinary and non-traditional sources including individual citizens as well as those in academia, industry, and other government agencies. The first competition was opened in 2005 and since then the program has conducted 19 challenges in technology development areas including: propulsion, robotics, communication and navigation, human health, destination systems, science instrumentation, nanotech, materials and structures, and aerodynamics. The length of the competitions have varied from one year for less complex challenges to five years for competitions requiring complex hardware demonstrations. The prize purse offered for challenges ranges from \$100,000 to \$5,000,000. Competing teams must provide proof that the members are U.S. citizens to qualify to win prize money. Fourteen of the 19 challenges have produced winners from 52 teams and awarded more than \$10 million [1, 2, 3].

Planning for the NASA 3D-Printed Habitat (3DPH) Challenge competition started in 2014 with the goal of incentivizing the public to design and construct housing solutions for extended-duration missions on planetary surfaces using advanced additive construction technology. At that time, this was a very ambitious goal because the technology to autonomously 3D-print large vertical structures, similar to what NASA needed to provide shelters for humans living and working on Mars, was not available. It was developed and executed in collaboration with partner America Makes in Phase 1 and Bradley University in Phase 2 and 3. Bradley University successfully secured the sponsorship of Caterpillar, Bechtel, Brick and Mortar Ventures, the American Concrete Institute, and the United States Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC). The partner and sponsors shared with NASA the goal of incentivizing the development of reliable automated additive construction technologies. The challenge asked teams to design and construct a scaled and simulated Martian habitat using indigenous materials and large-scale 3D automated printing systems. This paper will provide a summary of Phase 1 and 2 activities and results of the Phase 3 competition, focusing on technology outcomes that can potentially be infused into both terrestrial and planetary construction applications.

II. Summary of 3D Printed Habitat Competition Phase 1 and 2

Phase 1 of the 3DPH Challenge competition, held in 2015, was an architectural design competition for habitat concepts that could be 3D-printed with a prize purse of \$50,000. It challenged teams to develop state-of-the-art architectural concepts to take advantage of the unique capabilities offered by 3D-printing. The winner of this phase of the challenge was the Mars Ice House from SEArch+ (Space Exploration Architecture) and Clouds AO. The design was further explored by NASA's Langley Research Center in Hampton, Virginia. It mined water present in the northern regions of Mars to create a shell of ice covering a deployed lander habitat, which also provides radiation protection for human inhabitants [5].

Phase 2, completed in 2017, focused on development of materials and printing systems for planetary construction. This portion of the competition strongly emphasized materials formulation, as teams were asked to develop feedstock materials which consisted of indigenous materials (at least 70% of the formulation by weight) and trash recyclables which would otherwise be nuisance materials on space missions. It was divided in three levels and had a total prize purse of \$1,100,000. In levels 1 and 2, teams were scored on their material formulation and the strength (ultimate load) of their material in testing [6, 7]. Level 3 consisted of a head to head competition at the Caterpillar Edwards Facility in Peoria, Illinois, where teams printed mechanical specimens (tested onsite) and a 1.5-meter diameter dome structure representative of a habitat element. The dome structure was crush tested to determine the ultimate load to failure for the structure. Three teams advanced to the head to head: Foster+Partners and Branch Technology from San Francisco, California and Chattanooga, Tennessee; Moon-X from South Korea; and The Pennsylvania State University from University Park, Pennsylvania. The winner of the Phase 2, level 3 competition was Foster+Partners in collaboration with Branch Technology [8, 9, 17 and 18]. The winning material developed under the helm of the Phase 2 competition was PETG with basalt fiber reinforcement. It is now commercially available from the materials developer Techmer, from Clinton, Tennessee [10]. Summary overview of the timeline, goals and winners of Phase 1 and 2 competitions can be found in Figure 1.

Delivering a Concept of Operations (ConOps) for an autonomously constructed habitat in a future Mars mission



Figure 1. Overview, timeline and winners of 3DPH Challenge Phase 1 & 2.

prior to the arrival of crew presented a distinct multidisciplinary challenge that combined new concepts for the systems engineering of a robotic precursor mission with architectural design expertise. Long-term stays on the Martian surface require habitats that reduce both launch mass and cost while providing an effective working environment with a high level of shielding from Galactic Cosmic Rays (GCRs), which are a significant issue for human health on long-duration missions.

III. Winners of 3DPH Phase 1 & 2

A. Space Exploration Architecture LLC (SEArch+)

In 2015 SEArch+ participated in Phase 1 of the competition, and in collaboration with Clouds AO won first prize for the proposal “Mars Ice House.” In Phase 1, the SEArch+ / Clouds AO team consisted of architects with distinct interest in space, technology, additive manufacturing, as well as human-factors. Over 15 subject matter experts in fields as diverse as planetary geology and astrophysics were assembled to research, validate and deliver the research proposal. The opportunity to contribute a unique vision for future habitat concepts to NASA was inspiring and galvanizing to all team members throughout the Challenge. The challenge inspired and motivated all team members to contribute to a schematic vision of a future Mars habitat which would be endorsed by NASA. Mars Ice House introduced a concept of operations for an autonomously constructed 3D-printed habitat for a crew of four to live and thrive on a pioneering mission to Mars. Citing new evidence of the potential hazards of perchlorates in the Martian soil, and given the enhanced properties of water to shield against galactic cosmic rays and solar particle radiation, water-ice was chosen as a building construction material for the habitat. Based on the competition’s guidelines and brief, interior programming of crew activity zones and schematic allotment of volumetric area for mechanical, electrical, and plumbing (MEP) as well as ECLSS within the habitat were both designed and modelled virtually.

Mars Ice House generated numerous “spin-off” projects and collaborations since its inception, in addition to business development opportunities within the space sector for SEArch+. In 2016, SEArch+ /Clouds AO collaborated with NASA’s Langley Research Center’s Game Changing Development program to develop a ConOps for a deployable ice habitat as part of a NASA Internal Research and Development feasibility study. Titled “Mars Ice Home”, the concept was further explored in a risk reduction effort in 2017, which focused on a feasibility study to reduce the technical risk associated with water ice cells; this effort included physical testing and design updates to further investigate material selection, water cell structural configurations, filling methods, and initial radiation assessments. From 2016-2018, SEArch+ acted as a consultant to United Technology Aerospace Systems (UTAS) / Collins advising on how to integrate the design and encasement of ECLSS pallets within the inflatable habitat concepts of numerous prime contracts for the NextSTEP program. SEArch+ led a design charrette with all stakeholders and the outcomes of the project led to a design with enhanced mechanical strength and introduced key human factors improvements. Additionally, SEArch+’s success within the Centennial Challenge led to extensive exhibition within world-renowned museum institutions.

Subsequently in Phase 3, SEArch+ collaborated with concrete 3D-printing startup Apis Cor throughout both Virtual Design as well as Construction Levels of the competition. From 2018-2019, SEArch+ / Apis Cor won fourth place in Virtual Design Level 1 (60% Design), first place in Construction Level 1, first place in Construction Level 2, and first place in Final Virtual Design (100% Design) for the proposal “Mars X-House.” The virtual modeling stage of the Phase 3 competition challenged teams to integrate Building Information Modeling (BIM) workflows with construction sequencing and material handling simulation relevant to autonomous 3D-printing of a surface habitat. Unlike Mars Ice House, the Phase 3 Challenge asked teams to respond to material weight factors simulating the relevance of chosen material aggregates, binders, and additives to be used as indigenous resources on the Martian surface. Mars X-House introduced a concept of operations for an autonomously constructed habitat made of basalt-based sulfur concrete and high-density polyethylene.



Figure 1. Team SEArch+/Apis Cor won first place in the Phase 3: Level 4 software modeling stage of NASA’s 3D-Printed Habitat Challenge. The unique shape of their habitat allows for continuous reinforcement of the structure. Light enters through trough-shaped ports on the sides and top. (Image:Team SEArch+/Apis Cor)

B. Foster + Partners/Branch Technology Winners of 3DPH Challenge Phase 2

Foster + Partners and Branch Technology have historically shared a collective mission: to design and fabricate the first habitats on Mars. While both firms have been individually focused on innovations in fabrication technology, structural optimization, and material efficiency, the 3DPH Challenge has provided a platform for collaboration at a new level.

In 2015, Foster + Partners competed in Phase 1 of the NASA Centennial 3D-Printed Habitat Challenge, securing second-place for their proposal that used an array of semi-autonomous robots to 3D-print habitats for eventual human occupation. For Phase 2, Foster + Partners and Branch Technology came together to take that concept one step closer to reality.

The team goal was to change the future of construction. Typical construction methods are expensive, wasteful, and constraining. The United States construction industry loses over \$30 billion in processed products and \$73 billion in labor each year because of inefficiencies in traditional on-site fabrication techniques. At the moment, design customization and performance optimization are prohibitively expensive for most projects, and current building methods cannot keep pace with advances in digital technology. Branch Technology pioneered Cellular Fabrication (C-Fab™) and “Freeform” 3D printing where material solidifies in free space as it is printed. This approach is informed by a desire to minimize material used in printed structures while still allowing the structure to function optimally. At the same time, Branch developed a material that was composed of 70% indigenous Martian material and 30% mission-recycled materials that was used to print the structural components for the competition. The ability to freeform print a cellular matrix in midair without formwork produces hybrid 3D printed building components that can take on any shape, shedding the confines of traditional construction.

Foster + Partners’ advanced structural optimization and sequencing algorithms draw inspiration from naturally inspired cellular structures, allowing density to be placed where required to best resolve the applied loads. When these algorithms are combined with Branch Technology’s C-Fab™ cellular fabrication technology, the result is an evolutionary approach that ensures maximum material efficiency, lowering cost and waste. Looking to the future, this process has the potential to make building on Earth more efficient and to reduce mission costs for extraterrestrial habitats.

Flexibility and scalability were at the center of this project, particularly for extraterrestrial environments where onsite conditions are not completely understood, and requirements are continually changing. Architectural structures, whether on Earth or beyond, are complex and require unique building components, systems and assemblies. Within the various stages of the 3D-Printed Habitat Challenge, the focus was on the structural performance of smaller elements. The Foster + Partners and Branch Technology team was committed to providing creative answers to the questions set forth in the competition, but were also continually look beyond the Challenge, developing optimized solutions in parallel that were specifically designed for the complexities of space travel. Each of these proposals’ balances cost, weight, and structural performance against the stringent requirements of the long-term goal of extraterrestrial habitation. This kept the company focused on their collective mission: to design and fabricate the first habitat on Mars.

IV. Summary of 3DPH Competition Phase 3

The 3DPH Phase 3 competition was divided into two sub-competitions: 1) virtual construction, where teams created a high fidelity building information model (BIM) of their 3D-printed habitat design and 2) the construction competition, which required teams to 3D-print a structural foundation and subject materials samples to freeze/thaw testing and impact testing (Level 1), produce a habitat element and complete a hydrostatic test (Level 2), and additively manufacture a 1:3 scale habitat onsite in a head to head competition at Caterpillar, Inc.’s Edwards Demonstration & Learning Center near Peoria, Illinois, over the course of three days (Level 3). While the Phase 2 competition focused primarily on the development of novel feedstocks and robotic printing systems, Phase 3 emphasized the scale-up of these systems and autonomous operation (demonstrating the capability to operate systems on precursor missions prior to the arrival of crew, or terrestrially in field operation settings where human tending of a manufacturing system may



Figure 2. Branch Technology 3D prints with a patented process called C-Fab™ that allows material to solidify in free space, creating structures that use 20X less material than standard printing techniques. (Image: Branch Technology)

be limited). The Phase 3 virtual construction levels yielded a number of novel habitat designs, including both modular and vertically oriented habitat concepts. The Phase 3 construction competition also challenged teams to autonomously place penetrations and interfacing elements in additively manufactured structures.

V. Winners of 3D Printed Habitat Challenge Phase 3

A. AI. Space Factory

AI. SpaceFactory was founded in 2017 with the long-term goal of becoming a multi-planetary construction and technology company. The NASA Centennial Challenge provided an immediate path to innovate ways of building and living on Mars, and to develop materials and technology that also have the potential to disrupt the construction industry on Earth. The company is made up of architects and technologists with decades of experience designing skyscrapers on planet Earth. In the Centennial Challenge they organized and lead a diverse team of structural engineers, aerodynamic consultants, lighting designers, geologists, material scientists, and mining experts - integrating commercial practices with academic experts to develop a unique solution to building on Mars.

With their MARSHA project, AI. SpaceFactory proposed a number of radical new approaches to designing for Mars. Recognizing that the critical structural challenge was to efficiently contain an earth atmosphere, they proposed a tall, cylindrical, four-story habitat. This pressure vessel uses space more effectively than a dome. By allowing for stacked mission functions, it achieves a compact footprint, thereby minimizing foundation work and uplift stresses. Furthermore, it is a simpler operation for the 3D-printer to remain stationary and build vertically rather than making more complex horizontal operations.

In response to the challenge of using in situ resources, the team departed from concrete (reasoning that water is a precious resource for oxygen and fuel, and would sublime in the thin, frigid atmosphere during curing) and developed a biopolymer and basalt fiber matrix. This decision was validated in the final construction phase. Printing with biopolymer was precise, clean, represented a unique application for available Martian resources and the team achieved high points for autonomy. The material also showcased its remarkable compressive and tensile strength, which is especially exciting for future earth applications.

AI. SpaceFactory recognized that by addressing off-grid power, autonomous construction, and in-situ resource utilization for Mars, it had developed technologies that can be directly applied to the construction industry on Earth. Their TERA project, to be completed in 2020, includes recycled material from the MARSHA final print, presents a vision of how those concepts can contribute to a better future for our own planet. The company will continue to use this space-driven approach to illuminate a path towards sustainable construction practices on Earth.

The NASA 3D-Printed Habitat Challenge was an opportunity for the company to focus on the challenges of space as a way of rethinking problems on Earth. Furthermore, it allowed the company to transition from a background in design and architecture into a technology and engineering focused company. By researching autonomous systems and in situ resource utilization, AI. SpaceFactory is able to address immediate, pressing problems in the thirteen trillion-dollar global construction industry.



Figure 3. MARSHA concept by AI. SpaceFactory (Image: AI. SpaceFactory)



Figure 4. AI SpaceFactory wins first place in Phase 3: Level 5 of the 3D-Printed Habitat Challenge.

B. The Pennsylvania State University

The Pennsylvania State University team participated in Phases 2 and 3 of the 3DPH competition. The team felt that the alignment between NASA's challenge and their research toward advancing construction technology to provide for affordable housing provided practical and timely opportunities. To participate in the competition, they formed an interdisciplinary team of faculty experts and students from the disciplines of architecture, engineering design, mechanical, agricultural, architectural, civil and environmental engineering. They developed architectural and structural ideas; designed and engineered their own materials and printing system; and strategized the logistics of deployment for automated, autonomous additive construction.

With an interest in sustainable practices, the team decided to explore various mixtures of concrete using elements available on Mars. They considered sulfur concrete using basalt aggregates, which would require no water, and magnesium oxide mixtures, which set very quickly; but opted to develop a dry geopolymer binder called MarsCrete™, composed of minerals indigenous to both Mars and Earth. To create habitats using total automation in the cold and hostile environment of Mars, they envisioned a cohort of robots capable of harvesting, sorting, and mixing the needed elements and then storing the resulting dry mix. The developed mix required only a small amount of water to be added when printing, which could be obtained from ice found on Mars. The use of the engineered geopolymer binder in lieu of Portland cement, currently ubiquitous in concrete construction on Earth, would dramatically decrease the emission of greenhouse gases. They also foresaw the use of recycled light-weight aggregates with insulation properties to create functionally-graded concrete, capable of providing an external layer that protected the interior from cosmic radiation and low temperatures, and optimizing the design for structural performance. The team developed the technology to transition seamlessly between concrete and borate glass, thereby providing natural lighting and views towards the exterior, while guaranteeing a highly sealed environment.

Penn State's research approach was to model and coordinate the complex interrelationship between multiple and associated variables, including those related to material properties, printing system, and design. BIM technology and AI techniques were used to encode this model and concurrently design the operation logistics, the printing system and setup, the toolpath and printing process, as well as the design of the habitat. This approach permitted to identify optimized solutions for both Earth and Mars. Simple cylindrical structures were chosen as their basic unit to prevail over the forces of pressurized air pushing outward and dispersed onto the interior walls of the habitat on Mars. The cylindrical structures transition to a conical dome on top to enclose the habitat. The team succeeded in creating a structure in the final level of Phase 3 that was fully 3D-printed without reliance on any structural support during printing or any prefabricated parts to cap the structure. Accomplishing this goal confirmed that this technology can be relied on in harsh conditions on Earth and beyond.

To further explore the behavior of fresh concrete in space, the Penn State team sent a packet containing a sample of a 3D-print complementary cement mixture and water to the International Space Station on a rocket launched from NASA's Wallops Island in Virginia. Once in space, the space station crew member mixed the two components and managed to send back over 100 samples. The results have enabled them to begin constructing a small-scale 3D-printer that will return to the station for live printing experiments.

The Penn State research team cites the technological breakthroughs that have resulted from this Centennial Challenge have opened the possibility to applying the technology to create sustainable housing solutions that could revolutionize the construction industry and address larger societal issues such as homelessness. The awards earned in Phase 2: Level 3, and Phase 3: Levels 1, 2 and 3 have provided the funds needed for the university's continued research and opened the way to explore sustainable approaches in making and printing with different types of in-situ materials such as soil and clay-based concrete mixtures.



Figure 5. Pennsylvania State University with their completed 3D-printed sub-scale habitat at the Caterpillar Inc. Edwards Demonstration and Learning Center in Peoria, Illinois. The team won second place and \$200,000 in NASA's 3D-Printed Habitat Challenge, Phase 3: Construction Level 3 competition.

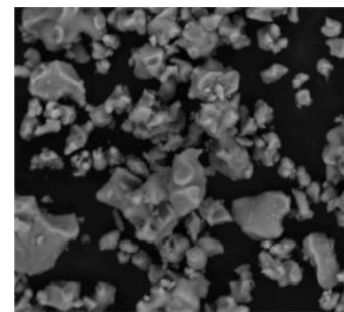


Figure 6. Microscopic image of the Penn State concrete mixture sent to the International Space Station set under zero gravity conditions. (Image: Penn State.)

VI. Media Attention

The 3D-Printed Habitat Challenge received significant media attention around the world and continues to generate media attention today. During Phase 3: Level 4, the competition was mentioned in 160 web and traditional media publications including Popular Science and USA Today. The competition also received international media exposure in countries including Switzerland, Peru, Mexico, Singapore, Vietnam and Germany. The potential audience from traditional media was more than 170 million views.



Figure 7. The 3DPH Challenge was featured in September 2019's issue of Diversity in Action magazine

The final head-to-head competition (Phase 3: Level 5) was featured in 382 media publications including Business Insider, Fox News, Mashable, Popular Mechanics, Popular Science, Diversity in Action (Figure 5) and CNN. A film crew for YouTube Premium's Age of A.I. attended to film for the 8-part documentary produced by Robert Downey that explores the latest in technology. The film is executively produced by Robert Downey Jr. Other notable guests included writers from Popular Science and IEEE Spectrum, Peoria's local NBC affiliate, Peoria Journal Star, and WMBD (Peoria radio station) also attended the final head to head competition. Middle school and high school students with STEM interests attended the first two days of the competition. The estimated reach from traditional media coverage was 113.5 million. Centennial Challenges continues to track the ongoing media coverage resulting from the challenge.

The competition was extensively covered on multiple NASA social media platforms, receiving millions of views. NASA360 and NASA TV hosted a Facebook livestream that was viewed 1,936 times during the event. Middle school and high school students with interest in science, technology, engineering and mathematics attended the first two days of the competition. On the final day of the competition, Caterpillar allowed the public to visit the facility and see the challenge in action. Approximately 2,000 people witnessed the challenge, learned about the value of NASA competitions and viewed various science, technology, engineering and mathematics themed exhibits.

VII. Conclusion

Because of this Centennial Challenge, there have been various business opportunities created/negotiated such as a number of graduate theses written, and three interns from the Allied Organization, Bradley university, are currently employed by two NASA centers. The Dean of Engineering at Bradley University stated that the university has received world-wide attention that was directly linked to their role as the AO for this challenge.

Significant technology advancements were made as a result of this challenge, including demonstration of safe and innovative new material compositions for 3D-printing large-scale pressure vessels with applications to planetary and Earth constructions. Additionally, the challenge demonstrated processes and equipment for large-scale vertical autonomous construction, diversity and innovation in viable designs for realistic planetary habitats, and of new software and control algorithms for depositing material in a non-two-dimensional layer.

For the acceptance of additive construction as a viable planetary and terrestrial construction technique by construction authorities including ASTM, standards for materials, specifications, design, manufacturing and testing must be developed. These standards and their appropriate application in design and construction must ensure that appropriate levels of reliability are achieved. This is equally important for planetary applications as well.

This Challenge has shown that hardware development and operation is clearly not trivial, especially for military and NASA applications. This Challenge has also enabled significant inroads into understanding the critical parameters associated with development of a robust additive construction system that with appropriate modifications, can be used on the Moon and Mars as well. As construction becomes increasingly automated and less labor intensive, additive construction will be at the forefront in facilitating changes in which structures, both on Earth and on other planetary surfaces, are traditionally designed and fabricated. Additive construction truly is a disruptive technology in this regard.

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