NASA's Centennial Challenge for 3D-Printed Habitat: Phase II Outcomes and Phase III Competition Overview

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The 3D-Printed Habitat Challenge is part of NASA's Centennial Challenges Program. NASA's Centennial Challenges seek to accelerate innovation in aerospace technology development through public competitions. The 3D-Printed Habitat Challenge, launched in 2015, is part of the Centennial Challenges portfolio and focuses on habitat design and development of large-scale additive construction systems capable of fabricating structures from in situ materials and/or mission recyclables. The challenge is a partnership between NASA, Caterpillar (primary sponsor), Bechtel, Brick and Mortar Ventures, and Bradley University. Phase I of the challenge was an architectural concept competition in which participants generated conceptual renderings of habitats on Mars which could be constructed using locally available resources. Phase II asked teams to develop the printing systems and material formulations needed to translate these designs into reality. Work under the phase II competition, which concluded in August 2017 with a head to head competition at Caterpillar's Edward Demonstration Facility in Peoria, Illinois, is discussed, including the key technology development outcomes resulting from this portion of the competition. The phase III competition consists of both virtual and construction subcompetitions. Virtual construction asks teams to render high fidelity architectural models of a habitat and all the accompanying information required for construction of the pressure retaining and load bearing portions of the structure. In construction phase III, teams are asked to scale up their printing systems to produce a 1/3 scale habitat on-site at Caterpillar. The levels of the phase III construction competition (which include printing of a foundation and printing and hydrostatic testing of a habitat element) are discussed. Phase III construction also has an increased focus on autonomy, as these systems are envisioned for robotic precursor missions which would buildup infrastructure prior to the arrival of crew. Results of the phase III competition through July 2017 (which includes virtual construction level 1) are discussed. This Centennial Challenge enables an assessment of the scaleability and efficacy of various processes, material systems, and designs for planetary construction. There are also near-term terrestrial applications, from disaster response to affordable housing and infrastructure refurbishment, for these technologies.

1. Vision of the 3D-Printed Habitat Challenge

NASA's Centennial Challenges is a prize competition program intended to directly engage the public in NASA's technology development efforts. Historically prize competitions have served as a highly effective means to spur innovation in a diverse array of fields, from maritime (the British government's Longitude Act of 1714, which ultimately led to the development of the marine chronometer and lunar distance method for longitude determination)[1], to aviation (the Orteig Prize was won by Charles

Lindbergh in 1927 for his transatlantic crossing)[2], and more recently space with the advent of the Google XPrize and Scaled Composite's development of SpaceShip One, the first crewed private craft to reach space. Previous NASA Centennial Challenges have solicited novel engineering solutions to the problems of green flight, design of astronaut gloves, and lunar landers[3]. Current ongoing challenges include small satellites (CubeQuest), bioprinting (vascular tissue challenge), and space robotics[4]. Since its inception in 2005, the Centennial Challenges program has resulted in spinoff technologies and companies which have gone on to have a significant influence on the aerospace industry. Centennial Challenges has also successfully engaged nontraditional partners in the aerospace field and brought participation in aerospace technology development to a much broader demographic.

The vision of NASA's 3D Printed Habitat Challenge, opened in 2015, is to develop and demonstrate the ability to manufacture a habitat on another planetary body using 3D printing technologies[5]. Construction materials for the habitat should primarily consist of mission recyclable materials (such as plastic packaging, which would otherwise be nuisance materials) and/or local indigenous materials (such as regolith). The competition was designed to take place in three phases:

- Phase I was a conceptual architectural design competition. Teams were asked to develop a rendering of a habitat concept which could be built using 3D printing technologies and indigenous materials. The winner of this challenge was Team Space Exploration Architecture and Clouds Architecture of New York, NY for their "ice house" habitat (shown in Figure 1), which has been the focus of a further conceptual study at Langley Research Center[6].

Figure 1. Mars Ice House design from Team Space Exploration and Clouds Architecture Office of New York.

- The phase II competition asked teams to develop material mixes and 3D printing systems to produce test specimens (compression, flexure) and demonstrate manufacture of the large dome structure shown in Figure 2.[5] The phase II competition was subdivided into three levels, culminating with a head to head competition at Caterpillar's Edwards Demonstration Facility. Additional details on the winners and outcomes of the phase II competition appear in the next section.

Figure 2. CAD-rendering of the phase II, level 3 dome.

- The phase III competition, announced in November 2017, consists of both architectural modeling and construction competitions. In the virtual construction levels of the competition, teams are asked to create building information models (BIM) for their habitat and provide detailed information on materials, design, and construction. In the construction levels, teams must develop printing systems and material mixes capable of producing a foundation, a habitat element, and ultimately a subscale habitat (the latter printed onsite as part of another head to head competition at Caterpillar). Articles produced in the construction competition will be evaluated for flatness, impact resistance, compressive strength, durability, and ability to form a hermetic seal. The construction competition also places a strong emphasis on autonomy, as teams are penalized for manual intervention with their robotic systems during construction. The framework of the phase III competition is discussed in detail in section 3.

Partners in NASA's 3D Printed Habitat Challenge include Caterpillar (the challenge main sponsor), Bradley University (challenge facilitator), Bechtel (sponsor), and Brick and Mortar Ventures (venture capital firm with a construction industry focus). To date, the program has brought together members of the construction industry, academia, venture capital, and the architecture field to advance the state of the art in additive construction technology for both space and earth. This development continues through the phase III challenge effort.

2. Outcomes of Phase II Competition

The purpose of the phase II competition was to spur innovation in additive construction by incentivizing teams to develop large-scale 3D printing systems which use mission recyclable and rock-based materials indigenous to planetary surfaces as feedstock. 3D printing of concrete is among the most promising and disruptive technologies for construction in recent memory. Earth-based applications of this technology include rapid infrastructure development (such as the recent bridge fabricated in the Netherlands)[7], disaster response, and army field operations[8]. Recently NASA and the Army Corps of Engineers completed the additive construction for mobile emplacement (ACME) project, which developed a 3D printing system to enable the army to rapidly construct "B Huts."[9] While development efforts for these technologies are ongoing, significant hurdles in robotic systems and material formulations remain. This is particularly true for planetary construction applications, where these systems would be deployed as part of robotic precursor missions and thus need to be capable of processing in situ materials and exhibit a high degree of autonomy. The phase II competition sought to develop technologies to address some of these challenges. As part of the phase II, teams had to create construction (feedstock) materials from indigenous materials and waste materials commonly found on space missions. Material systems not comprised of at least 70% indigenous materials were disqualified. Aggregates and binders commonly used in terrestrial applications were permissible, but not rated as highly as indigenous materials and recyclables. The use of water in material formulations was discouraged by applying a negative multiplier in material scoring calculations. The three levels of the phase II competition ran from January 2017 to August 2017, concluding with a head to head competition between three teams at Caterpillar's Edwards Demonstration Facility in Peoria, Illinois.

In level 1 ($100,000 prize purse), teams had to demonstrate their printed material could maintain shape via a slump test and also print a cylindrical specimen to assess its compressive strength. Material mixes had to consist of a minimum of 30% indigenous materials; a material score was assigned based on a sliding scale which favored materials with a high relevance to planetary missions. The winner of phase II, level 1 was Foster+ Partners and Branch Technology. University of Alaska-Fairbanks finished second. The seven teams completing level I advanced to level II[10].

Figure 3. Winning phase II, level 1 entry (compression test specimen) from Foster+Partners/Branch Technology.

Phase II, level 2 required teams to print a beam specimen for flexural testing. Scores were based on the ultimate load the printed specimen could withstand prior to breaking and the material mix. The winner of the level II competition was Moon-X Construction (affiliated with Hanyang University) of Seoul, South Korea (as an international team, Moon-X was not eligible for prize money). Form Forge of Oregon State University placed second and Foster+Partners/Branch Technology finished third. 7 teams completed the requirements of the level II competition[11].

Figure 4. Beam specimen from Moon-X (South Korean team) submitted as part of phase II, level 2 structural member competition.

The phase II competition concluded with the level 3 head to head competition at Caterpillar's Edwards Demonstration Facility in August 2017. 7 teams were invited to the head to head to compete for a $500,000 prize purse, with three teams accepting the invitation: Foster+Partners/Branch Technology, Moon-X from South Korea, and Pennsylvania State University. Over the course of the three-day competition, teams had to print three compression specimens (tested per ASTM C39[12]), three beam specimens (tested per ASTM C78[13]), and a large-scale dome (subjected to a crush test). These specimens were tested onsite to failure. Two teams (Foster+Partners/Branch Technology and Pennsylvania State University) were able to complete the dome. After the dome passed the transportation proof test (which consisted of application of an initial 50 kgf load), its dimensions were characterized using structured light scanning (the target tolerance was set at 7 mm). The dome was then transported to the center of the Caterpillar arena for a crush test. Scoring was a combination of material and strength measurements and considered all specimens produced during the head to head. 1st place was awarded to Foster+Partners/Branch Technology and Pennsylvania State University received 2nd place. As an international team, Moon-X was not eligible for prize money[14]. Images from the phase II, level 3 competition are shown in Figures 5, 6, and 7.

Figure 5. Dome 3D-printed by Foster+Partners/Branch Technology at the phase II, level 3 head to head competition.

Figure 6. Dome 3D-printed by Penn State at the phase II, level 3 head to head competition.

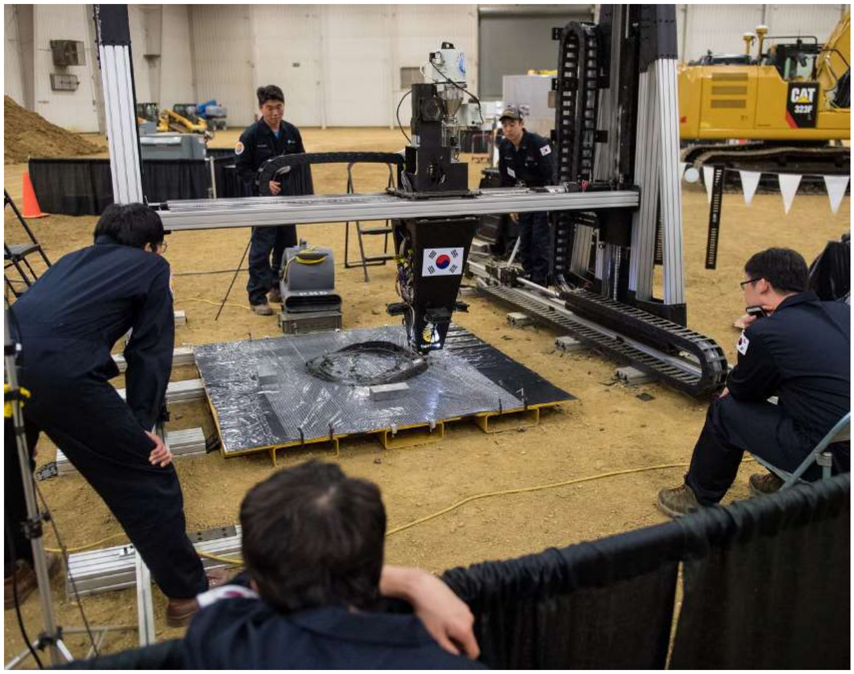

Figure 7. Gantry-style 3D printing system developed by Moon-X for the phase II, level 3 head to head competition.

The key technology developments under phase II were in materials and printing systems. Phase II saw the development of both large-scale gantry and robotic arm systems for 3D printing. As demonstrated in the phase II by Branch Technology, robotic arm systems (where material extrusion occurs at the end effector of a six degree of freedom robotic arm) can impart the ability to print overhangs of greater than 45 degrees without the use of supports and enable "freeform fabrication." Careful thermal management of this system resulted in a dome with virtually no structural curling or deformation from internal cooling stresses. Three-dimensional measurements of the Branch Technology dome collected during structured light scanning at the competition showed less than 1% variation between the printed specimen and the CAD model. This is a much higher standard of accuracy than is achievable with many 3D printing/material systems for very large structures. Since completing the phase II competition, Branch Technology built what is claimed to be the world's largest 3D printed structure, a bandshell for the OneCity mixed-use development in Nashville, Tennessee. The Carbon-fiber reinforced Acrylonitrile Butadiene Styrene (ABS) structure was manufactured using the company's Cellular Fabrication (C-Fab) process[15]. Branch Technology also plans to construct a 3D printed home in Chattanooga, Tennessee.[16]

In materials, teams used either traditional cementitious formulations (which incurred a penalty for use of water) or novel, polymer concretes with fiber loading/reinforcement. Print time for the polymer concretes was much longer than the cementitious formulations, but required no cure time to obtain full material strength. The absence of the need for cure time gave these polymer-based material formulations an inherent advantage in the head to head competition, where time from printing to testing was less than 24 hours. Advancements in material form under the competition included the development of polymer-based, rock-fiber reinforced feedstocks in the form of pelletized material. For Branch Technology, the high strength of their feedstock material (developed by the company Techmer PM) enabled 3D printing of the dome without support structures.[17] The Branch Technology beam at the level 3 competition had a maximum flexural load of 32,500 pounds. The maximum compressive load was recorded as 27.450 pounds. The dome was able to withstand 3,726 pounds prior to failure.[17]

Autonomy was also a component of the phase II competition. While teams were allowed to print a specimen with support structures if needed, these structures had to be removed autonomously prior to testing. The Pennsylvania State University team demonstrated a novel, robotic method to remove support structures following completion of their dome. Teams also incorporated in-line mixing technology coupled with cooling mechanisms to provide active thermal control (for cementitious formulations, mixing can be exothermic), innovations necessitated by the requirements on automation in material handling.

3. Overview of Phase III Competition

Announced in November 2017 and running through May 2019, the primary objective of the phase III competition is to incentivize further scale-up of additive construction systems to enable eventual construction of a full-scale habitat using indigenous materials. Phase III also strongly focuses on development of autonomous systems for construction and seeks to foster new ideas in habitat design through the virtual construction competition. The phase III competition include both virtual construction (BIM modeling) and physical construction subcompetitions. The scoring considerations and requirements for each level discussed below are fully detailed in the phase III competition rules at www.bradley.edu/challenge[18]. Teams are free to change their material formulation at any time during the course of the phase III competition; however, if the material mix is changed between levels, the teams must print and a test a compression specimen and a material durability specimen with the new material.

i) Construction Competition

The phase 3 competition is structured with three construction levels which lead to future construction of a full-scale habitat. In construction level I, teams are asked to use their printing system to fabricate a foundation measuring 2m x 3m with an optional wall interface (Figure 8). While less emphasis is placed on material selection in the phase III competition, a material score is assigned based on a sliding scale similar to that used in the phase II competition (Figure 9). While the use of nonindigenous/imported materials is not penalized, materials with greater relevance to space exploration missions will receive a higher score. The sliding scale for materials for phase III is shown in Figure 9 and acronyms are defined in Table 1. As in phase II, the material score represents the weighted sum of the amount of a material used in the mix multiplied by its corresponding 3DP factor. Materials not represented in the chart are assigned scores on a case by case basis by the judging panel.

An overarching goal of the phase III competition is autonomy and teams are penalized for any human interventions during construction. Remote intervention via teleoperation, depending on the nature and duration of the intervention, may also incur a penalty. In level 1, teams must print a foundation (Figure 8) measuring 2 m x 3 m. A portion of the foundation will be evaluated for flatness and levelness per American Concrete Institute (ACI) 117[19]. Foundation durability is assessed with an impact test (performance scored on degree of cracking and material deformation) and by subjecting rectangular specimens to freeze/thaw testing per ASTM C666[20]. Material strength is evaluated using a cylindrical compression specimen tested per ASTM C39 (this standard and test was also used in the phase II competition). The level 1 portion of the construction competition ended on July 25, 2018. 10 teams with highest scores will be awarded a prize proportional to their score. The total level 1 prize purse amount is $400,000.

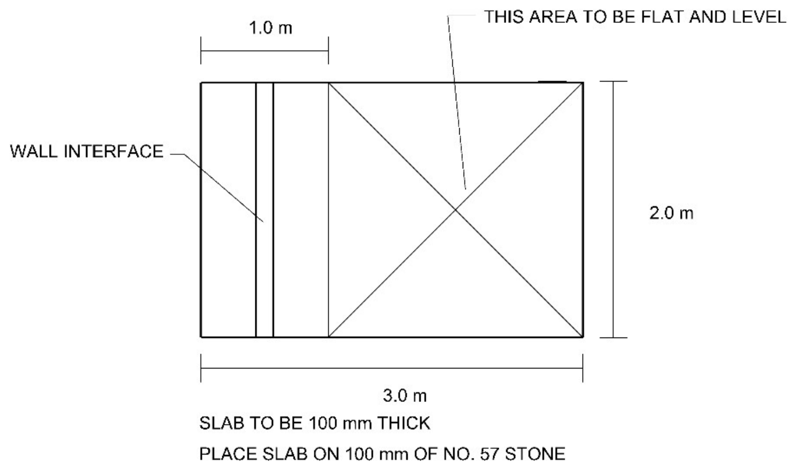

Figure 8. Diagram of printed foundation for phase III, level 1 construction competition.

Material Applicability	Earth Relevant								Mars Relevant	
Aggregate	LD	MG			SS			GS	BSR	CBI
Polymers (including fibers)	MR, EVOH	NY, PU	PT, ABS	S	PS, PC	PMMA, PET, PETG	PVC, VY	BR	PP	PE (HD and LD)
Additives	FP	AM	SC							B
Binders	PG	HA	IW					GST		MBC
3DP Factor	1	2	3	4	5	6	7	8	9	10

Figure 9. Sliding scale for materials in phase III competition. Materials with a greater relevance to planetary missions or which make use of trash recyclables receive a higher score. Material acronyms are defined in Table 1.

Table 1. Acronyms for materials list in Figure 9.

Aggregate	
CBI	Crushed basaltic igneous rock (SiO_2 weight percent less than or equal to 57)
BSR	Basaltic sedimentary rocks (talus, alluvium with very little alteration/weathering, or mine tailings)
GS	Gypsum (calcium sulfate dihydrate) and other sulfate minerals
SS	Siliceous sedimentary rocks and clays (sand box sand, mudstone)
MG	Marble and other metamorphic rocks (e.g., slate), granite
LD	Limestone and dolomite (carbonaceous sedimentary rocks)
Polymers	
PE (HD & LD)	Polyethylene (high density and low density, #2 and #4 recycle codes, respectively)
PP	Polypropylene (#5 recycle code)
BR	Polybutadiene (butadiene rubber)
PVC	Polyvinyl chloride
VY	Vinyl (#3 recycle code)
PMMA	Poly (methyl methacrylate)
PET	Polyethylene terephthalate (#1 recycle code)
PETG	Polyethylene terephthalate glycol
PS	Polystyrene (#6 recycle code)
PC	Polycarbonate
S	Styrene

Construction level 2 requires teams to fabricate a reduced scale habitat element and subject it to hydrostatic testing. The element, shown in Figure 10, is partially filled to levels of 500 mm and 1.25 m and leakage is measured over the course of a 15 minute period at each level. Wall penetration elements designed by the teams should also be placed autonomously, as physical or remote/teleoperated intervention of the system during fabrication is penalized. Compression and material durability testing is required if the material mix was changed from level 1. Level 2 ends on December 19. 2018. 8 teams with the highest scores will be awarded a prize proportional to their score for level 2. The level 2 prize purse is $600,000. A maximum of 8 teams will be invited to the level 3 construction competition.

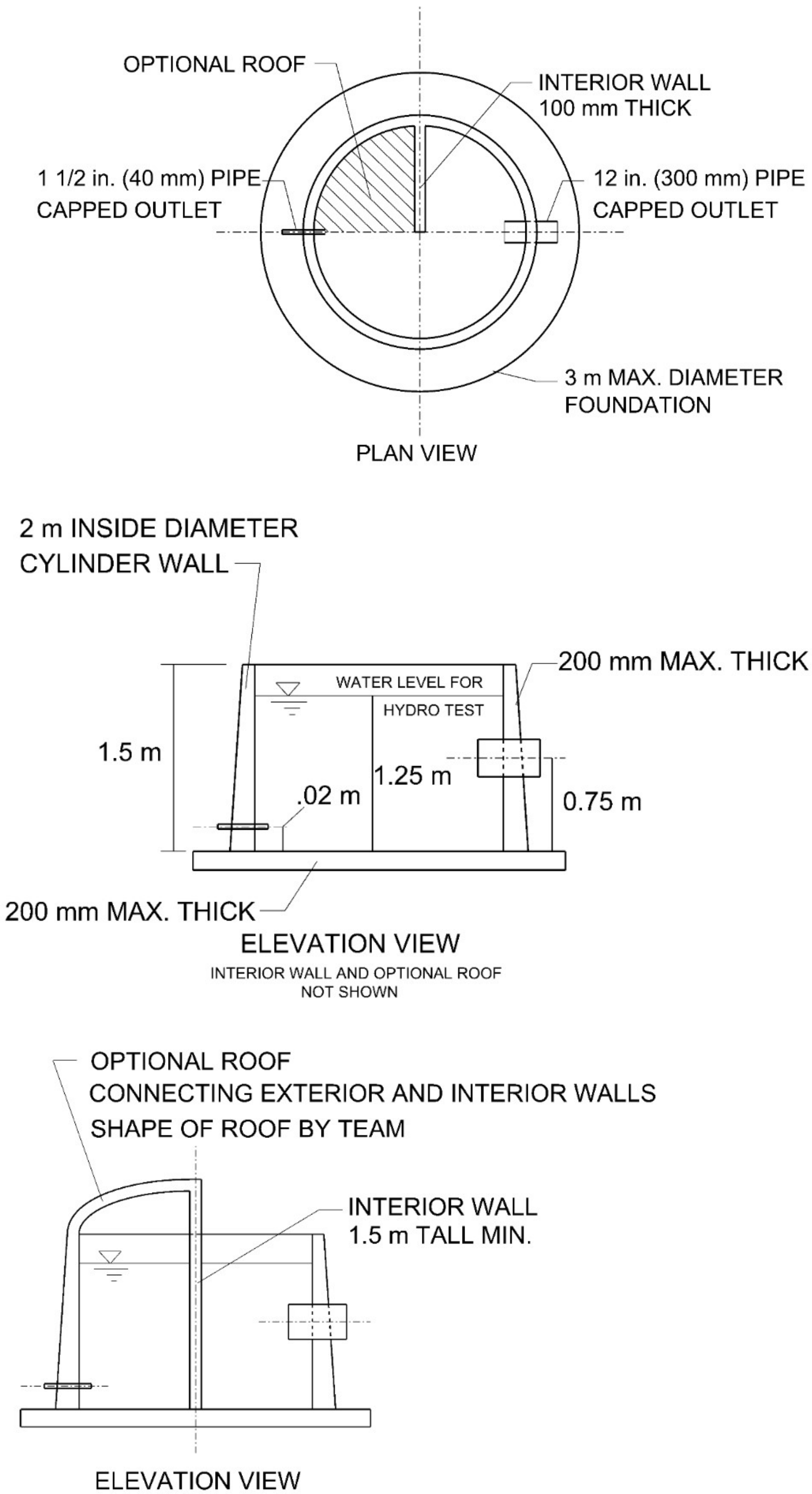

Figure 10. Drawing of reduced scale element for hydrostatic testing.

Construction level 3 is the onsite head to head to be held at Caterpillar's Edwards Demonstration Facility in Peoria, Illinois in May 2019. Teams must additively construct a 1/3 scale habitat. Habitat design is not prescribed, but is developed by the team prior to the head to head competition (teams must submit a BIM model of the habitat they will be constructing onsite). Construction again should be autonomous to the greatest extent possible – penalties will be applied per the scoring schema outlined in the rules for both remote and physical intervention in operation of the system. Habitats will be subjected to onsite testing to include: smoke test (to assess leakage), impact testing (judges will determine a vulnerable point on the structure and iron balls will be dropped from three different heights), and crush testing (using a hydraulic excavator, as in the phase II head to head to head). Scoring is based on the structure's performance, the material mix, and the degree of system autonomy. Level 3 is scheduled to take place April 29-May 4 at Caterpillar Edwards. The three teams with the top scores will receive $500,000, $200,000, and $100,000, respectively.

ii) Virtual construction

The virtual construction competition consists of two levels. In level 1 (competition closed in May 2018), teams used a BIM software tool to complete a full-scale design of a 3D-printed habitat. Submitted models provided a minimum of 60% of the information required for construction of the pressure retaining and load bearing portion of the habitat. Designs were evaluated by a panel of experts (consisting primarily of architects) on element level of development, system information, layout/efficiency, aesthetics, constructability/robustness, and BIM use functionality. 18 designs were submitted as part of Level 1 of the competition, which ended on May 16, 2018. 5 teams with the highest scores were awarded a prize proportional to their score from a total prize purse of $100,000.[21] The videos which accompany each of the top five submissions can be viewed online at www.bradley.edu/challenge.

First place in level 1 of the virtual construction competition (approximately $21,000) went to Team Zorpherus of Rogers, Arkansas. In the Zopherus concept, an initial lander deploys mobile robots to gather indigenous material from the Martian surface. The lander structure encloses the printer, providing a pressurized, thermally controlled print environment for processing of the extracted materials (ice, Calcium Oxide, and Martian aggregate) into feedstock and fabrication of the first habitat module. Once the print is complete, the lander module translates across the surface to begin the process again, eventually producing a series of modular habitats as shown in Figure 11. The modules consist of a communal shell (for coordination of surface operations), crew quarters, and a third shell which serves as a laboratory space.

Figure 11. Concept from first-place virtual construction level 1winner Team Zopherus.

Second place was awarded to AI Space Factory of New York (Figure 12). AI Space Factory designed a vertically oriented cylinder made of polylactic acid (PLA) reinforced with basalt fiber. The cylindrical geometry was chosen to maximize the ratio of usable living space to surface area and reduce structural stresses. A double shell structure allows for expansion and contraction of material with the thermal swings the structure will experience on the Martian surface. Each level in the habitat serves a particular mission function: exploration staging/preparation, workspaces, crew quarters, and exercise/recreation.

Figure 12. Vertical habitat design concept from AI Space Factory (2nd place).

Kahn-Yates of Jackson, Mississippi received third place with an egg-shaped dome structure (Figure 13). The habitat consists of an inner and outer polymer shell which sandwich a sulfur concrete. The sandwich layer is omitted in certain locations to provide natural light.

Figure 13. Kahn-Yates dome structure (3rd place).

SEArch+/ApisCor of New York finished in fourth place. The team presented a design with materials and thicknesses selected specifically to provide radiation shielding. The habitat is flanked by overlapping shells and oriented at 30 degrees above the horizon; these features allow for the entrance of natural light without compromising radiative protection.

Figure 14. Habitat concept from SEArch+/ApisCor (4th place).

Northwestern University's design was ranked fifth. In this concept, rovers additively manufacture a foundation and deploy an inflatable shell. The rovers print the habitat's outer shell, which overlays the inflatable. The layout is a hub and spoke design, with a central multi-use space surrounded by sectioned spaces programmed to support various mission functions (crew quarters, lab space, kitchen/dining, etc.) In this concept, a series of modular habitats such as the one pictured in Figure 15 are connected by a network of tunnels.

Figure 15. Northwestern University's single story modular habitat concept finished in 5th place.

In level 2, teams will mature their model to a full-scale design with 100% of the information required for construction. The level 2 design must include an appropriate level of metadata integrated with the 3D modelled objects. Level 2 designs will be evaluated on similar scoring criteria as level 1. Level 2 ends on January 16, 2019. 3 teams with the highest scores will be awarded a prize proportional to their score. The total prize purse for level 2 is $100,000.

In the phase III competition, teams can compete in the virtual construction competition without competing in any of the construction levels. However, teams competing in the construction levels must complete virtual level 1 and virtual level 2 as part of the construction competition.

4. Summary

The 3D Printed Habitat Challenge seeks to advance habitat architecture design and the accompanying construction technologies needed to translate those designs to reality. To date, a number of new materials for additive construction have been developed under the helm of the Centennial Challenge. These materials use recyclable binders with in-situ regolith resources and represent high performing materials whose applications extend beyond NASA. The Centennial Challenge has also spurred the development of new printing methods and the creation of new robotic hardware for material delivery, extrusion, and control. Autonomous operation of systems and removal of supports was also demonstrated in the phase II effort. With the phase III competition, NASA and challenge partners will continuing building upon this effort to drive additive construction technology that benefits both earth-based construction and the robotic planetary precursor missions NASA will undertake in advance of establishing a sustained human presence on the moon or Mars. The competition has far-reaching implication for construction on earth and in space.

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