Exploring how Prize Challenges Complement an Organization's Innovation Efforts

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***Abstract*—Increasingly, organizations use prize challenges to innovate: broadcasting a technology problem widely in hopes of getting useful solutions from the crowd. To better understand this tool for innovation, scholars have explored how the crowd solves the problem posed to them. However, less attention has been paid to the interaction between challenges and organizations' existing innovation processes. To address this gap, we studied the formulation, launch, execution, and outcomes of an important success in NASA's open innovation ecosystem: the 3D Printed Habitat Challenge (3DPH). As part of that study, we summarize the analytical chronology of our case in this paper. It illustrates how the 3D Printed Habitat Challenge (3DPH) was designed to complement ongoing efforts in NASA's additive construction ecosystem. We also describe how this case opens the door to new questions in our understanding of prize challenges.**

***Index Terms*—prize challenge, open innovation, crowdsourcing, NASA, 3D printed habitat challenge, additive manufacturing**

I. Introduction and Motivation

Prize challenges are catalysts for innovation. Here, teams of "solvers" in the crowd compete to achieve, or beat, technology performance goals set by an organization—the "seeker" [1]. The seeker benefits from the efforts of these non-traditional individuals [2] because their diverse solutions would otherwise be difficult for the seeker to access [3]. In many contests, winners even surpass the state-of-the-art of that domain [2], [4]. In turn, the solvers compete for an attractive (monetary) prize—the incentive to participate and do well [5]. In short, a contest can prompt a dedicated effort from a broad range of individuals, meet or surpass technical performance goals, and have a significant impact within its focal domain.

Technical organizations—both firms and government agencies—want to reap these benefits in their domains. As such, they are increasingly using contests to help address problems that are core to their mission(s) [6]–[8]. For example, when faced with the Deepwater Horizon oil spill in the Gulf of Mexico, BP launched a prize challenge in addition to their internal efforts. In total, it received 120,000 contributions on how to contain the spill's damaging effects [9], [10].

The increase in prize challenge usage increases the urgency to understand how they catalyze innovation. Here, the literature calls for a better understanding of how the contest fits into the organization's innovation efforts—both upstream challenge formulation and downstream solution absorption [11], [12]. Practitioners starting their own challenges echo this concern: they need this information to deploy this tool effectively [13], [14].

We took a step in that direction by unpacking the life cycle of one prize challenge. In our case study, we shine a light on how a contest complements an organization's existing innovation efforts. Between 2015 and 2019, we studied National Aeronautics and Space Administration (NASA)'s 3DPH, part of NASA's Centennial Challenges Program (CCP)'s portfolio. During this time, we performed a field study. We observed the challenge's events, interviewed CCP staff and subject matter expert (SME) integral to the challenge, and drew on the relevant project documents. Below, we describe how the challenge addressed relevant technical priorities, pushing past NASA's existing efforts in useful ways. We also describe how they drew on their existing knowledge and desired capabilities to limit the range of solutions returned. This balance resulted in relevant technical gains for the SMEs and for NASA.

We organized this paper as follows: first, we describe our research approach, setting, and data collection. Then, we describe the results of our case in narrative form. Lastly, we discuss how the challenge addressed priorities, and propose future research paths to understand how challenges fit with existing innovation efforts.

II. Methods, Setting, and Data

We conducted a longitudinal field study to address the lack of empirical analysis on a challenge's fit within an organization's processes. This inductive approach gave us the tools to analyze this understudied phenomenon [15]–[17]. We focused on a single case study to develop a strong understanding of the context and capture the relevant data through interviews, observations, and project documents [18]–[20]. With the data in hand, we relied on qualitative research techniques to triangulate occurrences among the different pieces of data and identify how these occurrences were related [21], [22].

We studied the 3DPH Challenge, considered one of NASA's most complex—and successful—prize challenges run to date. Through a $2 million prize, it aimed to advance additive

The authors gratefully acknowledge funding from the National Aeronautics and Space Administration in support of this work.

construction[1] technology, moving NASA closer to producing viable habitats for planetary surfaces. We chose to study 3DPH because it encapsulated several successes: it addressed important priorities; it connected NASA to large, non-aerospace firms interested in the subject matter; it allowed diverse SMEs to collaborate on shared interests; it resulted in useful solutions; and, it infused outcomes into ongoing NASA projects. Understanding what made these successes possible will allow us to build theory to support future challenge activities.

Below, we describe our case in narrative form, and describe our findings in the next section.

III. Case Narrative

A. A Response to National and Organizational Priorities

In the broadest sense, 3DPH recognized that additive manufacturing was the future, no matter the domain. This recognition crystallized at the highest policy levels of the Obama administration in 2013. It directed NASA and the U.S. Department of Energy (DOE) to spur innovation in manufacturing technologies, with robotics and additive manufacturing as key areas. As part of this larger push, NASA would draw on their prize authority to spotlight specific research and development challenges that overlap with their priorities. The administration hoped the prize mechanism would tap into new and existing sources of expertise in new ways—a dovetail with ongoing open innovation and open government initiatives [25].

The partnership between NASA and the DOE aimed to improve manufacturing technologies broadly. This meant finding important research and development priorities that were shared among the partners. Their mutual interest would increase the buy-in for the challenge(s) being posed, and potentially, the solutions being produced. The CCP initially explored printable electronics as a focus for the challenge, given its relevance to both NASA and DOE. However, the challenge pivoted after discussions between the stakeholders slowed. The CCP team branched out to other contacts for new potential partners and additional ideas for themes. Their discussions with United States Agency for International Development (USAID) revealed an interest in printing temporary housing, a key issue in disaster relief. Here, the CCP team drew parallels to printing habitats on other planets; an important technology development area for NASA. This theme gained significant traction among the NASA SMEs working on manufacturing in space, and it became the focus of the challenge. USAID remained as an advisor.

Printing habitats is a priority for NASA for three reasons: length of stay, launch costs, and deployment risks. First, Mars' orbital dynamics result in a stay of several months for any crewed landing on the planet. Adequately housing and keeping the crew alive in a Moon-landing sized capsule would not be feasible for that length of time. Second, putting objects in orbit is expensive: any additional kilogram in mass adds thousands of dollars in cost [26]. Since landing on Mars makes that problem many times worse, SMEs actively try to minimize their spacecraft's launch mass. Lastly, constructing a suitable building while minimizing construction risks and delays would require automation. The first astronauts could use their habitat as soon as they landed if it was constructed using automated equipment prior to their arrival.

The challenge pursued the "make it, don't take it" [27] solution to this problem: autonomously constructing a living quarters using materials found on the planet. While the capability had been pursued for at least a decade [28], it received new attention based on terrestrial interest [24] Thus, the theme for the 3DPH Challenge became automated additive construction using in-situ resources.

This theme addressed both national and organizational priorities. It bolstered national additive manufacturing efforts as expressed in the initial NASA-DOE partnership. It also aligned with efforts to create new habitation solutions for NASA. With those links established, CCP started gathering the SMEs to decide what that challenge would accomplish under that umbrella.

B. 3DPH's Fit with NASA's Existing Efforts

The 3DPH was not NASA's first, or only, additive construction program. Teams at NASA's Marshall Space Flight Center (MSFC) [28] and NASA's Kennedy Space Center (KSC) [29] had been independently pursuing this capability for several years before the prize challenge started. While they did not initiate the challenge, their expertise would play a key role in its formulation.

The two teams differed in printing methods and materials. At MSFC, the In-Space Manufacturing (ISM) team joined the U.S. Army Corps of Engineers (USACE) and other partners to form the Additive Construction with Mobile Emplacement (ACME) project, a follow up to previous additive construction activities at MSFC. Here, the partners found an overlap between printing temporary housing for the U.S. Army and the planetary structures required by NASA. Their focus was on demonstrating large scale structures. To accomplish this, they used a gantry style robot that printed with cement[2].

At KSC, the Swamp Works lab led a broad partnership pursuing a variety of approaches that could work on a variety of planetary surfaces. One approach focused on polymer concrete feedstocks: using plastics to bind, extrude, and layer regolith into the desired shapes. SMEs thought this approach would be beneficial for both Earth and planetary surface applications: recycling thermoplastics would support sustainability efforts as well as cut down on the mass needed to establish a human presence on the Moon or Mars. Their printer architecture was a robotic arm.

The CCP approached both MSFC and KSC teams for their input on 3DPH. SMEs in both were open to pursuing a challenge in their domain. They were familiar with challenges

[1] Additive construction uses additive manufacturing processes and knowledge, as well as specialized feedstocks to construct large-scale infrastructure [23], [24]: "3D printing" for e.g., roads, berms, or single story houses.

[2] We use "cement" to refer to Portland cement, the most common hydraulic concrete in the construction domain.

in the space context by the time 3DPH was starting; some ran their own. One SME stated: “let’s see what kind of R&D we can spur.”. As they saw it, 3DPH was supposed to push activity into areas of low technology readiness levels, and pursue questions that were adjacent to ongoing efforts.

The SMEs were crucial in shaping the direction and planned outcomes of the challenge, and their buy-in was important to its success within NASA. The MSFC and KSC teams integrated the most important areas for additive construction development based on the agency’s existing efforts. Success for 3DPH, then, meant achieving technical outcomes that contributed to the teams’ additive construction work. It also meant showing that the CCP could successfully develop early stage technology alongside programs like NASA’s Small Business Innovation Research.

C. 3DPH’s Technical Focus

The SMEs’ input would increase the challenge’s technical fidelity, increasing its relevancy to their own work as well. SMEs aligned the challenge with the technical priorities, their knowledge of physical and environmental constraints, and their ongoing work. In describing this process, one SME summarized one of their needs—a new feedstock with specific constraints on its contents—and how the challenge would help address that need.

> When we set out to do [3DPH], 3D printing with concrete was already happening on Earth, but had been done with Portland cement concrete, which needs water and limestone. [These are not commonly available in space]. So we really had to invent a new type of concrete. And that was one of the goals of the competition. It was to show the feasibility of 3D printing in space with a non-hydraulic cement concrete. [The ideal concrete] uses indigenous materials and preferably minimizes the water, or [uses] no water at all.

The challenge would address three technical priorities: new feedstock materials, autonomous operations, and robotic architecture required for large scale structures. The feedstock material is foundational to this process as it determines the design of the printer and its capabilities. Autonomous operations are required on Mars to protect astronauts from dangers associated with construction, to have structures ready before they arrive, and to be able to operate remotely. Lastly, habitats are only useful if they are printed to scale; printer systems should be designed and built with this in mind. To make progress on the capability of additive construction as a whole, one would have to consider these priorities together. As described by one SME, design decisions in one area impact the others: ”It’s a venn diagram. They’re all equally important, they all have their own challenges. They’re all enabling. If you’re missing any one of those— It’s a three legged stool.” This interdependence increased the complexity of the challenge: a habitat’s design would have to incorporate all three areas to resemble a deployment to Mars.

Yet addressing all three at the same time would be a ”big ask,” according to another SME. As the formulation process continued, the team writing the rules—the formulation team—decided to focus on these areas across several phases instead of a single prize award. Each phase would ramp up the difficulty and incorporate additional technical priorities. The achievements in early phases would also form a basis for the subsequent ones. This structure gave teams achievable milestones within reasonable timeframes, and intermediate funding via prizes in each phase. It would also maintain a forward momentum of accomplishments in the eyes of the public and give CCP the opportunity to make midstream course corrections to the challenge.

The deliverables of the challenge reflected the importance of the three legs of the stool. In Phase 1, the deliverable was an architectural concept of the 3D printed Mars habitat. In Phase 2, participants would demonstrate their feedstock by delivering a range of test articles via their (purpose-built) printer. In Phase 3, the deliverables were structures that approximated real-world scale and usage. The participants’ systems would have to print these autonomously. Phase 3’s deliverables also included an architectural concept of a higher fidelity than the one in Phase 1. Table I below summarizes the technical priorities addressed, what phase they were addressed in, and how each solution was tested for that need.

TABLE I
FOCUS AREAS ADDRESSED IN THE 3DPH CHALLENGE

Technical Priorities	**Performance tested in**		
	Phase 1	***Phase 2***	***Phase 3***
3D printed habitat designs	Architectural concept		Virtual model
Feedstock development		Feedstock recipe and print demonstrations	Feedstock recipe and print demonstrations
Autonomous operations		Print demonstrations (semi-autonomy)	Virtual model and print demonstrations
Large scale printing			Virtual model and print demonstrations

In sum, the challenge addressed national priorities and complemented the organization’s programs. It directed public attention and technical efforts toward additive construction, a nationally relevant area. Its deliverables also extended NASA’s ongoing efforts in this domain; because the SMEs weighed in and tailored the rules, the challenge explored areas they deemed more productive.

D. Challenge Execution

We summarize the three phases of the 3DPH Challenge below. The summary covers important aspects of each phase’s formulation, as well as technical and participation outcomes. A timeline of all phases appears in Figure 1. The number of participants per phase are listed in Table II; winners and their prizes are listed in Table III.

TABLE II
PARTICIPATION ACROSS THE 3DPH CHALLENGE

Phases and Levels	Participant affiliation[a]			Totals
	Industry	*Academia*	*Independent*	
1: Design[b]	15[c]	6	9	30
2: Level 1	2	5		7
2: Level 2	3	4		7
2: Level 3	1	2		3
3: Virtual 1	6	3	7	16
3: Virtual 2	5	3	3	11
3: Construction 1	2	2		4
3: Construction 2	2	4		6
3: Construction 3	1	1		2

[a]Includes non-US teams.
[b]Distribution of 30 finalists.
[c]Includes the European Space Agency (ESA) team.

TABLE III
PRIZE AWARD IN THE 3DPH CHALLENGE

Phases and Levels	Winner and Prize Share[a]	Total Prize[a]
1: Design	SEArch+ and Clouds AO; $25k	$40k
2: Level 1	Branch Technologies; $80k	$100k
2: Level 2	Moon X Construction; $0k[b]	$201k
2: Level 3	Branch Technologies; $250k	$400k
3: Virtual 1	Team Zorpheus; $21k	$100k
3: Virtual 2	SEArch+ and Apis Cor; $34k	$100k
3: Construction 1	SEArch+ and Apis Cor; $55k	$120k
3: Construction 2	SEArch+ and Apis Cor; $105k	$300k
3: Construction 3	AI. Spacefactory; $500k	$700k

[a]Rounded to nearest thousand.
[b]No prize money awarded to non-US teams; second place was awarded $67k.

1) Phase 1: Design Challenge: The aim of the first phase of 3DPH was to design architectural concepts for a 3D printed habitat on the surface of Mars. Accordingly, the deliverables for this phase were descriptions, renderings, and a 3D printed tabletop model of the proposed habitat. The most important scoring criteria were the architectural design and description of the habitat's implementation.

Formulation: The detailed planning for Phase 1, and for the 3DPH challenge more generally, started in early 2015. At the time, NASA headquarters pressured the CCP to launch an additive manufacturing challenge; it had been several years since the NASA-DOE announcement. However, creating rules that would produce valuable outcomes would risk further delays to an announcement. So CCP staff proposed Phase 1 as "something [that] would buy us more formulation time." The delay would give the team more time to "really look at the details of the material portion of the competition," per a CCP staff member.

With the added time, CCP staff recruited the MSFC and KSC SMEs to help create the rules for a challenge. The habitat would be designed to accommodate four astronauts, with specific constraints on floor space and its usage. Together with the administrative partner for the challenge, CCP organized brainstorming sessions to determine the aims, sketch the rules, and determine the desired outcomes for each phase.

However, Phase 1 did not connect to the technical priorities. While its deliverables were appropriately themed, its rules did not test for the performance that would provide meaningful information to the SMEs. The connection between what the participants would submit and the priorities that the SMEs cared about was, therefore, weak. Accordingly, there was some skepticism among SMEs about the potential utility of the submissions. For example, one SME recalled the "tension" that existed between the aims of Phase 1 and the expectations of other SMEs. They quoted their colleague's assessment of the Phase 1 solutions, saying, "Yeah this concept art looks pretty, but you couldn't actually ever, ever build this thing."

Technical Outcomes: The results confirmed this skepticism. No submission impacted the work or knowledge bases of the SMEs involved in the challenge, despite praises for the novelty of the participants' designs. While the additive construction community produced a taxonomy of the architectural designs submitted, it remains to be seen whether future NASA designs will benefit from this knowledge.

Participation Outcomes: Phase 1 was, nevertheless, very successful in sparking public interest in the challenge and the technology. CCP participated in popular technology conferences such as Maker Faire and South by Southwest. It reached communities and levels of participation that previous challenges had not. This broad outreach attracted expertise in domains that rarely interacted with technology development teams at NASA: architecture and design. It also attracted a wide range of teams and a large amount of solutions for a Centennial Challenge: more than 160 submissions from 40 countries, with hobbyists, academia, start-ups, medium and large firms, and even the European Space Agency (ESA). The challenge also successfully communicated NASA's interest in additive construction. Firms involved in the challenge expressed interest in engaging with NASA outside of the challenge. Furthermore, the resulting architectural designs made a 3D printed Mars habitat seem more real, a big public relations win.

2) Phase 2: Structural Member Challenge: The aim of the second phase of the challenge was to develop and demonstrate a suitable printing material for usage on Mars. This area was the least developed, as measured by NASA's internal technology readiness levels. In Phase 2, participants needed to demonstrate the performance of their feedstock by printing increasingly complex structural members. Across three levels, the participants' scores would heavily depend on the ease of producing their feedstock on Mars and their printed material strength (compressive and flexural).

Formulation: The connection between what the challenge was asking for and the SMEs' current activities was much stronger in Phase 2. The ISM team at MSFC was working on reducing the amount of material that needed to be launched into space across a broad portfolio. The Swamp Works team at KSC was exploring thermoplastics as a potential feedstock material prior to the challenge. Translating these priorities into

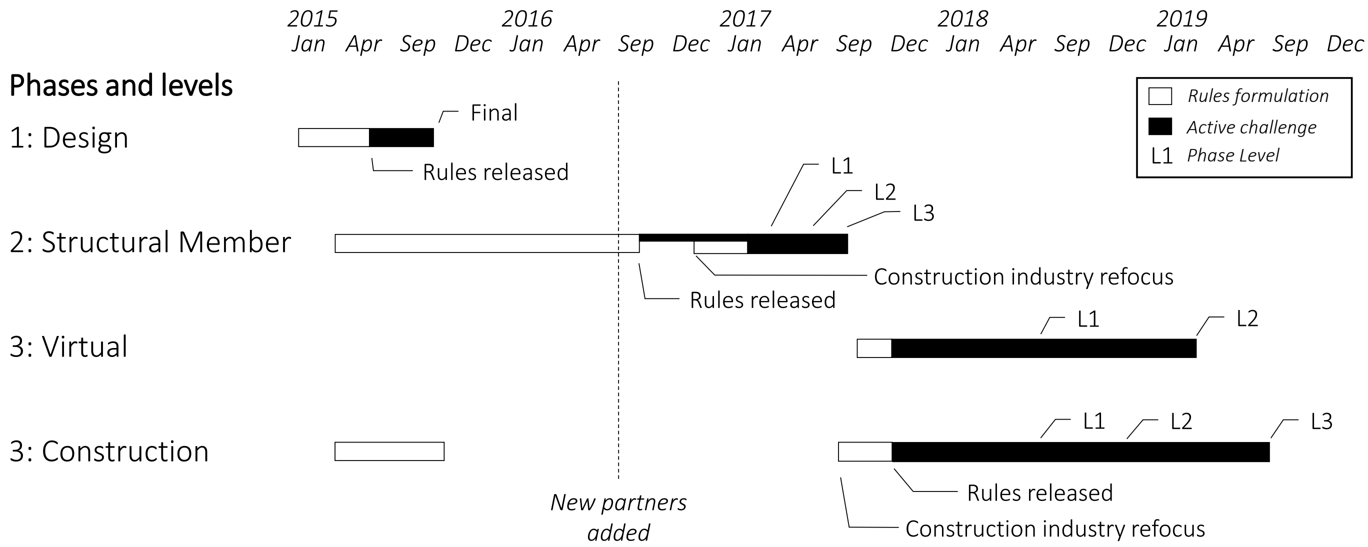

Fig. 1. Timeline of the 3DPH Challenge

deliverable requirements would nudge participants in useful directions.

As such, both priorities became key drivers for the rules governing the feedstock selection. First, to emphasize the need to reduce the amount of material sent to space, the rules stated that a minimum of 70% of the participants' feedstock would be indigenous materials. Furthermore, imported materials—e.g., additives and binders produced on Earth that would help create a viable feedstock on Mars—would be severely penalized in the points structure. Water was also penalized, as it was seen as too valuable to be used as a building material. Second, the rules strongly favored the use of (recycled) polymers as binders: these were given the highest point values by mass. While still allowing some "freedom of thought" per one SME, these rules would—likely—narrow the range of options that participants considered and encourage the selection of polymer concretes over other cementitious feedstocks.

The focus on materials and their performance shifted the challenge towards the construction industry, with effects on the challenge's partners, participants, and rules. First, the CCP replaced their Phase 1 administrative partner: the scope that they envisioned for Phase 2 and 3 exceeded that partner's capabilities. Instead, CCP reached out—and landed—new academic and corporate partners in the construction industry: Bradley University, Caterpillar Inc., Bechtel Corporation, and Brick and Mortar Ventures. The addition signaled a legitimate attempt to connect with the construction industry. The partners provided their services and sponsorship to help run the challenge. They also provided their expertise in the construction industry by joining 3DPH's formulation team.

Second, CCP recruited participants from the construction domain as well. To the SMEs, this phase demonstrated the importance of targeting the right kinds of solvers. Phase 1's participants possessed the wrong kinds of skills to address the problem. As one SME recalled, the they were:

> . . .not the right kind of crowd because they were involved with small scale 3D printing. And what we were doing was large scale 3D printing, which is a whole different thing. It's more involved with the construction industry, with civil engineering and construction. After Phase 1, we realized that and we re-vectored the whole competition to a new target audience.

Accordingly, CCP presented at several construction-specific conferences, and advertised the challenge domain-specific outlets. This outreach was in addition to the general technology conferences and space-themed outlets that CCP previously engaged with.

Third, the shift impacted the rules for Phase 2, and later, Phase 3 as well. While its planned outcomes remained the same, the construction industry provided the right stepping stones to achieve them. With the addition of construction SMEs, the (new) formulation team drew on the industry's standards and tests for material performance measures. Phase 2 required participants to print and test pre-determined shapes—cones, cylinders, beams—in well understood ways[3].

Technical Outcomes: Participants produced high performing materials and meaningful insights; a big return on the efforts by the SMEs. The winning team was a partnership between Branch Technologies Inc., Techmer Polymer Modifiers, and returning participant Foster + Partners. Their material performance in the final—and most complex—level achieved "the holy grail in 3D printing," according to one SME. Branch printed their material horizontally without supports—something that the NASA SMEs did not think would be possible with these materials. Their printing system produced

[3]Material strength tests included the ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM C78 Standard Test Method for Flexural Strength of Concrete, and a simile of the ASTM C143 Standard Test Method for Slump of Hydraulic-Cement Concrete.

complex shapes without the complex robotic architecture that other teams required to produce the same thing. The printing system also outperformed its cement counterpart in terms of strength, a desirable property for a building material. Branch's material also addressed other problems that NASA additive construction SMEs were having. It demonstrated a strategy to improve print quality by pre-processing the raw feedstock into homogeneous pellets. Other teams also produced meaningful insights for NASA. For example, teams like Penn State University (PSU) explored ways of making their cement feedstock using indigenous Martian materials to avoid severe points penalties.

One SME describe how satisfied they were with the overall progress on materials during this phase:

> I think the teams came up with really— Especially in Phase 2, [they] came up with really interesting and different [material] formulations. . . I think that [Branch's] material [was] just a good, good outcome. And I think Techmer might make that material commercially available now. It's a very high strength blend.

Participation Outcomes: Between Phase 1 and 2, the effort required to produce the (printing system and) deliverables rose and participation declined. Eight teams participated across the three levels of Phase 2, with only two completing all requirements. However, several teams that participated in Phase 1 shifted their focus and expertise to meet the requirements for Phase 2—Fosters + Partners is one example—as the challenge stakeholders originally hoped.

3) Phase 3: On-Site Habitat Challenge: The aim of the final phase of the 3DPH Challenge was twofold, spread across two segments. In Phase 3's "virtual construction" segment, participants would design a high fidelity architectural concept of the 3D printed Mars habitat. In the "construction" segment, participants would develop and demonstrate a printing system for larger and (more) realistic structures. While both segments awarded their own prizes, participants in the construction segment were required to submit designs in the virtual segment as well.

The architectural concept integrated building modeling approaches that were gaining traction in the construction industry[4] into the habitat design process. Across two virtual levels, participants would model their design of a pressure-retaining 3D printed habitat. To show its feasibility, participants would provide the information required to construct the load bearing portion of their model. Functionality, aesthetics, and completeness were the main factors in scoring the submissions.

In three construction levels, participants would print three large structures: a flat foundation[5], a water retaining vessel, and a scaled version of their design. While each level had its own quality rubric, all levels emphasized autonomy of the printer. These levels also included scoring for participants' feedstock recipe and material performance[6]. Combined, these expanded the scale, usage, and complexity of the printed structures as NASA envisioned.

Formulation: The formulation team reintroduced an architectural design in Phase 3. While the SMEs were pleased with the technical outcomes of Phase 2, they acknowledged that the bar for participation was set very high. It would only get higher considering the construction deliverables, effectively restricting participation to only highly capable teams. Adding the virtual phase would give opportunities for smaller teams—usually individuals—to participate, thereby broadening the potential audience. A design deliverable in Phase 3 would also reestablish the connections to the architecture community they reached out to in first phase.

Phase 3 focused on two technical priorities: autonomy and printing systems that could create large scale structures. Recall that a printer that could operate autonomously was an important capability to ensure safe pre-deployment of these structures on Mars. Furthermore, demonstrating the ability to print large structures was key to moving the technology towards a realistic deployment scenario.

In the virtual phase, prioritizing autonomy meant focusing on the printer's tool path algorithm. This algorithm converts the habitat model into the print head's circuit, taking into account deposition rates, drying or solidification times, real-time sloughing, etc. SMEs pushed participants to come up with efficient ways of performing this conversion. This was a necessity for the teams that participated in the construction phase, but offered as a bonus for those who only participated in the virtual segment. SMEs believed nudging the virtual participants towards this kind of realism would ground the more novel concepts, closing the gap between modeling and the printed structure.

In the construction phase, prioritizing autonomy meant focusing on the kinds and amounts of operator interventions allowed. The SMEs differentiated two kinds of interventions: remote and physical. The former approximated a software update sent from Earth—standard practice when communicating with rovers on Mars, but a source of delays nonetheless. The latter required the operator to tend to the machine in person; SMEs penalized these more heavily as these were the interventions that they wanted to discourage. Penalizing both these kinds of incidents would—likely—force teams to (re)design their systems to minimize the amount of tending that the machines required.

The focus on large printed structures also impacted the deliverables for both virtual and construction segments. The virtual segment expanded on the rules provided in Phase 1 and connected to developments that SMEs envisioned. For example, several teams proposed using inflatable structures inside their prints—a technically feasible approach for Martian

[4]The challenge adopted the Building Information Modeling Level of Development set by the BIMForum community.

[5]The tests for flatness and levelness were based on ACI 117 Specification for Tolerances for Concrete Construction and Materials.

[6]This phase included the ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, and the ASTM C666 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.

habitats. However, this approach would not satisfy the SMEs' needs for systems that could print pressure-retaining structures without the added component. This led SMEs to penalize inflatable structures in participants' designs. Furthermore, participants' virtual models required significant detail to its load bearing sections and content, with functionality being the most important criteria. Participants would earn bonus points for describing the process and timing for construction of the habitat; this took the habitat's scale and materials required into account.

In the construction segment, participants would print three structures. The first was a large slab that approximated a foundation; it was tested for flatness and levelness. The second was a large "bucket" that could safely approximate a pressure vessel; it was tested for its ability to retain water over time. The last deliverable was a print of their habitat design; it was tested for its ability to withstand impact and positive pressure. SMEs planned a full scale print initially, forcing participants to develop systems that could provide this capability. In the rewrite of the rules, the formulation team decided on a 1/3 scale model instead. At this scale, the challenge required teams to print their structures side-by-side at Caterpillar's headquarters.

Phase 3 placed an emphasis on autonomy and printing systems, but removed the emphasis on materials. This change was driven by the successes, and failures, of Phase 2. While SMEs were satisfied with the technical outcomes, four Phase 2 teams struggled to meet the strict material requirements. In response, the SMEs eased the requirements on the participants' feedstocks. Materials mattered less in Phase 3: SMEs reduced the fraction of participants' scores based on feedstock design and did not severely penalize participants for the usage of imported materials or water. The rules still incentivized feedstocks that were more suited for the Martian surface, but participants were free(r) to use materials that were more suited to their printing systems.

Technical Outcomes: Phase 3's construction outcomes were notable in several ways. A technical report described how Phase 3 "spurred the development of new printing methods and the creation of new robotic hardware for material delivery, extrusion, and control." SMEs commended participants for exploring different robotic options for printing at scale. Through the demonstrations at each level, the SMEs evaluated the maturity of the systems, envisioned how they could operate under more challenging conditions, and set the benchmark for the state of the art. One SME described how they "don't mind admitting when [they're] wrong," and would revisit a previous tradestudy using the knowledge provided by the solvers in the challenge.

The focus on autonomy emphasized the advantages of the polymer concrete printing systems over hydraulic cement ones. The latter had to be tended to more often than the former: mixing issues, water pressure issues, intolerance for delays, and the amount of dust being produced severely hampered the system's autonomous performance. A "messy" printer that prints "slurries" might "[be] a problem in space," according to one SME.

Teams also made progress on feedstocks for Mars despite the easing of the requirements on materials. The winner of the final level, a partnership between AI Spacefactory and Techmer, developed a recyclable polymer concrete that experienced minimal shape changes with temperature. With appropriate manufacturing infrastructure, all of the feedstock could also be produced on Mars.

Participation Outcomes: NASA reestablished the connection it made with the architectural domain in Phase 1 through the virtual levels of Phase 3. This phase saw the return of independent architecture teams as participants. But in contrast to Phase 1, the participation outcomes were closely tied to technical outcomes. Participants solved a NASA problem using established approaches and design tools from their field—demonstrating a modeling approach that may surpass those currently in the space industry. They used this approach to model the autonomous construction of their habitat and its construction. The resulting designs were novel and (more) feasible (than in Phase 1). In short, NASA benefited from the efforts and skills offered by the non-(aero)space participants in the virtual levels. According to one challenge stakeholder:

> What the architects did for us is amazing. I don't know how I'm going to repay them. We opened the doors for them to be part of NASA, which they didn't have before. In return, the PR we got from those images is [like] nothing we could have ever bought. NASA can't draw anything like that.

E. Continued Engagement

Participants did not stop contributing to NASA's efforts after the challenge ended. Instead, they formed collaborations with NASA to continue development of autonomous additive construction technology for planetary surfaces. The collaborations were sparked by the solutions produced in the respective phase, or the connections made between the individuals involved. Accordingly, the collaborations further demonstrated or expanded on the participants' solution or capabilities in ways that were relevant to NASA. Challenge stakeholders maintain that these collaborations would not have occurred were it not for the effort and attention that the challenge drew.

The winners of Phase 1 connected with a NASA team pursuing a similar project with similar design choices. The submission produced by Space Exploration Architecture (SEArch) and Clouds Architecture Office caught the attention of the Mars Ice Dome project at NASA's Langley Research Center. Here, both the NASA and 3DPH teams shared water ice as their main building material for a Mars habitat. The two collaborated on a follow up design project—the Mars Ice Home—where the NASA team drew on the winners' architectural experience for their joint design. Similarly, SEArch drew on their architectural experience to consult on hardware design for NASA's NextStep program.

Branch Technology Inc. continued the material advancements that won them first place in Phase 2. The KSC additive construction team was so impressed with their material that they organized a project to print launchpad infrastructure at KSC as an additional demonstration opportunity. Branch also caught the attention of 3DPH's venture capital partner, receiving $5M to continue their work.

Several teams continued their development of printers and feedstocks after Phase 3. The two finalists, in partnership with MSFC's ISM team, are testing samples of their materials on the International Space Station. AI Spacefactory will fly their polymer concrete, and PSU has flown their hydraulic cement. These experiments will test the feedstocks' properties under conditions relevant to future NASA applications.

With the experience and systems developed in Phase 3, participants also provided their services to other teams within NASA. ICON—the corporate partners of a Phase 3 university team—partnered with NASA's Johnson Space Center (JSC) to print a full-scale Mars analog. The connections made by participating in the challenge was a significant factor in ICON's selection according to the SME who directly recommended ICON to the JSC team.

Lastly, NASA's recent focus on the Moon has expanded the efforts of some Phase 3 alumni. As part of this lunar push, the ISM team launched a $14M+ project with ICON and SEArch. Both partners will develop systems for the lunar surface instead of Mars: the former will develop printing systems with lunar soil, and the latter on the design of the lunar habitats. Separately, AI Spacefactory partnered with NASA to develop simulated lunar regolith, a key component for a feedstock suitable for the Lunar surface.

IV. Discussion

Organizations are increasingly turning to prize challenges as a viable tool in their technology development toolbox. We studied NASA's 3DPH Challenge to help us understand how challenges can systematically benefit an organization's technology development process. We are just beginning to unpack how this challenge complemented related additive construction programs at NASA. Insights from this work will allow us to better understand the workings of prize challenges, as well as help practitioners launch their own.

How did 3DPH complement NASA's efforts to develop automated additive construction technology? The connection between ongoing (traditional) programs and the challenge was crucial in usefully directing the crowd's efforts. NASA's SMEs began their interaction with the challenge early on in the rules writing process. Their involvement allowed them to choose (each phase's) problems and shape the deliverables. They made sure that the problems posed to the crowd would be useful extensions of areas that they were pursuing. The performance requirements demanded from the participants were directly informed by ongoing projects, as well as additional work that SMEs performed for the challenge. Combined, these bounded the problems and their potential solutions; focusing the non-traditional efforts of the participants on the kinds of technology development that were—thought to be—the most useful to NASA.

Thus, 3DPH's successes stem partly from NASA's matching of the challenge rules to existing knowledge and efforts. The challenge outcomes furthered NASA's programs because the MSFC and KSC teams heavily incorporated their knowledge in this process. By partitioning the "three legged stool" of technical goals across several phases, participants were able to pick up where SMEs left off. Participants' solutions, then, reduced technical risks by demonstrating aspects of the performance that the SMEs cared about. These advances allowed SMEs to calibrate their expectations for the technology's performance on future projects.

Our in-depth study of 3DPH revealed new areas of prize challenges that could deliver useful insights to scholars and practitioners alike. We briefly describe five areas and their related questions below.

First, this case showed the importance of the challenge formulation process. In 3DPH, SMEs spent considerable effort connecting the challenge's problems to their knowledge. SMEs had to select relevant problems within their scope of work, and tailor—or approximate—them in ways that could be broadcast to, and solved by, the crowd. In this process, SMEs balanced the accuracy of the real conditions with complexity of the challenge problem in order to obtain valuable technical outcomes. This tradeoff had a significant impact on its outcomes. Potential research avenues include: How does one formulate a challenge problem as a useful approximation of the real conditions? How should these approximations be shaped by those who might potentially be solvers?

Second, in formulating the later phases of 3DPH, SMEs targeted the construction domain for partners, measures, and solutions. While the performance of the solutions was surprising, their domain was not: all stemmed from the targeted domain(s). This could suggest a more nuanced version of broadcast search: one that narrowly targets a specific domain for its knowledge using a prize challenge instead of a broad call. Potential research avenues include: Should one target a particular domain or open it to a general audience? If a domain is selected, how should the targeted domain(s) be integrated in the challenge?

Third, the SMEs and CCP described how the solvers' solutions to the problems were only part of NASA's benefit derived from the challenge. Both praised the (planetary) additive construction community that was formed and strengthened in the wake of each phase, for example. SMEs in particular benefited from this new community through their continued involvement, expertise in adjacent problems, and their extended networks. Proposed research avenues include: What is the complete value stream stemming from a prize challenge? How do different benefits impact the seeker's technology development?

Fourth, technologies produced in the challenge had a significant impact on some solvers and their home domains. For some, their participation in the challenge marked a turning point in their own technology development path. Because of 3DPH's requirements, teams pursued design options that they had not previously considered. In one case, their challenge solution outperformed their original design; tailoring their domain's technology for NASA's use produced one that excelled in both domains. Potential research avenues include: How can one identify, and derive benefit from, shared problems between disparate domains? How do challenges impact the solvers' home domains in addition to the seeker's?

Fifth, 3DPH participants—both winners and non-winners—partnered with NASA on related projects after the contest was over. Through these collaborations, participants transitioned from contest solver to organizational partner; formalizing their position in the domain and entering NASA's industrial base. Potential research avenues include: How can prize challenges be (made to be) on-ramps for traditional innovation mechanisms? What mechanisms drive solvers towards these transitions?

Broadening our lens in these ways will allow us to further understand how prize challenges can complement an organization's innovation efforts.

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