Copyright ©2019 by the International Astronautical Federation (IAF). All rights reserved.

IAC-19-A5,3-B3.6,9,x49449

Robotic Construction & Prototyping of a 3D-Printed Mars Surface Habitat

Melodie Yashar[a]*, Nikita Chenniuntai[b], Sergey Nefedov[c], Christina Ciardullo[d], Michael Morris[d], Rebeccah Pailes-Friedman[d], Adam Day[e], Joe Aronis[e], Stephanie Pender[e]

[a] *Co-Founder, Space Exploration Architecture (SEArch+ LLC), Team Leader SEArch+ / Apis Cor,* melodie@spacexarch.com
[b] *CEO, Apis Cor Engineering,* info@apis-cor.com
[c] *Principal Material Scientist, Apis Cor Engineering,* info@apis-cor.com
[d] *Co-Founder, Space Exploration Architecture (SEArch+ LLC)*, info@spacexarch.com
[e] *Shop Supervisor & Specialist, Autodesk Technology Center, Boston,* build.space@autodesk.com
* Corresponding Author

Abstract

Team SEArch+ (Space Exploration Architecture) / Apis Cor won first place in Construction Level 1 (slab durability test), first place in Construction Level 2 (hydrostatic or seal test), fourth place in Virtual Design Level 1 (60% design), and first place in Virtual Level 2 (100% design), within NASA's Phase 3 Centennial Challenge for a 3D-Printed Habitat on Mars. The team won the greatest number of individual levels at the highest success rate within the competition, which took place from February 2019 – May 2019. Systems for large scale additive manufacturing are envisioned for robotic precursor missions which would build infrastructure prior to the arrival of crew. Part of this effort will include autonomous construction of in-situ resource utilization (ISRU) surface habitats on the Moon and Mars. The Construction Level submissions to the 3D-Printed Habitat Challenge demonstrate early experimentation in the robotic placement of habitat elements within a 3D-printed structure, while limiting human interventions as best as possible to simulate risks associated with communication latency and limited bandwidth in a future mission to Mars. Future ISRU surface habitats will incorporate precision manufactured elements such as windows and apertures, hard-shell modules for ECLSS and telecommunications, airlocks, structural reinforcement, as well as integrated sensor networks that will need to be autonomously integrated and/or placed within the 3D-printed structure. While none of the winning Challenge submissions exhibited autonomous decision-making capabilities let alone managed to execute submissions without numerous human interventions throughout the construction process, it is clear that much like early examples of automation within the architecture, engineering and construction (AEC) industries today, that human-robotic teaming will be a significant area of future research within a comprehensive concept of operations for 3D-printed surface habitats. The most necessary application for future work will be to incorporate robotic actions within building information modeling (BIM) workflows and a BIM model. Because autonomous 3D-printing systems must coordinate and function in real-time to integrate not only habitat elements launched from Earth but also ISRU materials handling equipment and excavation machinery within a strictly defined construction sequence, integration of robotic support with 3D-printing construction systems is an area of research needing much development.

Keywords: 3D-Printing, Autonomous Construction, Human Robot Collaboration, Mars Habitat, Surface Habitat

Acronyms/Abbreviations

Additive Construction with Mobile Emplacement (ACME), Architecture, Engineering, Construction (AEC), American Society for Testing and Materials (ASTM), American Concrete Institute (ACI), Building Information Modelling (BIM), Computer-Aided Design (CAD), Environmental Control & Life Support (ECLS), Human Robot Collaboration (HRC), In-situ Resource Utilization (ISRU), Light Detection & Ranging (LIDAR), Mechanical, Electrical & Plumbing (MEP), National Aeronautics & Space Administration (NASA), Ordinary Portland Cement (OPC), Technology Readiness Level (TRL), U.S. Army Corps of Engineers (USACE)

1. Introduction

Large scale additive manufacturing technologies will be applied to autonomously construct surface infrastructure prior to a crew's arrival in deep space. Future Mars missions depend on the creation of safe, durable and protective housing and infrastructure. Robotic precursor missions will rely on in situ resource utilization (ISRU) for the construction of landing pads, roads, berms, garages and habitats. Planetary surface construction will not only leverage ISRU additive manufacturing, but will also depend on robotic support to translate, maneuver, and place pre-integrated hardware modules and precision-manufactured habitat elements brought from Earth on the construction site or

Copyright ©2019 by the International Astronautical Federation (IAF). All rights reserved.

assembled within the structure at the appropriate time. NASA's Centennial Challenge program for a 3D-Printed Habitat solicited industry involvement within a competition for the advancement of large-scale 3D-printing technologies that can ultimately contribute to the autonomous construction of surface habitats on the Moon and eventually Mars.

NASA's Phase 3 Challenge for a 3D-Printed Habitat on Mars asked teams to introduce the design for a durable structure supporting a crew of four on a pioneering mission to Mars for one Earth-year. Team SEArch+ (Space Exploration Architecture) / Apis Cor won first place in Construction Level 1 (slab durability test), first place in Construction Level 2 (hydrostatic or seal test), fourth place in Virtual Design Level 1 (60% design), and first place in Virtual Level 2 (100% design), within NASA's Phase III Centennial Challenge for a 3D-Printed Habitat on Mars. The technology demonstrations and Construction Level submissions to the 3D-Printed Habitat Challenge advance present research on the coordination of 3D-printing systems with robotic deployment and placement of precision habitat components in an autonomous construction sequence. SEArch+ / Apis Cor submissions to the Challenge demonstrate how the 3D-printing system must integrate with the robotic deployment of habitat elements brought from Earth.

2. NASA Mission Objectives: Autonomous Additive Construction for the Moon and Mars

In efforts to establish a permanent human settlement on the Moon and eventually Mars, durable, self-maintaining, and resilient surface infrastructure must be constructed in robotic precursor missions prior to a crew's arrival. Robotic additive construction will be used within planetary applications to develop a wide range of surface site infrastructure including: landing pads, rocket engine blast protection berms, roads, dust free zones, equipment shelters, and of course human habitats and radiation shelters [1]. Multiple sheltering aspects will be needed for early settlements to reliably protect crews against radiation, micro-meteoroids, and provide exhaust plume protection during subsequent launches.

NASA, ACME, USACE and Contour Crafting Corp have developed and advanced technologies addressing the viability of large-scale additive manufacturing within Earth-based prototypes for the eventual application of autonomously constructed surface habitats since as early as 1994 [2,3,4]. These projects and organizations are committed to raising the technology readiness level (TRL) of 3D additive construction (e.g., contour crafting) and excavation and handling technologies to effectively and continuously produce in-situ feedstock for surface site establishments.

2.1 Why Autonomous 3D-Printing

Deep space mission infrastructure will enable autonomous construction of habitats, garages, berms, landing pads, radiation shielding, etc. and will be essential to minimize the amount of material launched from Earth. Transportation costs make it prohibitively expensive to launch pre-integrated habitat systems for long-duration exploration missions to Mars. 3D-additive manufacturing is appealing for surface site construction because it provides great versatility in being able to manufacture a wide range of structural geometries on-demand.

Research pushing towards the realization of 3D-printed surface habitats will advance in parallel with technology development in construction robotics, ISRU capabilities, autonomous systems, and human-robot collaboration. NASA has designated three classes of space habitat paradigms: Class I consists of hard-shell modules pre-integrated on Earth (i.e. the ISS), Class II habitats are prefabricated and surface-assembled modules (such as inflatable structures), and Class III space habitats utilize ISRU for the autonomous construction of structures that integrate with Class I and II modules [5]. Currently 3D-printed ISRU surface habitats constitute a later-stage development initiative with low technology readiness. To advance the viability and technology readiness of additively manufactured ISRU surface habitats, technology development not only depends on the 3D-printing mechanisms themselves, but likewise in the robotic integration of pre-integrated hard-surface modules and precision-manufactured elements launched from Earth.

2.2 ISRU Capabilities

In situ resource utilization is the foundational principle for making autonomously constructed surface habitats cost-effective. Future deep space missions will require the use of in situ planetary materials for construction and manufacturing of habitats and other infrastructure. Surface structures that use local and indigenous materials for construction will drastically reduce launch and transportation mass. Payload mass-optimization is the principal rationale for ISRU manufacturing of materials, technology, and resources supporting autonomous surface habitat construction.

The many months of travel between Earth and Mars necessitate greater self-sufficiency from both the crew as well as robotically deployed elements for ISRU processing and habitat construction [6]. ISRU capabilities are essential to an overall mission architecture in which multiple technical discipline elements such as mobility, material processing, product storage and distribution are connected and tied to other systems [7].

Copyright ©2019 by the International Astronautical Federation (IAF). All rights reserved.

2.3 Surface Site Preparation, Excavation & Materials Handling Technologies

Before 3D-printing is deployed for infrastructure development, site establishments will rely on construction machinery for excavation, levelling, grading, and preparation of the terrain. Space robotics will be an integral part of surface site preparation relevant to ISRU for the construction of deep space infrastructure (artist conception shown in Figure 1). Robots will assist in scouting and surveying build and excavation sites, in addition to prospecting and processing raw materials such as regolith. Tasks such as material transport, equipment positioning and assembly will be managed by robot fleets on precursor missions [8]. Machinery for site preparation will not only need to mobilize autonomously, but connect and integrate with other ISRU systems (such as for power).

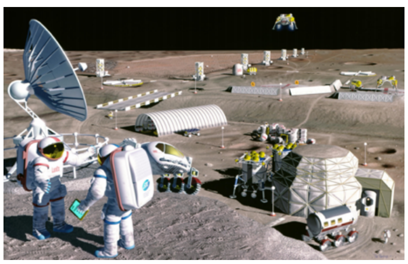


Fig. #1. Artist conception of human-robot lunar operations [8]

After initial infrastructure elements and habitats are constructed and crewed missions arrive to Mars, humans will work collaboratively with robots to perform field activities such as mining, collecting, transporting, and processing materials such as regolith. For ISRU systems to be cost effective in the long term, initial technologies for site preparation and construction will continue to operate alongside crewed missions, and will address issues such as maintenance and repair collaboratively as teams.

2.4 3D-Printing Regolith Structures

Regolith is the primary candidate for a building construction material in manufacturing future habitats given its abundance on the Martian surface. Regolith 3D-printing methods representing the current state-of-the-art were evaluated within the "Three Dimensional (3D) Additive Construction For Space Using In-situ Resources study," a workshop of subject matter experts at the W.M. Keck Institute for Space Studies in 2016 [7]. Within this workshop, a survey of regolith-based printing systems was conducted and evaluated based on whether the construction methods were partial or zero-g capable, whether they could be implemented with ISRU materials processing, in addition to power consumption rate and deposition rate etc. Within the study, a variety of extrusion deposition and layered in-situ binding mechanisms were explored and compared such as: cementitious, fused-deposition method, microwave melting, powder spray, laser sintering, solar sintering, and selective inhibition sintering, among others [7].

Large scale additive manufacturing prototypes on Earth today presents opportunities for critical case studies to be developed serving the long-term development of autonomously constructed habitat systems on the Moon and Mars. NASA Centennial Challenges' 3D-Printed Habitat Competition sponsored by Caterpillar, Bechtel, Brick & Mortar Ventures solicited the general public for future 3D-printed habitat designs and followed with two competition phases intended to accelerate technology development for large scale additive manufacturing of the habitat designs within private industry. In order to advance the technology readiness of large scale additive manufacturing for the construction of deep space surface infrastructure, terrestrial prototypes must advance the fidelity of 3D-printed mock-ups by demonstrating autonomous construction processes in addition to integration with other robotic tasks, such as emplacement of pre-integrated and hard-shell habitat elements.

3. NASA's Centennial Challenge for a 3D-Printed Habitat on Mars

SEArch+ / Apis Cor's participation within NASA's Phase 3 3D-Printed Habitat Challenge enabled the team to contribute and advance this area of research. The 3D-Printed Habitat Challenge is part of NASA's Centennial Challenges Program and focuses on both habitat design as well as technology development of large-scale additive construction systems capable of fabricating structures from in situ materials (such as regolith) and/or mission recyclables (such as plastic packaging) [9].

The Centennial Challenge program issued solicitations in 2015 and 2018 for virtual designs relevant to building information modeling (BIM) for additive construction. The Phase 2 Challenge asked teams to develop material mixtures and 3D-printing systems and produce test specimens (compression, flexure) and manufacture a small dome structure [9]. The Phase 3 3D-Printed Habitat Competition was subdivided into multiple Virtual Design as well as Construction submission levels, with the ultimate intent of advancing the applicability of BIM to large-scale additive manufacturing projects in space.

3.1 ISRU Material Relevance for Additive Construction

For the purposes of the 3D-Printed Habitat Competition Construction submissions, the competition rules specified which materials would be more or less relevant to future ISRU deployment within a Mars mission scenario. Materials were assigned a 3D-Printing

Copyright ©2019 by the International Astronautical Federation (IAF). All rights reserved.

weight factor (3DP factor) which was multiplied by the percentage of the component within the material mix in order to score the suitability of the construction material for future ISRU deployment within a Mars mission (see Figure 2). 3DP weight factors were subdivided into relevant weight classifications for additives, binders, and aggregates, respectively [10].

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

Scoring Rewards Planetary Relevance and Use of Mission Recyclable Materials

Fig. #2. Material applicability scale provided by NASA

A material score was assigned based on the sliding scale above (Figure 2), and materials with greater applicability to a Mars exploration mission received a higher score. The material score represents the weighted sum of the amount of a material used in the mix multiplied by its corresponding 3DP factor [9].

3.2 Virtual Design Levels of NASA's 3D-Printed Habitat Challenge

In the Virtual Construction levels of the competition, teams were asked to create BIM models of autonomously constructed habitat structures and provide detailed information on materials, design, and construction sequencing [9]. Mars X-House by team SEArch+ / Apis Cor won first place within Final Virtual Design (100% Design) within the Phase 3 NASA 3D-Printed Habitat Challenge (see Figure 3 below).

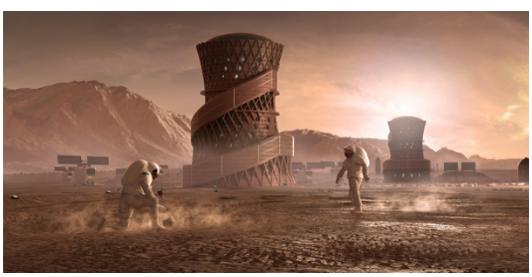


Fig. #3. Mars X-House Exterior View

The habitat designs required a pressure-retaining living space of at least 93 m^2 with the intent of supporting four astronauts for one year. Teams were asked to deliver a BIM model as well as a 4D construction sequence simulating the activities of all autonomous activities at the site including: construction machinery, additive manufacturing, and emplacement of pre-integrated components (ECLS, airlocks, etc). Teams were asked to incorporate (at minimum) a suit hatch, a view port, an equipment/rover hatch, and two combined communications-power-instrumentation penetrations within the habitat design and structure [10].

Mars X-House celebrates innovation in radiation shielding techniques while allowing natural light to penetrate the structure, supporting the astronauts' physiological and psychological well-being in a long-duration mission [11]. Our human-centered approach prioritizes safety, redundancy, and the wellbeing of the crew. Considerations such as tensile loading, printability as well as simulation of an appropriate construction sequence given a mobile printing apparatus factored into the design decisions made for the habitat.

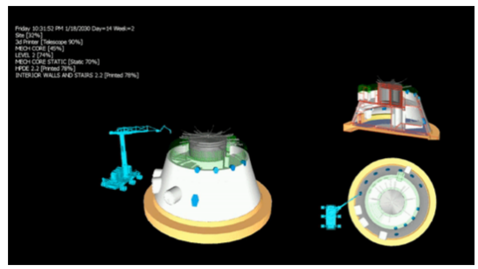


Fig. #4. Still from 4D Habitat Construction Sequence

Simulation of construction sequencing of the habitat (4D-BIM) demonstrated two mobile 3D-printers as well as mobile platforms coordinated in the building construction process. Installation of habitat windows, a pre-integrated mechanical core, as well as pre-integrated hardware modules for laboratory experiments and communications were represented within the construction simulation (see Figure 4).

3.3 Construction Levels of NASA's 3D-Printed Habitat Challenge

In construction levels of the competition, teams were asked to develop printing systems and material mixes for the fabrication of: a foundation prototype, a habitat element, and ultimately a subscale habitat which would be 3D-printed onsite at a head-to-head event at Caterpillar Edwards Research & Demonstration facilities [9]. The individual prototypes produced for each of the Construction submissions were evaluated for: flatness, impact resistance, compressive strength, durability, and the ability to form a hermetic seal.

Phase 3 Construction Levels to the Challenge placed an increased focus on autonomy and teams were penalized for manual intervention with robotic systems during construction. Through the competition, the Centennial Challenge program seeks to evaluate the scalability and efficacy of various construction processes, material systems, and designs for planetary construction [9].

Copyright ©2019 by the International Astronautical Federation (IAF). All rights reserved.

3.4 Teleoperation & Human Interventions

An overarching goal of the Phase 3 competition was autonomous operations and teams were penalized for human interventions during construction. Remote intervention via teleoperation also incurred a penalty. Scoring was based on the durations of physical interventions and remote operations/human interventions (teleoperations) during the printing process. Physical interventions were scored on the total time of intervention events. A "safety keep out" zone where potentially hazardous human/machine interaction could occur was required to be marked with red tape. A second, larger "construction zone" including all areas around the printer and its support equipment was required to be marked with yellow tape [10]. Physical interventions that only required entering the construction zone would be timed from when personnel enter the construction zone and would be stopped when they exit the construction zone. Teleoperations are measured as the total time spent by personnel touching any electrical or control inputs to the printing system [10].

3.5 3D-Printer & Construction Process

Apis Cor's 3D printing technology features a mobile construction 3D-printer (see Figure 5) and an automatic system for mixing dry construction mixtures. Apis Cor has also developed equipment for automated mixing and mixtures feed-in. To date, Apis Cor has gained impressive experience in printing on 5000 square-foot construction sites in uncontrolled natural conditions.

Fig. #5. Apis Cor printer

For both Construction Levels 1 and 2 the technology setup included a 3D-printer, controlling unit, mixing system and silo. The 3D-printer deposits material at a rate of 10 meters per minute, with the average thickness of each material layer being 23 mm and width being 40 mm. When printing right angles, the deposition rate drops to 1 meter per minute (additional specifications are provided in Table 1). The material setting process initiates in the range of 30-40 minutes, and setting finishes within an hour. This time bracket ensures excellent interlayer adhesion. The number of layers which can be printed is only restricted by the height of the printer gantry, which is currently 3.8-meters.

The printing process follows generated g-code downloaded to the printer's management software. This also specifies the height of each layer and the volume of the supplied material. Hydraulic cylinders located at the printer's base provide lifting and lowering of the 3D-printer.

Table #1. Apis Cor 3D-Printer

Specifications	Values (AC-03 Model)
Printing radius (max/min), mm	5800 / 900
Trajectory velocity, m/min	10
Printing height, mm	3800
Lift Speed, m/min	0.2
Printer Hardware Dimensions (max height x max width x max depth) m	5.15 x 8.2 x 1.65
Printer Hardware Dimensions (min height x min width x min depth) m	1.6 x 4.8 x 1.65
Mass, kg	2700

* Printer model AC-03 was used for Construction Levels 1 and 2 of the 3D-Printed Habitat Competition.

At the moment, a dry mix (either based on mineral raw materials or polymers) is used for printing. The dry mix is delivered to the construction site in mobile silos or bags. The dry mix is transported from the mobile silo to the mixing station by means of pneumatic transporters, where it mixes with the liquid component. Then the liquid mortar is fed to the printer's mainline and finally the printhead.

3.6 Material Mix

The same material mix was used for Construction Level 1 and Construction Level 2. We selected a printing mix based on a gypsum cement pozzolanic binder (see Table 2 below for calculation of 3DP factors). To improve the low water resistance, and thus the low frost resistance of the gypsum binder, cement and a pozzolanic additive (metakaolin) were added to the material mixture. As a result of this addition low basic calcium hydrosilicates are formed, which increases the water resistance and frost resistance of the material. At the same time, the gypsum binder possesses fast setting times combined with high strength. A citric acid retarder was added which allows the material setting time to an accuracy of several minutes (whereas, for example, with tartaric acid, it is possible to control setting time within 10-minute increments). To increase water retention and interlayer adhesion, a low-viscosity cellulose ether was added to the material composition, and starch ether was used to reduce stickiness. The

Copyright ©2019 by the International Astronautical Federation (IAF). All rights reserved.

beginning of mortar setting is in the range of 30-40 minutes, and the end of setting is within an hour.

Table #2. Material calculation of 3DP factors

Component	Percentage of Mix	3DP Factor	Calculation
Gypsum Binder	38.46	8	307.7
OPC	7.69	1	7.7
Metakaolin	0.77	1	0.8
Quartz sand	29.69	5	148.5
Cellulose ether	0.12	2	0.2
Starch ether	0.04	2	0.1
Retarder (citric acid)	0.15	2	0.3
Water	23.08	3	69.2
			534.5
3DP Factors			5.3

* Binders comprised of: Gypsum, OPC, Metakaolin and Water; Aggregates comprised of Quartz sand; Additives comprised of: Cellulose ether, Starch ether, and a Retarder (citric acid).

Verification of the material mix rheology is critical for additive manufacturing processes. Cameras were installed within the mixing system in addition to above the material silo to anticipate issues and moments in which human interventions would be necessary. In future iterations and work, additional sensor-based technology for rheology verification may improve the system.

4. Construction Level 1 / Slab Durability Test of 3D-Printed Habitat Challenge

Team SEArch+ / Apis Cor won first place within Construction Level 1 (Slab Durability Test) within the Phase 3 NASA 3D-Printed Habitat Challenge. Teams were asked to fabricate a foundation measuring 2m x 3m with an optional wall interface.

4.1 Construction Level 1: Requirements

Construction Level 1 asked teams to 3D-print a foundation and wall interface for flatness and levelness testing according to ACI (American Concrete Institute) 117 [12]. Foundation durability was assessed with an impact test (performance scored on degree of cracking and material deformation) and by performing freeze/thaw testing per ASTM C666 [13]. Material strength was evaluated using a compression specimen tested per ASTM C39 [14]. The CAD drawing for the 3D-print was provided by the competition (see Figure 6).

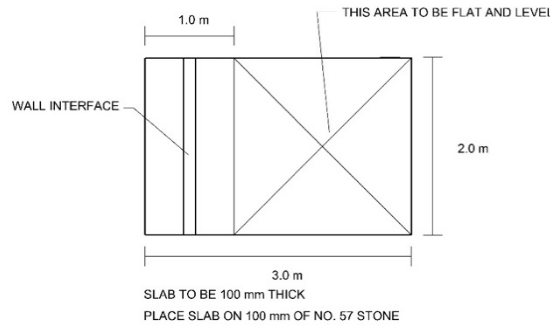


Fig. #6. Foundation and wall interface

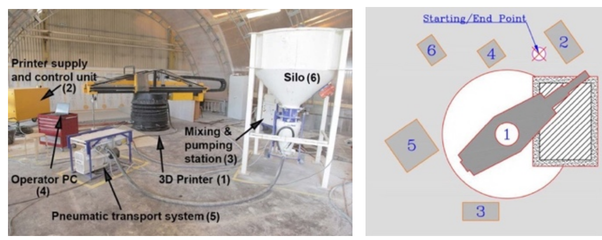


Fig. #7. Printing setup for slab test

4.2 Construction Level 1: Printing Process & Interventions

To start the printing process all elements are powered on and the control program is loaded. The mixing station is powered on and begins a compounding cycle, while the operator of the printer starts the operation of the control program. Before the printer translates its position, the pipeline of the 3D-printer is first filled with mortar and only then does the first layer of printing begin. After each individual layer, the printhead returns to the same initial point adjacent to the foundation to remove residual material from the line.

Fig. #8. Slab & wall interface prototype

The printing time for the slab and wall interface was 2 hours 5 min. In the process of printing, one intervention was made lasting 50 seconds. The reason for the intervention was to change the mixture consistency. The mixture consistency needed to be changed because the water-to-solid ratio was out of balance. The operator of the plaster station then reduced water dosage.

Copyright ©2019 by the International Astronautical Federation (IAF). All rights reserved.

Fig. #9. Nozzle attachment on the extruder

To achieve a smooth surface on the slab a special nozzle was installed on the extruder (see Figure 9). This approach does not require additional surface treatment for the printed plate.

4.3 Construction Level 1: Material Performance & Test Results

Flatness results from testing were 49.6 and levelness results were 20.0, with an average surface deviation of 0.058 in. (1,67 mm). Based on these values, ACI's floor surface classification is moderately flat. Levelness was measured with a Lika IXB inclinometer, and measurements were taken along two diagonals. The obtained values were: –0.017° and = +0.056°.

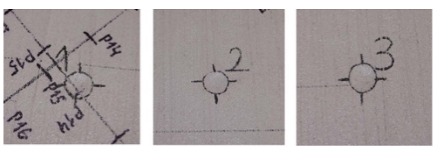


Fig. #10. Measurements from impact test

The durability of slab was measured by dropping an Olympic shotput from a predefined distance. Cracks on the slab surface were not visibly present after the drop of the shotput, however they were measured and documented (see Figure 10).

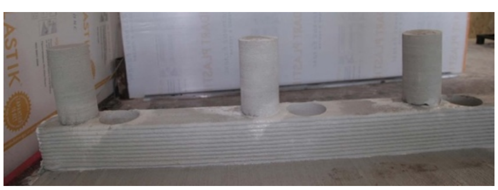


Fig. #11. Samples extracted from slab for ASTM C39

Samples from the foundation prototype were extracted and tested by specialists at Moscow State University within the department of Construction Materials and Products analysis (see Figure 11) in order to conduct compressive strength and freeze thaw testing (see Tables 3 and 4 below for test results).

Table #3. Compressive Strength Results (ASTM C39)

Identification Number	S0	S1	S2
Age, days	4	4	4
Average measured diameter, (mm)	149.6	153.9	151.7
Cross-Sectional Area (mm^2)	17579	18602	18074
Maximum Load, kN	167	175	174
Compressive Strength, MPa	9.5	9.4	9.6
Fracture Type	Type 3	Type 3	Type 3

* The average compressive strength after 4 days of hardening is 9.5 MPa. Fractures after the test have the following character: columnar vertical cracking through both ends with no well-formed cones, equal to type 3.

Table #4. Durability of Material (ASTM C666)

Identification Number	S3	S4	S5
Number of Freeze/Thaw Cycles	150	150	150
Fundamental Transverse Frequency at 0 cycles	19260	20273	19980
Fundamental Transverse Frequency after 150 cycles	15215	16360	16264
Relative dynamic modulus of elasticity	62.4	65.1	66.3
Average relative dynamic modulus of elasticity	64.6	64.6	64.6
Durability factor	64.6	64.6	64.6

5. Construction Level 2 or Hydrostatic / Seal Test of 3D-Printed Habitat Challenge

Team SEArch+ / Apis Cor won first place within Construction Level 2 (Hydrostatic Test/Seal Test) of the Phase 3 NASA 3D-Printed Habitat Challenge. The total printing time for the structure was 5 hours, 47 minutes. There were 4 human interventions lasting 16:04 min and 4 teleoperations that lasted 20:27 min.

Fig. #12. 3D-Printer, ABB robot, and final structure

5.1 Construction Level 2: Requirements

The requirements of Construction Level 2 were to fabricate a reduced scale habitat "element" and subject

Copyright ©2019 by the International Astronautical Federation (IAF). All rights reserved.

it to hydrostatic testing. The element (see Figure 12) would then be partially filled to levels of 500 mm and 1.25 m with any leakage measured over the course of a 15-minute period at each level. Teams were asked to place wall penetration elements within the structure autonomously, given that physical or remote/teleoperated intervention of the system during fabrication is penalized. CAD drawings for Construction Level 2 were provided by the competition and shown in Figure 13.

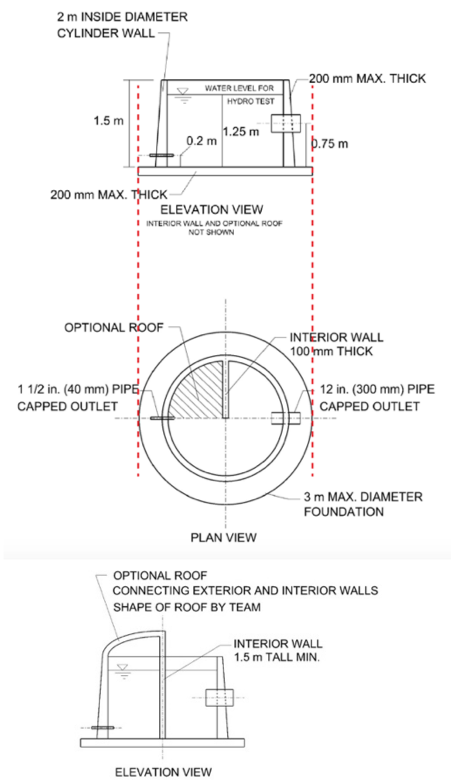


Fig. #13. Plan & elevation view of habitat element structure for hydrostatic test

5.2 Construction Level 2: Material Preparation

A rotating barrel drum (see Figure 14) was run automatically by means of motor and angle between the barrel at a rotation axis of 20 degrees. The dry mixture was then loaded into the material silo manually. The water supply was then added directly into the a mixing unit at a 100: 30 ratio.

Fig. #14. Mixing barrel and material silo

5.3 Construction Level 2: Robotic Emplacement

An ABB 4800 robotic arm was used to install the habitat penetrations, which included a big pipe, small pipe, and a roof element (see Figure 15). A digital signal sent from the printer to the ABB robot was inserted within g-code to minimize human intervention and simulate a fully automated (as opposed to autonomous) construction sequence. The signal would initiate the robot's automated routine to lift, lower, and drop into place the big pipe, little pipe, and the PVC roof, respectively, at the appropriate times in the printing process. Once the routine was complete the robot arm would return to a designated "home" position, at which point a subsequent digital signal would be sent back to the printer and 3D-printing would recommence.

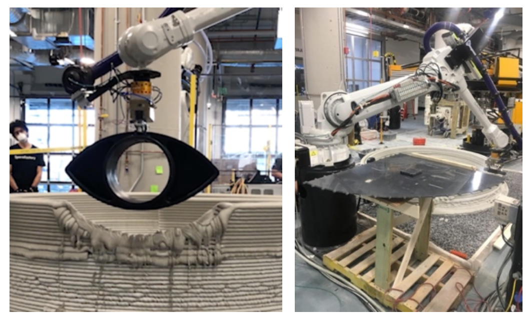


Fig. #15. (Left) Emplacement of large pipe. (Right) Emplacement of small pipe and setup for PVC roof

The pipe elements were designed specifically for emplacement within the printed structures. The penetrations were 3D-printed out of PLA plastic, making the 3DP material factor of the penetrations 7.

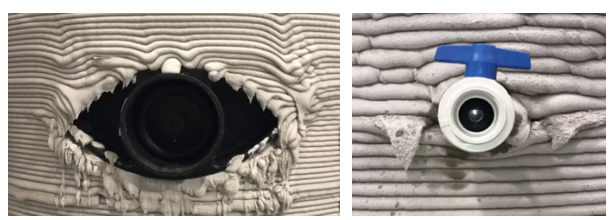


Fig. #16. (Left) Tire and cap for big pipe. (Right) Tap for small pipe.

To block and open the pipe elements a tap was used for the small pipe and a tire and plastic cap for the big pipe (see Figure 16). Once the pipe elements were emplaced, positioning of the printhead was pre-programmed to move around each of the pipe interfaces and stop depositing material when in close proximity. These manoeuvres were hard-coded within g-code (see Figure 17). There were no additional measures taken for obstacle avoidance at this stage of the demonstration and naturally there was substantial risk that the small pipe, in particular, would collide with the printhead and be knocked out of the structure.

Copyright ©2019 by the International Astronautical Federation (IAF). All rights reserved.

Fig. #17. (Left) Bases for pipes. (Right) Avoidance of pipe by the printhead after emplacement

To print the optional roof a supportive plate was laser-cut out of PVC plastic. Penetrations and roof were set on special bases where the ABB arm picked them up in order to insert them into the habitat structure.

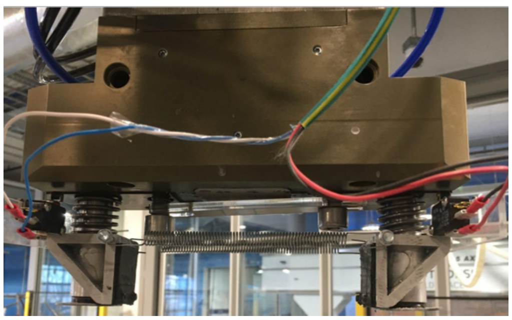


Fig. #18. Gripper / end effector for pipe emplacement

An end effector was specially designed as a gripper with sensors to stop the robot arm's routine before a collision with hardened material takes place (see Figure 18). When lowering the pipe interfaces into the structure the robot lowered exclusively on the z-axis. The sensor served as a countermeasure in case the material slurry cured too quickly or alternatively was too wet. The gripper release was actuated by the sensor and a maximum z-value where the gripper would release the pipe was hard-coded within the robot routine. These values derived from the habitat element CAD model. Corresponding lift tabs on the pipes and roof were designed specifically for the gripper itself so that only one grasping mechanism would be required (see Figure 19).

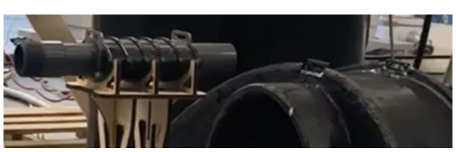


Fig. #19. Grasping tabs for emplacement of the pipes

In future missions universal design of grippers and handles will be critical for the assembly of habitat elements within human-robot teams. For true collaboration, robotic dexterity will require habitat elements to be grasped and emplaced dynamically, but at this stage we did not have a reason to investigate further. Additional research may be conducted to better correlate the design of rigid and pre-integrated hardware components with robotic gripping systems for emplacement. We did not take additional measures to seal the structure given time and budgetary constraints, but instead relied on the hydrophobic characteristics of the material. In future work, anomaly detection within a vision system would enable additional sealing tasks to be performed autonomously.

5.4 Construction Level 2: Print Process & Interventions

Both pipe interfaces (penetrations) within the structure were installed in automatic mode and without human intervention. However, four human interventions having to do with the material mixing process required stopping the print process and resolving issues with the material handler. The human interventions consisted of the following:

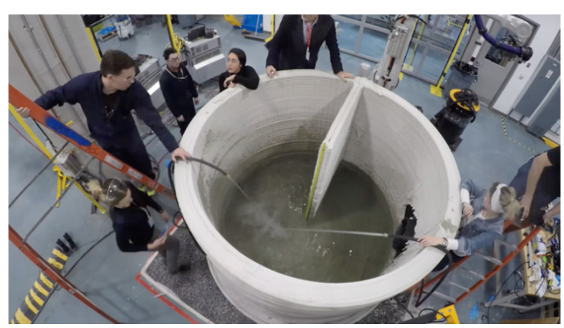
1. 12 seconds. We needed to clean the sensor of level of the mixture in the filling chamber of a pump.
2. 3:31 min. Changing of the mixture consistency; to solve this we cleaned the filling shaft.
3. 21 sec. We needed to clean the sensor of level of the mixture in the filling chamber of a pump.
4. 12 min. Changing of the mixture consistency; to solve this we needed to clean the filling shaft and filling chamber.

5.5 Construction Level 2: Material Performance & Test Results

The same material mix was used for the submission to Construction Level 2 as in Construction Level 1. This material mix had previously been tested for strength and durability. The hydrostatic test proved successful within the parameters of the competition, but much work remains to be done to fully evaluate the integrity of large scale 3D-printed structures once pressurized.

Table #5. Hydrostatic Test Results

	Leakage after 15 min, cm
500-mm Fill	0 cm
1.25-m Fill	Incomplete



Copyright ©2019 by the International Astronautical Federation (IAF). All rights reserved.

Fig. #20. Filling the structure for the hydrostatic test

After filling the structure 500 mm the structure did not show any leakage after 15 minutes (see Table 5). The decision was made to not fill the structure to 1.25 m given the high risk associated with high pressure water volume within the advanced working environment at Autodesk Build Space. No additional sealing, caulking, or manual revisions were made to the structure after the printing process was complete.

Table #6. Structural Conformity

	Horizontal	Vertical
Inside diameter of the wall	2000 mm	1485 mm

* The structure was measured in accordance with "Specifications for Tolerances for Concrete Construction and Materials (ACI 117-10)."

Table #7. Accuracy of Penetration Placement

Penetration Type	Small Pipe	Big Pipe
Horizontal Positioning	+8 mm	-8 mm
Vertical Positioning	0 mm	+10mm
Alignment Parallel to Slab	4 deg	0 deg
Alignment Perpendicular to Tangent Line	1.6 deg	0 deg

5.6 Observations & Learnings

For the equipment setup of Construction Level 2, the material handling system was the most vulnerable and prone to interventions. Within a larger facility alternate resources could have been used for dry goods and liquid materials handling and delivery. In a future Mars mission, autonomous construction robots will require sub-systems that communicate seamlessly with one another. This includes delivery of loose noncompacted regolith from the planetary surface and liquid material (water) from ISRU containment systems to a material delivery system hopper. The material delivery system would then deliver measured amounts of dry and liquid materials to a hopper where the material is mixed and delivered to a concrete pump. The materials would then transferred by hose to a 3D-print head whose 3-dimensional positioning is controlled by g-code.

5.7 Building Envelope Tightness & Sealing

To date, 3D-printed structures have yet to demonstrate a capacity for airtightness that will be critical for pressurized habitat interiors that maintain Earth-standard atmospheric pressure. Habitat shell structures are at risk to impacts from micrometeorites and other debris. The Hydrostatic / Seal test performed within Construction Level 2 was intended to advance knowledge and understanding of the hurdles involved in creating air-tight 3D-printed structures.

Autonomous sealing solutions for 3D-printed structures are a necessary countermeasure for the success of autonomous construction robotics within a mission scenario. Most industrial applications of sealing robotics remain outside the AEC (Architecture, Engineering and Construction) industries. Historically, sealing robots have been used in industrial applications requiring hard-to-reach ergonomic and difficult environmental conditions. Cementitious extrusion and layer-based deposition printing technologies are not gravity-neutral processes and few function in six-axes. However risks associated with ensuring appropriate sealing between emplaced habitat elements (such as vision windows, airlocks and pre-integrated hard-shell modules) warrant supporting technologies that can ensure airtightness and pressurization. An appropriate sealing material should achieve not only good bonding performance but also heat-resistance, elasticity, plasticity as well as tension-compression cycling performance. The design of expansion joints and their performance within habitat systems will also be a critical area of development for structural design.

Non-destructive inspections and testing of 3D-printed structures such as ultrasonic or 3D laser scanning will be critical for validating airtightness and internal pressurization. Computed tomography (CT) scanning is a common x-ray imaging procedure for validating the material properties of additively manufactured parts. However one key differentiator for additive manufacturing is the fact that non-destructive testing can take place after each layer is made. Both high resolution imaging systems and ultrasonic online monitoring methods can ensure quality control as the structure is being printed. Thus, should a fault within the material handling system or deposition end-effector impact structural integrity, autonomous sealing robotics may detect the fault and respond accordingly.

Internal pressure vessel inspection is just as significant an area of concern and space robotics for surface habitats will need to function along these lines as well. The aircraft, submarine, oil, gas, and petrochemical industries have introduced robotic inspection solutions for pressure vessel interiors. The robots used for inspection of pressure vessels have included crawlers and so-called snake-arm robots [15] and usually carry a payload of inspection tools such as camera and ultrasonic transducer. The scale of a human habitat may justify the use of small unmanned aerial vehicles to carry out visual inspections.

5.8 Construction Level 3 ($^1/_3$ scale habitat print)

Construction Level 3 took place onsite at the Caterpillar Edwards Research & Demonstration Facility in Peoria, Illinois in May 2019. Two teams, AI Space Factory and Penn State, competed within the "head-to-head" live printing demonstration and structural testing.

Copyright ©2019 by the International Astronautical Federation (IAF). All rights reserved.

Teams were asked to additively manufacture a $^1/_3$ scale habitat design. The design was not prescribed, but teams were asked to submit a BIM model of the habitat. As in prior levels, construction was intended to be autonomous to the greatest extent possible and penalties were applied for both remote and physical interventions in operating the system [9]. Structures were subjected to onsite testing including: a smoke test (to assess leakage), impact testing (judges determined a vulnerable point on the structure and iron balls were dropped from three different heights), and crush testing (using a hydraulic excavator). Scoring was then based on the structure's performance, the material mix, and the degree of system autonomy.

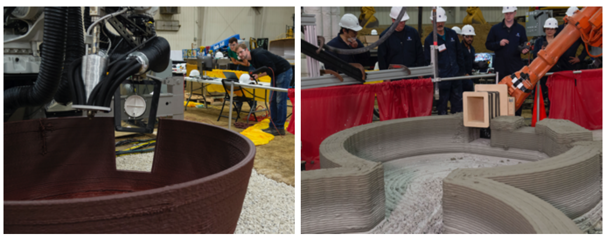


Fig. #21. Examples of window emplacement from the head-to-head event

Neither team robotically emplaced habitat elements within the structure (see Figure 21) without human interventions, on account of substantial perceived risk. Interventions were tracked and documented by competition judges.

6. Towards Construction Automation Robotics

Terrestrially, the AEC industry is still in the early days of leveraging construction robotics and autonomous machinery for construction automation of buildings. Construction sites are challenging environments for robots as conditions tend to be highly variable, unstructured, and can present difficult working conditions for automated machinery that would need to be easily portable. Robots are extremely time and cost efficient for repeated actions where reliability and value can be easily perceived, and thus robotic implementation has focused on high volume production [16]. Examples of construction robotics on building sites are typically single-task construction robots [17]. Buildings are each uniquely designed and rarely contain repeated elements that would benefit from investment in industrial-scale assembly and automation.

6.1 BIM & Sub-System Integration

The complexity of MEP (mechanical, electrical, plumbing) installation tends to contribute to an understanding of buildings as one-off structures with little if any repeated assembly tasks and procedures. The potential to embed building utilities such as heating, electrical and plumbing components has been celebrated by early pioneers of additive construction such as Khoshnevis [3,4], however standards for sub-system integration of mechanical, electrical, and plumbing (MEP) hardware are yet to be developed for integration with large-scale additively manufactured structures. For AEC and future space habitat construction alike, building information modeling (BIM) represents a critical software capability to represent and manage all information relevant to a structure's construction elements and components within a single digital model.

However, BIM alone is not sufficient for the direct planning of automated construction processes both off-site and on-site. Construction tasks well suited to execution with industrial robotics include: installing thermal insulation, stacking, nailing elements together, or painting. Each of these tasks requires moderate force and is repetitive in nature. However a majority of building elements, particularly prefabricated components, are highly customized products. Even if a BIM model provided information for assembly and installation of a repeated component, there still would not be a clear path for automated or autonomous task execution by a robot. BIM can be conceived more as a planning and management asset, and does not specifically benefit the use of robotics in construction [18]. Merging BIM workflows with 4D construction sequencing geared towards robotic construction thus remains a critical task to advance autonomous construction at the building scale.

6.2 Dynamic BIM for Autonomous Systems

Sensing, perception, and situational awareness will be critical capabilities for multiple robotic agents to execute complex tasks within a construction sequence. Object recognition often requires fusing multiple sensing modalities, whereas a perception function can associate the sensed object with a reference that is understood in advance [19]. Sensing approaches to date have combined machine vision, stereo vision, LIDAR, and RADAR. Perception approaches often start with CAD models or 3D-models created by a scan of the object in question. For autonomous systems to effectively operate on a building construction site, they must be able to refer to or derive a semantic model of the environment [20,21]. It is extremely important that human-robot teams be able to access and contribute to a dynamically updated BIM model [22]. Autonomous robotics for extra-terrestrial building construction will incorporate computer vision hardware and optical object-locating sensors such as: CCD cameras, 2D laserprofilers and 3D cameras [16]. In industry, 2D machine vision has been a standard solution to flexible object localization. In theory, a vision system on a mobile robot could sense common worksite objects as well as events and a computer vision algorithm could not only detect objects but characterize them. At that

Copyright ©2019 by the International Astronautical Federation (IAF). All rights reserved.

point real-time building information modelling could enable building components to spawn, modify, or be revised in some way within a unified cloud-based model accessible by all agents.

A framework for all robotic and autonomous agents to reference a dynamic BIM model and perhaps even more importantly, the 4D construction sequence or schedule of the overall construction process, will be critical in the development and advancement of autonomous construction for both earth and space. Eventually, dynamic building information models could be used alongside extensive simulation and machine training to anticipate errors and predict collisions, near-misses and safety issues in real-time [20,21]. The framework for a dynamic BIM model updated in real-time with the events, processes and milestones of the construction site itself will prove indispensable to human-machine collaboration within autonomous construction, as it will ensure a shared mental model of construction progress.

6.3 Supervisory Control

Prior to a crew's arrival, exploration field labour will be performed telerobotically (human at ground control, robot on planetary surface). Communication delays and limited bandwidth over the course of a Mars mission will prevent real-time teleoperation from the ground while surface site infrastructure is constructed.

To function autonomously, mobile construction robots will need to engage higher-level goals that assume various sub-tasks and sequenced behaviours. An autonomous system for extra-terrestrial construction will need to resolve choices on its own—the decision-making process is done locally. Autonomous construction robotics will thus need to partake in complex decision-making, in addition to an "ability to self-adapt as the environment in which the system operates changes, and the ability to understand system state" [19]. Variable or mixed initiative autonomy may provide greater possibilities for teleoperation within a Mars mission. Comprehensive simulation of the many possible system states within autonomous construction of surface infrastructure simply will not be possible if done manually. Therefore new verification techniques will be needed "to more fully confirm system behaviour in all conditions" [19].

Autonomous robots will need to identify when to request help from ground support. Because real-time teleoperation will not be possible, decisions made by the robotic fleet will need to be weighed and factored against risks associated with stopping what could be a time-dependent construction processes. For example, a pause in additive manufacturing could introduce critical ramifications to interlayer adhesion and material bonding. As time delays approach the time constants of robot tasks, the ability to teleoperate the machine degrades [19]. Ground support is then only engaging in supervision of a robot with autonomous skills, performing a sequence of tasks. Within human supervisory control, the functions of the supervisor (ground support) include: planning off-line, teaching the automation, monitoring the automation's execution of the plan, intervening to abort or assume control as necessary, and learning from experience [23]. Crew decision support and supervision despite communication latency on a Mars mission will thus be a critical area for development [19].

6.4 Human-Robot Collaboration

The aim of human-robot collaboration (HRC) is to leverage the best characteristics of a human participant (such as analytical reasoning) as well as a robot collaborator (such as efficient and highly reliable task performance) within the context of collaborative construction. For successful human-robot collaboration, robotic counterparts will need to sufficiently develop to request human help when appropriate or most needed [8]. Humans will be able to provide high level strategic reasoning and problem-solving in the event of a malfunction or deviance from a pre-established plan within construction sequence. Collaborative decision making will likewise contribute to mission success within a teleoperation scenario. Human-systems interfaces will need to focus on crew decision support and supervision across the time delays of space [19]. Thus human-robot teams will require appropriate user interfaces in order to effectively perform exploration field labour [8].

Repair and maintenance tasks will be most efficiently and effectively be performed by human-robot teams. Field labour, inspection, maintenance, and servicing of equipment and the habitat structure will be most efficiently performed collaboratively. Maintenance activities should be planned for both 3D-printed regolith but also mechanical and electrical components and hardware integrating with the structure itself.

Once humans arrive at the planetary surface, crews will interact with robots of different levels of autonomy and across different "spatial ranges" – from shoulder to shoulder (human and robot in a shared space), to line-of-sight interaction (human in habitat, robot outside), to over the horizon (human in habitat, robot far away) [8]. Maintenance tasks will include monitoring and repairing the exterior habitat structure from exterior impacts from micro-meteorites or other debris, in addition to monitoring and maintaining the interior. For example, robots could be used to search, identify and repair elements on habitat interiors and exteriors, while requesting human help only when necessary [8]. Therefore it is equally important that robots are designed with manipulator arms and mobility systems that are safe for working with and near humans. As

Copyright ©2019 by the International Astronautical Federation (IAF). All rights reserved.

mentioned, human-robot teams will work most efficiently by leveraging one another's strengths. Designing mobile robotics that interface and interact safely and efficiently with human counterparts remains a leading technical challenge in the development of autonomous robotic systems.

6.5 Robotic Emplacement of Habitat Elements

Robot manipulation systems will need to develop, if not exceed human-like dexterous manipulation for a variety of field work for both in situ scientific research that will be critical for exploration-class missions as well as construction tasks. Wall apertures (windows), interior systems (partitions and flooring), structural reinforcement, building integrated sensor networks, among others will need to be robotically placed within 3D-printed structures at the appropriate time. Surface habitats will feature windows and apertures so that the crew may survey the surrounding terrain and maintain situational awareness at the site without conducting an EVA. Hard-shell modules that contain pre-integrated hardware such as ECLS or airlocks will most likely launch from Earth and assemble with additively manufactured structures. The deployment, positioning, and manipulation of hard-shell sub-systems will need to be autonomously executed by multiple mobile robots at the construction site. The timing and scheduling of emplaced habitat elements thus need to be closely correlated with the 3D-printing technology as well as the overall construction schedule for the habitat.

7. Conclusions & Future Areas for Development

The 3D-printed structural prototypes and submissions by SEArch+ / Apis Cor to the Phase 3 3D-Printed Habitat Challenge demonstrate early advancements in autonomous construction relevant to future surface habitats. Once crewed missions arrive to Mars, site operations, field labour and regular repair and maintenance activities will be performed by both the crew and their robot counterparts collaboratively. In robotic precursor missions occurring prior to crew arrival, 3D-printing systems, machinery for ISRU regolith and water acquisition technologies, as well as space robotics for field labour, site excavation and preparation will need to coordinate and synchronize within a unified construction sequence, or 4D BIM plan. Remote supervision and control by ground support will occur with communications delays as well as limited bandwidth, further indicating the need for construction robotics to function and solve problems autonomously, while nonetheless consulting and conferring with mission control when help is needed. Testing and validation of pressurized 3D-printed structures remains a challenge still to be undertaken in large-scale earth-based additively manufactured prototypes anticipating the autonomous construction of habitats in future Mars mission scenarios.

A summary of areas for future work and development is provided below:

3D Printing and Deposition Technologies:
- Multi-agent swarms for 3D-printing
- Real-time material rheology validation within the material handling system
- Dynamic g-code, responsive real-time 3D printing
- Synchronization of BIM and construction sequencing with robotic task execution
- Dynamic BIM model corresponding with construction tasks and progress in real-time
- Non-destructive testing, anomaly detection, and validation of structures

Human-Robot Collaboration
- Seamless Human-Machine Interfaces across technologies
- Decision making protocols for HRC relevant to construction processes and particularly additive construction
- Protocols for collaborative repair & maintenance activities

Acknowledgements

We would like to thank Autodesk Build Space staff and management for providing us with the residency that enabled us to complete the Construction Levels of the Competition. O3 and Gerdau sponsored the work for Construction Level 2.

References

[1] M.R. Fiske, J.E. Edmunson, J.C. Fikes, "The Disruptive Technology That is Additive Construction: System Development Lessons Learned for Terrestrial and Planetary Applications" AIAA SPACE and Astronautics Forum and Exposition, September 2018.

[2] R.P. Mueller, J.C. Fikes, M.P. Case, B. Khoshnevis, M.R. Fiske, J.E. Edmunson, R. Kelso, and R. Romo, "Additive Construction with Mobile Emplacement (ACME)," 68th International Astronautical Congress (IAC), Adelaide, Australia, 25-29 September 2017.

[3] B. Khoshnevis, M. P. Bodiford, K.B. Burks, E. Ethridge, D. Tucker, W. Kim, H. Toutanji, and M.R. Fiske, "Lunar Contour Crafting – A Novel Technique for ISRU-Based Habitat Development," in proceedings of the *43rd AIAA Aerospace Sciences Meeting and Exhibit*, American Institute of Astronautics and Aeronautics, Reston, VA, 2005, Paper AIAA-2005-0538.

Copyright ©2019 by the International Astronautical Federation (IAF). All rights reserved.

[4] B. Khoshnevis, Automated construction by contour crafting - related robotics and information technologies, Autom. Constr. 13 (1) (2004) 5–19.

[5] A. S. Howe, B. Sherwood, "Out of This World: The New Field of Space Architecture," Vernacular of Space Architecture, Vol. 1, AIAA, Reston, Virginia, 1st ed., 2009, pp. 7–21.

[6] J. Edmunson, M. R. Fiske, R. P. Mueller, H. S. Alkhateb, A. K. Akhnoukh, H. C. Morris, I. I. Townsend, J. C. Fikes, and M. M. Johnston, "Additive Construction with Mobile Emplacement: Multifaceted Planetary Construction Materials Development" ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments (Earth & Space 2018), American Society of Civil Engineers, 2018.

[7] R.P. Mueller, S. Howe, D. Kochmann, et al., "Automated Additive Construction (AAC) for Earth and Space Using In-situ Resources." ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments (Earth & Space 2016), American Society of Civil Engineers, Reston, Virginia, 2016.

[8] T. Fong and I, Nourbakhsh, "Interaction challenges in human-robot space exploration." Interactions 12, 2 (March 2005), 42-45

[9] T.J. Prater, T. Kim, M. Roman, R. Mueller, "NASA's Centennial Challenge for 3D-Printed Habitat: Phase II Outcomes and Phase III Competition Overview." AIAA SPACE and Astronautics Forum & Exposition, Orlando, Florida. 17-19 September 2018.

[10] "3D-Printed Habitat Challenge – Phase III Competition Rules: Phase 3." Bradley University.www.bradley.edu/sites/challenge/rules/Accessed 16 January 2018.

[11] M. Yashar, et al., "Mars X-House: Design Principles for an Autonomously 3D-Printed ISRU Surface Habitat." 49th International Conference on Environmental Systems (ICES), Boston, MA July 2019.

[12] American Concrete Institute (ACI). Specification for Tolerances for Concrete Construction and Materials (ACI 117-10) and Commentary. ACI Committee 117. Farmington Hills, MI. 2010.

[13] American Society for Testing and Materials (ASTM). ASTM C666/C666M-15: Standard Test Method for Resistance of Concrete to Freezing and Thawing. ASTM International. West Conshohocken, PA. 2015.

[14] American Society for Testing and Materials (ASTM). ASTM C39/C39M-18: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM International. West Conshohocken, PA. 2018.

[15] B. Van Den Bos, J. Strand, et al., "Robotic Inspection Solutions for Petrochemical Pressure Vessels developed and tested in the PETROBOT project" 19th World Conference on Non-Destructive Testing 2016

[16] T. Salmi, A. Jari, H. Tapio, P. Kilpeläinen, T. Malm, Human-Robot Collaboration and Sensor-Based Robots in Industrial Applications and Construction. Robotic Building. Ed. H. Bier. Springer, (2018)

[17] T. Bock, T. Linner, "Construction Robots: Elementary Technologies and Single-Task Construction Robots. Cambridge: Cambridge UP, 2016.

[18] S. Meschini, K. Iturralde, T. Linner, T. Bock. "Novel applications offered by integration of robotic tools in BIM-based design workflow for automation in construction processes." (2016)

[19] Ambrose, Wilcox, et al. NASA Technology Area 4 Roadmap: Robotics, Tele-Robotics and Autonomous Systems, 2010.

[20] M. Ferguson, L. Kincho. "A 2D-3D Object Detection System for Updating Building Information Models with Mobile Robots." IEEE Winter Conference on Applications of Computer Vision (WACV). 2019.

[21] M. Ferguson, J. Seongwoon, K.H. Law. "Worksite Object Characterization for Automatically Updating Building Information Models,"ASCE International Conference on Computing in Civil Engineering (i3CE). 2019.

[22] F.R. Correaa, "Robot-Oriented Design for Production in the context of Building Information Modeling" 33rd International Symposium on Automation and Robotics in Construction (ISARC 2016)

[23] T. Sheridan, R. Parasuraman, (2005). Human-Automation Interaction. Reviews of Human Factors and Ergonomics. 1. 89-129.