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NASA CENTENNIAL CHALLENGE:
THREE DIMENSIONAL (3D) PRINTED HABITAT, PHASE 3

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Abstract:

NASA's Centennial Challenges program uses prize competitions with the goal of accelerating innovation in the aerospace industry. Competitions in the Centennial Challenges portfolio have previously focused on advancements in space robotics, regolith excavation, bio-printing, astronaut suit design, small satellites, and solar-powered vehicles. NASA's Three Dimensional (3D) Printed Habitat Centennial Challenge represents a partnership between NASA and the non-profit partner: Bradley University, with co-sponsors 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) to spur development in automated additive construction technologies. The challenge asks teams to design and construct a scaled and simulated Martian habitat using indigenous materials and large scale 3D automated printing systems. Phase 1 of the competition, held in 2015, was an architectural design competition for habitat concepts that could be 3D printed. Phase 2, completed in 2017, asked teams to develop feedstocks from indigenous materials and hydrocarbon polymer recyclables, and demonstrate automated printing systems to manufacture these feedstocks into test specimens to assess mechanical strength. This paper will discuss the Phase 3 competition, focusing on technology outcomes that can potentially be infused into both terrestrial and planetary construction applications. The 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 be limited). The Phase 3 virtual construction levels yielded a number of novel habitat designs, including both modular habitats and vertically-oriented habitat concepts. The Phase 3 construction competition also challenged teams to autonomously place penetrations and interfacing elements in additively manufactured structures. The paper will emphasize potential applications for the new materials and technologies developed under the umbrella of the competition within NASA's portfolio and in Earth-based applications such as disaster response and infrastructure improvement.

1. Overview of competition and previous phases

NASA's Centennial Challenges program is a portfolio of public-facing prize competitions with the goal of incentivizing rapid innovation and technology maturation in the aerospace sector [1]. Historically competitions have served as a viable means of generating revolutionary solutions to known technology gaps. Perhaps the most well-known example is the Longitude Prize from the British Government, which was awarded to the clockmaker John Harris in the 1700s for his development of the marine chronometer, a device which enabled sailors to precisely determine their longitude during voyages [2]. In the 1860's butter shortages and rising prices in France prompted the emperor to issue a prize competition for a butter replacement – the result was oleomargarine, a substance made from vegetable fats. Lindbergh's transatlantic flight in 1919 was motivated in part by the Orteig Prize, a \$25,000 prize purse for the first aviator to fly from New York City to Paris (prior to Lindbergh, six pilots died in pursuit of the prize). More recently, the Google XPrize resulted in the development of the first commercial suborbital launch vehicle, Scaled Composite's Spaceship One.

Since its inception in 2005, the Centennial Challenges program has overseen competitions addressing challenges in aerospace technology development. Previous competitions include astronaut suit glove design, bio-printing, space robotics, regolith excavation, life support systems, and small satellites. NASA's 3D Printed Habitat Challenge, which focused on developing technologies for the autonomous construction of infrastructure on planetary surfaces using indigenous materials and/or trash recyclables, was conducted in three phases from 2015-2019. Partners in NASA's administration of the challenge included Bradley University, Caterpillar, Inc., Bechtel Corporation, Brick and Mortar Ventures, the American Concrete Institute, and the United States Army Corps of Engineers Engineer Research and Development Center. 3D Printing (or Additive Manufacturing) is the process of constructing an object by depositing material layer by layer based on a 3D digital part file. 3D printing is currently revolutionizing the

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manufacturing industry across many sectors, including aerospace. To date, 3D printing of hydrocarbon thermoplastic polymers has been demonstrated on the International Space Station (ISS) as a potential means to reduce logistics (specifically the amount of supplies and spares which must be carried on long duration space missions) [3]. Techniques for 3D printing of metals are now used in the aviation industry and have been shown to significantly reduce the cost and part lead time for rocket engine components [4]. Large scale 3D printing for construction imparts unique advantages over traditional construction practices. 3D Automated Additive Construction (3DAAC) removes design constraints, enables building and testing to occur earlier in a project's lifecycle, reduces waste by depositing material only where it is needed, has the ability to work with new material formulations, and can maximize the use of in situ resources as feedstock [5]. The world's population is projected to rise to levels between 9.5 billion and 12.9 billion by 2100 [5]. 3DAAC offers one potential solution to the exponentially greater needs for terrestrial infrastructure development which will accompany this expected population growth. 3DAAC technologies are poised to change the way structures are fabricated, but will also expand the range of materials and designs which can be realized. From the space perspective, autonomous systems can fabricate infrastructure (potentially from indigenous materials) on precursor missions to build infrastructure such as hangars, habitats, roads, blast mitigation walls and landing pads prior to the arrival of crew. 3DAAC techniques serve as a key enabling technology for exploration by reducing logistics (launch mass) by enabling use of local resources for manufacturing. Autonomous operation will eliminate the need for crew tending of manufacturing systems.

Common printing processes for 3DAAC come in two general varieties. In the most common approach, cement-based materials may be extruded through a nozzle. This is the process used by NASA/Army Corps of Engineers/Contour Crafting in the Additive Construction for Mobile Emplacement project [6] and [25]. Other approaches rely on forced extrusion of filament in wire form (similar to desktop 3D printing systems for polymers). Printing systems may be Cartesian coordinate gantry-style (the extruder is attached to a frame which translates in 3-

dimensions), cable driven, or 6 degree of freedom robotic systems (the extruder is the end effector of an industrial robot arm).

The overarching goal of the 3D Printed Habitat Challenge is the advancement of additive construction technology to create sustainable housing solutions for Earth and space. The first phase of the challenge in 2015 asked teams to develop state of the art architectural concepts which 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 (Figure 1). The design, which was further explored by NASA Langley Research Center, 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 [7].



Figure 1. Mars Ice House. Image credit Space Exploration Architecture and Clouds AO.

The Phase 2 competition from 2016-2017 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. A sliding scale for materials and weighting factors (Figure 2) was used to assign a numerical materials score to a formulation. Table 1 defines the material acronyms which appear in Figure 2. A composite materials score was calculated by multiplying the 3DP factor by the proportion of the corresponding material used in the formulation and summing over all constituent

materials. Higher scores thus correspond to formulations which make significant use of polymer recyclables commonly used in plastic packaging for launch (for example, polyethylenes (PE)) and basalt crushed rock regolith, which would be plentiful on the Martian surface. Polymers such as PE can also be produced from the CO₂ present in the Martian atmosphere (Mars has an atmosphere which is 95% CO₂) and H₂ found in sub-surface water deposits and hydrated minerals.

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



Figure 2. Scoring scale for feedstock materials.

Table 1. Material acronyms.

Acronym	Material	Material class
CBI	Crushed basaltic igneous rock (SiO ₂ weight percent less than or equal to 57)	Aggregate
BSR	Basaltic sedimentary rocks (talus, alluvium with very little alteration/weathering, or mine tailings)	Aggregate
GS	Gypsum (calcium sulfate dihydrate) and other sulfate minerals	Aggregate
SS	Siliceous sedimentary rocks and clays (sand box sand, mudstone)	Aggregate
MG	Marble and other metamorphic rocks (e.g., slate), granite	Aggregate
LD	Limestone and dolomite (carbonaceous sedimentary rocks)	Aggregate
PE (HD and LD)	Polyethylene (high density and low density, #2 and #4 recycle codes, respectively)	Polymer

PP	Polypropylene (#5 recycle code)	Polymer		thermites (reacted metals and regolith mixtures), geopolymers that do not contain fly ash and silica fume	
BR	Polybutadiene (butadiene rubber)	Polymer			
PLA	Polylactic acid	Polymer			
PVC	Polyvinyl chloride	Polymer	IW	Ice or water	Additive
VY	Vinyl (#3 recycle code)	Polymer	HA	Hydroxyapatite (phosphate material)	Additive
PMMA	PMMA Poly (methyl methacrylate)	Polymer	PG	Portland cement and geopolymers containing fly ash and silica fume	Additive
PET	Polyethylene terephthalate (#1 recycle code)	Polymer			
PETG	Polyethylene terephthalate glycol	Polymer			
PS	Polystyrene (#6 recycle code)	Polymer			
PC	Polycarbonate	Polymer			

Table 1. Material acronyms

Table 1. Material acronyms (continued)

Acronym	Material	Material class
S	Styrene	Polymer
PT	Polythiophene	Polymer
ABS	Acrylonitrile Butadiene Styrene	Polymer
NY	Nylon (one of the polymers with a #7 recycle code)	Polymer
PU	Polyurethane	Polymer
MR	Melamine resin or melamine formaldehyde	Polymer
EVOH	Ethyl Vinyl Alcohol Additives	Polymer
A	Acetone	Additive
B	Basalt rebar and fibers	Additive
SC	Steel or other metal rebar, Carbon fullerenes	Additive
AM	Admixtures that require major chemical processing to create, including rheology control, super-plasticizer, and water reducers	Additive
FP	Fine particles (e.g. fly ash and silica fume) produced by wood and coal burning binders	Additive
MBC	Magnesium oxide or basalt-based cements	Additive
GST	Gypsum binders, sodium silicate, potassium silicate, sulfur (elemental),	Additive

The Phase 2 competition (total prize purse of 1.1 million dollars) was divided into three levels. In level I, teams were asked to print a truncated cone specimen (subjected to a slump test) and a cylindrical compression specimen. The specimen measured 300 mm in height and 150 mm in diameter and was tested per American Society of Testing Materials (ASTM) standard C39 [8,9]. In level 2, teams printed a flexure specimen for mechanical testing per ASTM C78 [10]. In level 1 and 2, teams were scored on their material formulation and the strength (ultimate load) of their material in testing. Level 3 consisted of a head to head competition at Caterpillar Edwards, where teams printed additional mechanical specimens (tested onsite) and a 1.5 meter diameter dome structure representative of a habitat element [11]. 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, Moon-X from South Korea, and Pennsylvania State University. The winner of the Phase 2, level 3 competition was Foster+Partners (San Francisco, CA) and Branch Technology (Chattanooga, TN). Detailed results of the Phase 2 competition were published in references [12], [13], [23] and [24]. The winning material developed under the helm of the Phase 2 competition, PETG with basalt fiber reinforcement, is now commercially available from the materials developer Techmer (Clinton, TN) [14].

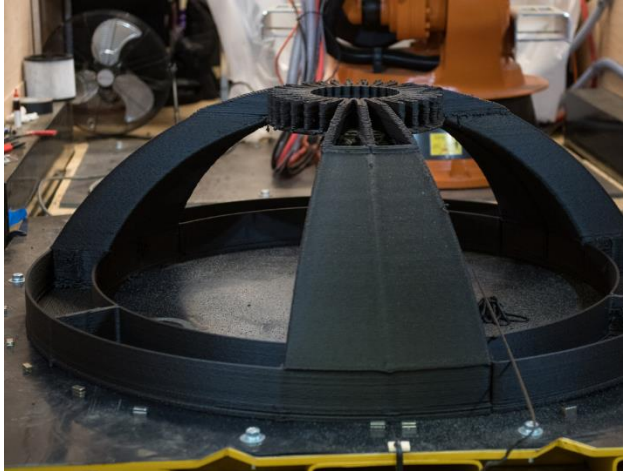


Figure 3. Dome printed by Branch Technology and Foster+Partners at head to head competition.

The Phase 3 competition began in 2018 with a total prize purse of 2 million dollars. The Phase 3 objective was to build on the manufacturing system, process, and material development efforts in Phase 2 to construct a 1:3 subscale habitat. The detailed results of Phase 3 are presented in the next section.

2. Phase 3

The Phase 3 competition consisted of two sub-competitions: virtual construction and physical construction. In the virtual construction competition, teams used building information modeling (BIM) software to develop full scale architectural models of a habitat and provide detailed information on materials, design, and construction. Complete rules and scoring for the Phase 3 competition can be found in reference 15. In level 1 of the virtual competition, models were required to be at 60% BIM level of development (LOD). In level 2, models were matured to 100% BIM LOD. In the construction levels, teams developed 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 were evaluated for flatness, impact resistance, compressive strength, durability, and ability to form a hermetic seal.

2.1 Virtual construction

Designs for the virtual construction were evaluated by a panel of experts (consisting primarily of architects) on element level of development, system information, layout/efficiency, aesthetics,

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constructability/robustness, and BIM use functionality. Eighteen (18) designs were submitted as part of level 1 of the competition, which ended on May 16, 2018. The five winning designs are detailed in reference [16] and reference [13]. Level 2 of virtual construction ended in January of 2019.

Several novel habitat designs were developed through the Phase 3 competition. Habitat designs are typically either: a) modular, one-story habitats arranged in a cluster with connecting tunnels (teams Zopherus, Mars Incubator, Northwestern University, Penn State) or b) vertical, multi-level habitats with each level corresponding to a specific mission function (teams Kahn Yates, AI Space Factory, SEArch+/Apis Cor).

SEArch+/Apis Cor (1st place) proposed a vertical habitat design. The habitat is an inward facing arch design (a hyperboloid) with two layers. High density polyethylene (a polymeric material with good properties for radiation shielding) functions as the inner layer, while the exterior is regolith. Radiation shielding is accomplished via overhangs.



Figure 4. Image from SEArch+/Apis Cor

In the Zopherus concept (2nd place) 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.



Figure 5. Image from Team Zopherus

Mars Incubator (3rd place) presented a series of habitats arranged in a hub and spoke design, with the largest, primary volume at the center. Panels in the design consist of polyethylene and basalt fiber. The habitat in this design is not fabricated via continuous additive manufacturing; instead, additively manufactured panels are mechanically assembled via robotic manipulation. Environmental control and life support systems (ECLSS) and mechanical, electrical, and plumbing (MEP) systems are located below the habitat modules.



Figure 6. Image from Mars Incubator

AI Space Factory designed a vertically oriented cylinder (4-story habitat) made of poly lactic acid (PLA) bio-polymer 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 7. Image from AI Space Factory.

Kahn-Yates of Jackson, Mississippi proposed a habitat consisting of an inner and outer polymer shell sandwiching a sulfur concrete. The sandwich layer is omitted in certain locations to provide natural light. The habitat contains a central cylinder with panels that unfold horizontally to divide the structure into three floors.



Figure 8. Image from Kahn-Yates.

In Northwestern University's design, rovers additively manufacture a foundation and deploy an inflatable shell. The rovers print the habitat's outer shell, which overlays the inflatable structure. The layout is a hub and spoke design, with a central multiuse 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 are connected by a network of tunnels.



Figure 9. Image from Northwestern University.

In the X-Arc habitat concept, materials for feedstock are extracted from the planetary surface via excavating robots. Polyethylene can be readily manufactured on the Martian surface, which has an atmosphere of approximately 95% CO₂ and water available. Ground basalt is added to the polyethylene and extruded into feedstock from a gantry-style 3D printer. The habitat concept is a printed shell structure with 3 levels. Prefabricated components are placed inside the habitat and as penetrations via robotic assistance.



Figure 10. Image from X-Arc.

Hassell + EOC's concept relies on a swarm of wheeled mining robots to excavate and collect regolith for processing into feedstock. Concurrent printing along the x-y footprint of the structure by the fleet of robots enables rapid and efficient fabrication. The resulting Mars habitat has a contoured structure intended to complement the surrounding environment.



Figure 11. Image from Hassell + EOC.

2.2 Construction

In level 1 of the construction competition (completed in July 2018), teams printed a foundation measuring 2 meters by 3 meters with a 100 mm slab thickness was printed on a 100 mm thick sub-base of #57 stone. A portion of the foundation was evaluated for flatness and levelness per American Concrete Institute (ACI) 117 [17]. Foundation durability was 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 [18]. Material strength was evaluated using a cylindrical compression specimen tested per ASTM C39 (this standard and test was also used in the Phase 2 competition). The winner of the level 1 construction competition was SEARCh+/Apis Cor [19]. The print of their foundation is shown in Figure 12.



Figure 12. SEARCh+/Apis Cor foundation print.

Construction level 2 required teams to fabricate a reduced scale habitat structural cylindrical element (2 m inside diameter and 1.5 m height) and subject it to hydrostatic testing. The element was partially filled to levels of 500 mm and 1.25 m and leakage was measured over the course of a 15 minute period at

each level. Wall penetration elements designed by the teams were also placed autonomously. Teams were evaluated on the outcomes of the hydrostatic test, autonomy (penalties were imposed for interventions), accuracy of penetration placement, conformity (measurement of inner diameter of habitat element), and materials. Teams were required to submit new tests for material durability and compressive strength if their material formulation had changed from the previous construction level. The winner of this portion of the competition was also SEArch+/Apis Cor [20].



Figure 13. Habitat element printed by SEArch+/Apis Cor.

Two teams (Pennsylvania State University and AI Space Factory) accepted invitations to participate in the construction head to head competition at Caterpillar Edwards Demonstration Facility near Peoria, Illinois in May 2019. At the head to head competition, teams were given thirty hours (in three ten-hour print windows) to print a 1:3 scale habitat. The competition emphasized autonomy and scoring penalties were imposed for any interventions (remote or physical) during printing. Teams were also asked to perform automated placement of three penetrations during construction. In addition to the habitat, teams manufactured three beams on site for flexure strength testing.

AI Space Factory used a Polylactic Acid (PLA) plastic material infused with basalt fibers. The thermo-setting, recyclable feedstock material was in the form of pellets that were pneumatically transported from a storage hopper to an auger-fed, heated nozzle (at the end of a robotic arm) for deposition. The AI SpaceFactory manufacturing robot was mounted to a forklift to increase the robot's workspace in the vertical direction and facilitate

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construction of the team's vertically oriented habitat: MARSHA (Figure 14). PSU used a metakaolin based geopolymers concrete mortar material extruded through a nozzle on the end of an industrial robot arm. A second industrial robot was used to facilitate placement of penetrations (Figure 15).



Figure 14. AI Space Factory's MARSHA habitat at the onsite competition.



Figure 15. Penn State University's completed habitat.

Following habitat construction, habitats were subjected to three tests, shown in Figure 16:

- i) Smoke test: introduce smoke at a nominal low pressure to qualitatively assess the air-tightness of the habitat
- ii) Impact test: select a vulnerable location on the habitat structure to impact with iron balls released from different heights to simulate meteoroid debris.
- iii) Crush test: Habitats subjected to a crushing force applied by a large hydraulic excavator bucket.

Scoring for the head to head competition based on interventions and onsite testing can be found in the Phase III challenge rules document [15]. Based on numerical scoring, first place in this level was awarded to AI Space Factory (\$500,000) and second place went to Pennsylvania State University (\$200,000) [21].



Figure 16. Onsite tests of printed habitats (top to bottom): smoke test, impact test, and crush test.

3. Technology assessment

The technology development for the Phase 3 construction challenge focused primarily on three technical areas: printing systems, materials, and autonomy.

3.1 Printing Systems

The printing systems developed under Phase 3 fall into two general classes: robotic arm systems and gantry-style systems. Gantry style systems (where the extruder is attached to a frame that translates it in three Cartesian coordinate planes) impose size limitations on structures commensurate with the build envelope of the gantry equipment. Robotic arm systems may be able to fabricate much larger structures with a smaller system footprint, but pose other complexities in control systems, vertical access and algorithms for print head path planning for 3DAAC. The system developed by SEArch+/Apis Cor for the Phase 3 was a polar coordinate robotic arm system with a micro/macro manipulator architecture and a working envelope with a very large radius enabled by the retractable boom (Figure 12 and 13). The platform is mobile, mounted on a forklift machine, which would enable sequential construction of multiple structures with remotely commanded repositioning of equipment. AI Space Factory and Penn State both used robotic arm systems at the Phase 3 head to head competition. The systems developed under the Centennial Challenges competition represent state of the art systems for large scale, rapid 3DAAC which may have wide-ranging applications in the construction industry and future planetary surface operations for creating in-situ infrastructure.

3.2 Materials

While Phase 2 was heavily focused on material development, Phase 3 shifted the focus of the competition toward autonomy and manufacturing scale-up. Teams in Phase 3 were still evaluated on materials selection according to a sliding scale (Figure 2 and Table 1), which favored use of indigenous and recyclable materials, but materials evaluation comprised only a small portion of the phase III scoring. There was also no minimum indigenous material requirement for Phase 3. Even though some constraints for materials were removed for this segment of the competition, material formulations were required to be in the spirit of the

rules (using indigenous Mars resources) and acceptance of a formulation was at the discretion of the judges. A number of novel and innovative material formulations were submitted as part of the Phase 3. In many instances, materials were tailored to the constraints of the competition, which require rapid material deposition and curing of material to achieve full strength. AI Space Factory used a pelletized polymer composite concrete of Polylactic Acid (PLA) and basalt fiber. PLA is a thermoplastic commonly used in 3D printing and has the additional advantage that it is able to be produced on Mars by synthesis as a bio-polymer derived from growing plants. The PLA, basalt fiber, and admixture can also provide radiation shielding, has a low coefficient of thermal expansion (advantageous for the thermal swings on Mars), and attains its full strength nearly instantaneously, as the thermoplastic PLA cools. The thermal cooling rate in space will be different due to the vacuum conditions and remains as a future challenge. Penn State University (PSU) also made materials choices which were driven in part by cure time and the time constraints for printing at the head to head competition. The team used a fast-setting metakaolin geopolymer based cement custom formulation for their mix. The material advances and complementary material modeling efforts of PSU are detailed in reference [22]. In the Phase 3 competition, the freeze/thaw test proved difficult for teams using polymer composite concretes, as this test was intended for typical cement formulations (however, there are also no standards for this evaluation which are readily applicable to 3D printed polymers with or without reinforcement material).

3.3 Autonomy

Autonomy and manufacturing scale-up (an increase in size and production rates) were viewed as the overarching technical challenges for the Phase 3 competition. Two teams (SEArch+/Apis Cor and AI Space Factory) demonstrated precise, automated placement of penetrations in the habitat element during the competition and deposited concrete materials at rates greater than 45 kilograms/hour. Given the scale of the structures, all teams had to manage substantial quantities of feedstock for 3D printing. These feedstocks had to be stored, conditioned, dispensed, metered, conveyed, and delivered to the print head via a robotic mechanism. Two main technologies were used to achieve these functions. If the feedstock was in a pelletized form,

then the method used by at least two teams was pneumatic conveying of the pellets. Another team used gravity-fed pellets. Feedstocks were all automatically fed to the print head since the rules did not permit manual intervention for this task.

Robots used to build the domes in Phase 2 as well as the foundation and water pressure retaining structures in Phase 3 exhibited a high degree of autonomy. The rules challenged teams to emplace water tight inserted pre-fabricated components in construction level 2. Penn State University used two robots working in tandem for autonomous placement. In this operations concept, one robot was used to print the structure with concrete and a second robot was used to place the components. This required considerable dexterity and coordination between the two robots. In future NASA space missions, teams of robots may work together as well as with humans (“cobots”) to build infrastructure and shelters.

4. Conclusion

At the outset of this Centennial Challenge competition, the hypothesis was that 3D printing systems, that are becoming common in industry, could be scaled up to print large structures typically seen in civil engineering applications, such as infrastructure for a Martian pressurized habitat to house a human crew. The competitors were challenged to devise autonomous robotic printing systems with concrete like materials using simulated Mars resources. The competition also invited architects to use their imagination and creativity to design habitats that are optimized for 3DAAC technology in the Mars environment.

The competition was organized in a three phased approach [12, 13, 23, 24] from 2015 to 2019 which developed architectural design concepts, novel Mars concrete structural materials, and autonomous robotic systems terrestrial prototypes at large scales. A 92 m² (1,000 ft²) area habitat was designed and the competitors were asked to demonstrate automated robotic construction of a 1:3 scale version to reduce logistics and cost in this competition.

The outcome of this competition was that the feasibility of three dimensional automated additive construction (3DAAC) was proven in a terrestrial environment. Before the competition, this technology was at a speculative technology readiness level

(TRL) of 2 (technology concept and/or application formulated), and after the competition concluded it had advanced to TRL 3 (analytical and experimental critical function and/or characteristic proof of concept).

By investing a total prize purse of \$3.1 million, NASA was able to inspire the public, universities and industry to participate in this challenge, which provided significant leveraging of funding when the private investment of the competitors is considered. The resulting technology development and concepts were observed and noted by NASA and are under consideration for further technology development and possible future lunar and martian mission implementation. This multi-phase challenge was designed to advance the automated construction technology needed to create sustainable housing solutions for Earth and beyond. This goal was successfully achieved.

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