

Centennial Challenges Program Update: From Humanoids to 3D-Printing Houses on Mars, How the Public Can Advance Technologies for NASA and the Nation

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The Centennial Challenges (CC) program, part of NASA’s Space Technology Mission Directorate (STMD), was founded upon the principle that engaging the public at large was a very important part of garnering the true magnitude of grassroots American innovation and ingenuity. The program uses a focused problem-statement approach to obtain solutions and/or stimulate innovation in key NASA technology gaps by catalyzing sources outside of the traditional aerospace community. The CC program announced the first two challenge competitions in 2005 incentivizing the public to participate using a congressionally authorized prize purse. Since then, the program has developed and executed more than 18 competitions and has awarded over \$9 million in prize money. The challenges have covered a variety of technology areas, including propulsion, robotics, communications and navigation, human health, science instrumentation, nanotech, materials and structures, and aerodynamics. Centennial Challenges’ accomplishments from October 2016 to December 2017—including significant increases in the amount and diversity of participants; increase in prize purse awards; strong alignments with NASA missions; and partnerships with industry, academia, and other government agencies—are summarized in this paper. Technological advancements, communication strategies, and legal authority are also discussed. NASA is leading the government agencies in the area of prizes and competitions to push technologies, and the CC program is one powerful example of NASA’s continuing commitment to technological advancement and innovation through non-traditional programs. Currently, the Agency has in place the proven infrastructure, policies, and people needed to enable the successful use of competition tools, including the ones used as part of the CC program.

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Nomenclature

<i>CQ</i>	=	Cube Quest Challenge
<i>EM-1</i>	=	Exploration Mission 1
<i>ISS</i>	=	International Space Station
<i>OSTP</i>	=	Office of Science and Technology Policy
<i>SLS</i>	=	Space Launch System
<i>SME</i>	=	Subject Matter Experts
<i>SR</i>	=	Space Robotics Challenge
<i>SRR</i>	=	Sample Return Robot Challenge
<i>STMD</i>	=	Space Technology Mission Directorate
<i>VT</i>	=	Vascular Tissue Challenge

I. Introduction and Background

Throughout history, competitions have been successfully utilized to push boundaries of what is considered state of the art. Competitions have created avenues to incentivize innovation from seemingly unlikely sources. Examples of historical prize contest include the Longitude Prize, the Orteig Prize and the Ansari X Prize. The Longitude Prize was a reward offered by the [British](#) government for a simple and practical method to precisely determine a ship's [longitude](#). The prize was established through an Act of Parliament (the [Longitude Act](#)) in 1714. Though attempted by mathematicians, astronomers, and veteran navigators, it was a clockmaker named John Harrison who won the prize with his invention of the marine chronometer in 1761. In the 1920s, Raymond Orteig, an American hotelier with a passion for aviation, established a \$25,000 prize for any person who could fly across the Atlantic Ocean. Ultimately, it wasn't a daredevil stunt pilot or WWI fighter ace that won the Orteig Prize, but a mail pilot named Charles Lindbergh. It is believed that this competition was one of the important factors that started the quick evolution of the aviation industry. The Ansari X Prize was developed by the X Prize Foundation to stimulate the development of future low-cost spaceflight opportunities. The prize was won on October 4, 2004, the 47th anniversary of the [Sputnik 1](#) launch, by the [Tier One](#) project designed by [Burt Rutan](#), using the experimental spaceplane 'Space Ship One'.

Inspired in part by these historical accomplishments, in 2005, Congress amended the National Aeronautics and Space Act to authorize NASA to create a program, eventually named Centennial Challenges (CC), through which prizes could be awarded to United States citizens or entities who succeeded in meeting the challenge requirements. The CC name originated during the celebration of 100 years of the first self-propelled aircraft successful flight in history. In 1903, near Kitty Hawk, North Carolina, Orville and Wilbur Wright piloted a gasoline-powered, propeller-driven biplane, which stayed aloft for 12 seconds and covered 120 feet on its inaugural flight. The main goal of the program, as defined by the legal authority, is to stimulate research and technology solutions to support NASA missions and inspire new national aerospace capabilities through public prize competitions. The challenges selected by the program are expected to align with the Agency's technology needs and thoroughly deliberated through broad consultations with subject matter experts (SME), both inside and outside the federal government. The CC program was NASA's first prize program and offers prize purses ranging from \$100,000 to millions. In the past 13 years, the CC Program has initiated 18 challenges in a variety of technology areas including propulsion, robotics, communications and navigation, human health, science instrumentation, nanotech, materials and structures, and aerodynamics. Eighty-eight prizes totaling more than \$9 million have been awarded (Fig. 1), and several new companies have been born in the private sector using those technology advancements.

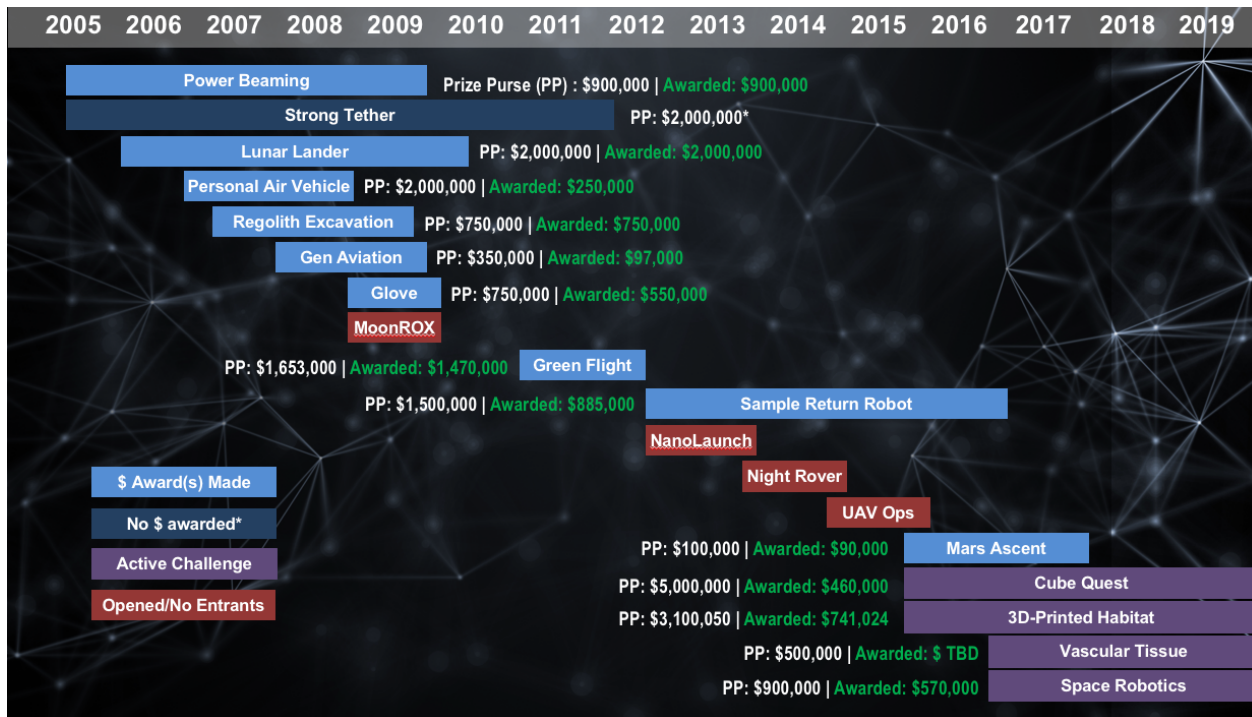


Figure 1. Summary of Program Competitions and Prize Purse awards from 2005 to December 2017

International teams may participate in competitions, granted that the team meets eligibility requirements, is accepted by the program, and acknowledges that it is not eligible to win prize money. Despite that ineligibility, more than nine countries have entered competitions, and five teams (Japan, Singapore, Spain, Germany and South Korea) have won top honors in two challenges (3D-Printed Habitat and Space Robotics).

II. Centennial Challenges Program Status

The CC program has worked to push the boundaries of technologies for the past 13 years; but from 2011 to 2015, the program had some difficulties maintaining a cadence of awards and designing/executing successful challenge competitions strongly aligned with NASA needs. As a result, in April 2016 the NASA Executive Council (EC) requested an official assessment of the program; and in Fiscal Year 2017 (FY17), the CC Program was the subject of an independent assessment board conducted by NASA and non-NASA evaluators. The EC requested that the following topics were evaluated:

- alignment of CC Program challenges with agency goals,
- types and scope of CC Program challenges in the context of other NASA prizes and challenges programs,
- infusion of new technologies from completed CC Program challenges into Agency programs and impact on Agency goals.

Results of the independent review included recommendations in 17 areas the following areas: program management, organization, documentation and analysis of long-term impact of challenges. The report acknowledged that changes made to the program since 2015 had yielded measurable positive outcomes. The panel also noted areas in which the CC Program was leading other government agencies, especially in the process of development and executions of challenges. The STMD management concurred with all recommendations provided, and the CC program either has or is in the process of incorporating the recommendations.

Individual challenge competition highlights are discussed in sections below. Top-level program accomplishments during the period of October 2016 to December 2017 include:

- The completion of seven challenge competitions from four active challenges—the most in any year since the start of the program (Fig. 2)

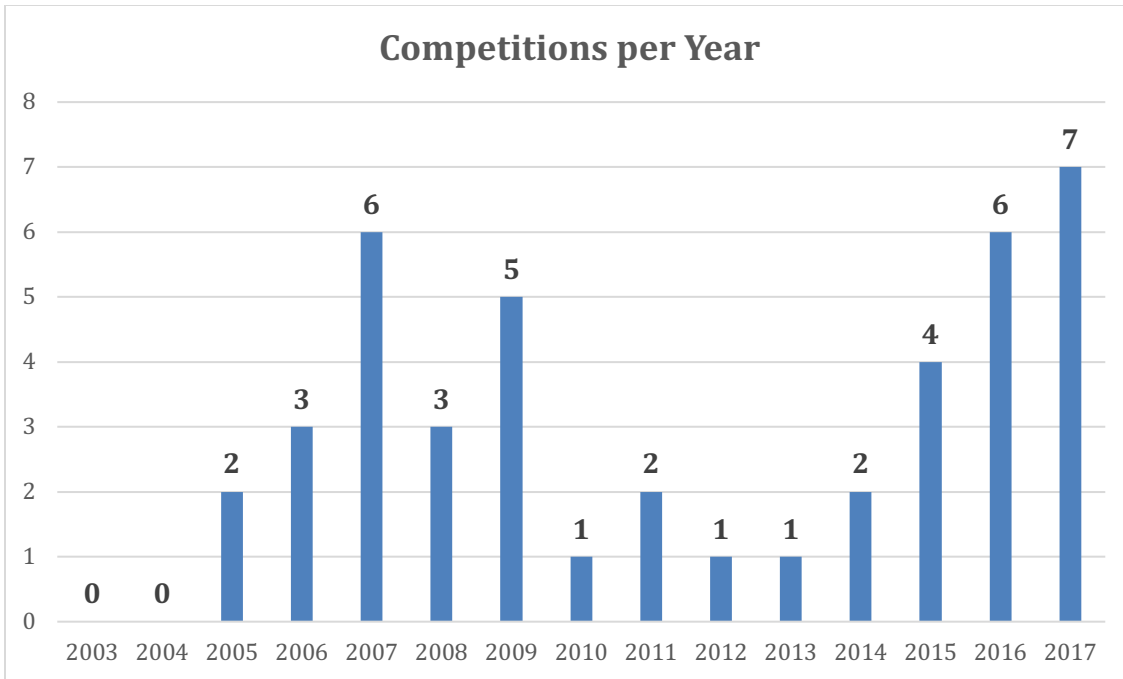


Figure 2. Total number of competitions from all of the active challenges for each year that Centennial Challenges has been in operation.

- The program exceeded the NASA STMD Annual Performance Goal of four competitions by completing three additional competitions
- Centennial Challenges awarded \$1.5 million in Prize Purse (PP) to 34 teams—66% of the PP available during FY17. In 2016, the percentage of awards was 62% (Fig. 3).

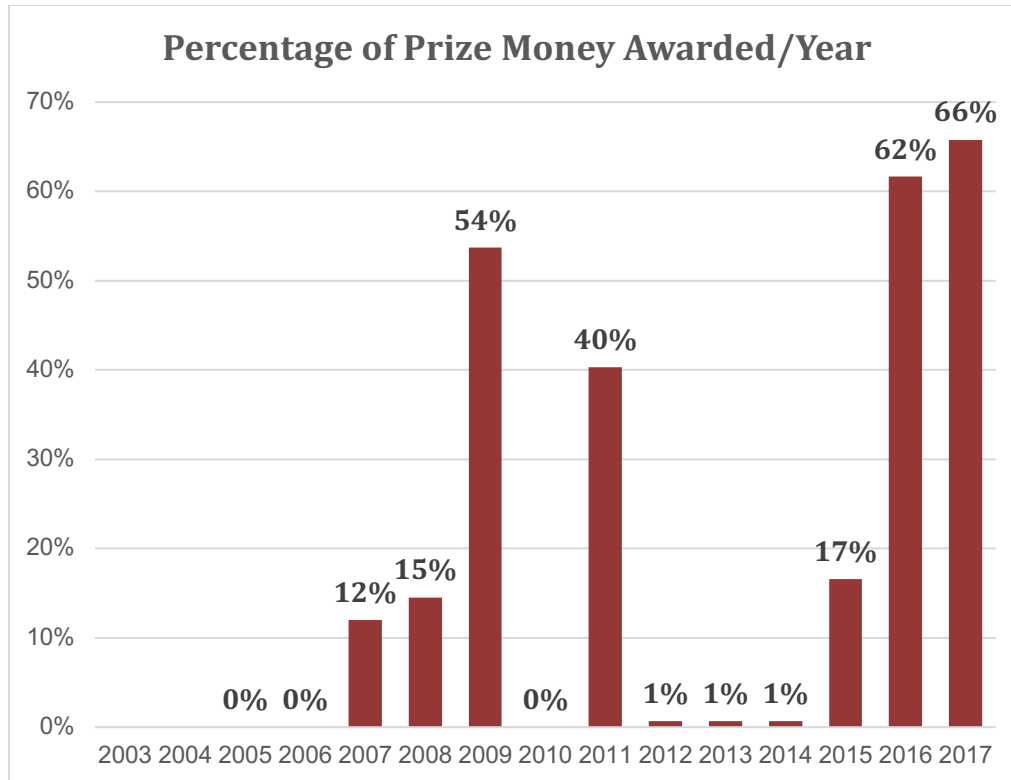


Figure 3. Percentage of the total available prize purse awarded to winning teams by the Centennial Challenge program by fiscal year.

- CC Program competitions were supported by a variety of organizations and groups:
 - Three Allied Organizations with industry sponsors; two with Venture Capital investors;
 - Four NASA Principal Technologists (PT) involved in the challenge design and the competition execution;
 - Subject matter experts (SME) from seven NASA Centers; five from other-government agencies
- CC Program continues the trend of attracting a large number of participants (started in FY15) to the portfolio of challenge competitions per year with 154 registered teams (130 US, 24 International) in FY17.
- This is the first time CC program partnered with another NASA Mission Directorate (MD) that provided funding to formulate and execute a new challenge competition
- During one of the CC Program competitions, the NASA 360 video team covered the event using the live-streaming Facebook Live tool and reported that the viewership from that was second only to the solar eclipse for the year.
- Products/solutions from challenges cover the spectrum of Technologies Readiness Levels (TRLs) from early research concepts to flight hardware.
- CC program team members, SMEs, and competitors published at least 14 papers related to CC competitions and technologies in technical meetings/conferences.
- Two teams from CC competitions are currently working with NASA teams to develop flight hardware that could be flown in the next three years. These are public-private partnerships resulting from challenge competitions.
- At least two team ideas have been transferred to other NASA programs for consideration in future missions.
- One challenge competition produced three SLS secondary payloads that will launch on the EM-1 mission.
- A minimum of \$5 million was invested by venture capital organizations on technologies demonstrated by a team in a CC competition.
- Three new small companies formed as direct result of CC competitions.
- Technology developed for a CC competition was funded by another government agency for a different application; the same team used this technology to get a university proposal funded by the NASA Experimental Program to Stimulate Competitive Research program.

- Solution of one challenge is directly fostering commercial expansion in Low Earth Orbit; companies are working towards solutions to be tested on the International Space Station.
- A company recruited a participating team to write a proposal for an upcoming small business innovation research (SBIR) subtopic.
- For the active challenges in FY17, NASA partnered with allied organizations for the execution of three out of four challenges, two universities and one space museum; one of the challenges was executed by NASA.
- Industry sponsors of the allied organizations had a crucial role in the execution of virtual or on-site competitions; the competitions could not have been executed without their support. Two of the challenges have strong support of venture capital organizations.

Currently, the program is formulating new competitions, including the CO₂ Conversion Challenge, which seeks to incentivize the development of technologies needed to manufacture ‘food’ for microbial bioreactors from carbon dioxide (CO₂) and hydrogen molecules — abundant in space habitats — to produce glucose. Producing glucose will allow in-situ microbial production systems to generate products needed to support future missions, such as food, nutrients, fuels, medicines, plastics and adhesives. The formulation of this challenge is different because the program has selected a support contractor to help execute portions of the challenge to include crowdsourcing, website development, communications, registrations, judge coordination and hosting workshops. The CC program worked with NASA’s Center of Excellence and Collaborative Innovation (CoECI) to select a vendor available from the NASA Open Innovation Services contract. The competition is expected to open August 30th, 2018. In addition, the program is in the early formulation stages of the following challenges:

- (1) Designing and building autonomous monitoring technology for detection and identification of microorganisms in a spacecraft during a long-duration mission as well as detection of life on Mars and/or Europa.
- (2) Demonstration of scalable solutions to support humans inside a lunar or planetary habitat with a sustainable system engineering approach to design and integrate life support, trash management, and other critical needs.

Centennial Challenges is an embodiment of NASA’s continuing commitment to technological advancement and innovation through non-traditional programs. Specifics about the program’s accomplishments over the last year will be discussed, including strategic objectives, past challenges and current challenge development and execution. This program exemplifies the values that have formed the bedrock of the culture at NASA since the beginning—innovation, imagination and passion for exploration. The challenges create greater leverage for competition-derived technological advancement, while simultaneously enabling contestants to expand their business models and customer base. The CC Program is dedicated to encouraging innovation and imagination through its organic approach to utilizing the great talents this nation has to offer, while also capturing the public imagination, engaging communities, and attracting greater public attention to these endeavors.

III. Centennial Challenges Legal Authority

NASA's Prize Authority (51 U.S.C. 20144) allows NASA to partner with private, domestic, U.S. non-profit organizations as Allied Organizations to administer prize competitions. The Allied Organization is responsible for the planning and formulation of the challenge activities. This includes, but is not limited to, recruitment and registration of challenge competitors, marketing, and publicity.

Each prize competition is published in a notice in the Federal Registrar. The notice includes the subject of the competition, the rules, the amount of the prize and the basis on which a winner will be selected. Those competing for the prizes can be individuals, independent teams, students or private companies.

Funding for prizes may consist of federal appropriated funds and funds provided by the private sector. Funds may be accepted from other federal agencies for cash prizes. To be eligible to win a prize an individual or entity (1) must register to participate in the competition pursuant to the competition rules; (2) have complied with all requirements of the competition; (3) in the case of a private entity, shall be incorporated in or maintain a primary place of business in the United States; and the in the case of an individual, whether participating individually or as part of a group, shall be a citizen or permanent resident of the United States; and (4) shall not be a federal entity or federal employee acting within the scope of their employment. International teams may participate but are not eligible to win prize money.

Registered participants must assume any and all risks and waive liability against the federal government, and its related entities, for activities associated with the challenge. Registered participants must also obtain liability insurance, or demonstrate financial responsibility, in an amount determined by NASA.

IV. 2016-2017 Challenge Competitions

A. 3D-Printed Habitat Challenge

1. Objective

The 3D-Printed Habitat (3DPH) Challenge seeks to develop housing solutions for extended-duration missions on planetary surfaces (particularly on Mars) using advanced additive construction technology. This technology will use indigenous materials, mission recyclables and the capabilities of 3D printing to achieve efficient and sustainable building materials and construction. These developments will be applicable both to the fulfillment of the Mars mission and to the creation of cheaper and more sustainable housing solutions on Earth. Bradley University- the allied organization - and Caterpillar Inc., conducted the Phase 2 competition with excellence and the final Level 3 competition culminated at Caterpillar's Edwards Training Facility near Peoria, Illinois, and set a great example for future competitions.

2. Structure

The challenge was divided into three phases: design, materials development and habitat fabrication. Phase 1 has been completed, and the final head to head competition for Phase 2 was conducted on August 24–27, 2017. Phase 3 is currently being conducted and on schedule for completion in May 2019.

Phase 1 conducted in 2015 asked teams to design a home for both living and working based on the capabilities of 3D printing technology. NASA partnered with America Makes (National Additive Manufacturing Innovation Institute) in carrying out this challenge. This phase drew media attention from many major publications, including *Architectural Digest*, *Popular Science* and *Wired*.

Phase 2 asked teams to develop materials using indigenous materials and recyclable materials (optional), and to 3D print specimen parts using those materials. This phase was divided into three levels. Teams must have successfully completed each level to advance to the following level. Bradley University (the allied organization for the challenge) partnered with Caterpillar, who in turn were co-sponsored with Bechtel Construction Company and Brick & Mortar Ventures – a venture capitalist company with interests in commercialization of developed materials.

- Level 1–Compression Test Competition: Teams must develop 3D printable materials and print a truncated cone and cylinder for compression strength test.
- Level 2–Beam Member Competition: Teams must develop 3D printable materials and print a beam for bend strength testing.
- Level–Head to Head Competition: The top 30 teams from Levels 1 and 2 are invited to compete against each other on-site in Peoria, IL at the Caterpillar proving ground facility.

Phase 3 will build on the material technology to fabricate an entire habitat using an automated 3D printing system. This phase is currently being conducted and on schedule to finish in May 2019.

3. Competition and Results

Phase 1 was announced in May of 2015 and completed the following September; 165 teams competed and the top 3 teams were awarded at the World Maker Faire in New York:

- First Place: SEArch (Space Exploration Architecture) and Clouds AO (Clouds Architecture Office) for their Mars Ice House design (\$25,000);
- Second Place: Team Gamma of Foster + Partners (\$15,000);
- Third Place: LavaHive (international team; not eligible for monetary prize)

Announced in October 2016, Phase 2 received initial submissions of interest from 77 teams (44 U.S. teams and 33 international teams); 20 teams registered and submitted proposals by deadline (15 US teams and 5 International Teams).

Level 1 finalists were awarded May 4, 2017.

- First Place: Foster + Partners and Branch Technology (\$85,930);
- Second Place: University of Alaska, Fairbanks (\$14,070)

Level 2 finalists were awarded July 6, 2017. Of the \$500,000 prize purse, approximately \$201,000 was awarded. The cost-effective design of the Centennial Challenges program (where monetary prizes are given only if teams meet requirements) translates into significant savings for the NASA budget.

- First Place: Moon X Construction of Seoul, S. Korea (international team; not eligible for monetary prize);
- Second Place: Form Forge, Oregon State University (\$67,465);
- Third Place: Foster +Partners and Branch Technology of Chattanooga, TN (\$63,783);
- Fourth Place: University of Alaska of Fairbanks (\$35,573);
- Fifth Place: CTL Group: Mars of Skokie, IL (\$34,202);
- Sixth Place: ROBOCON (international team; not eligible for monetary prize)

Level 3 finalists were awarded from the prize purse of \$500,000 on August 24–27, 2017 at the head-to-head competition on the Caterpillar Edwards Facility near Peoria, IL (Fig. 4):

- First Place: Foster+Partners and Branch Technology of Chattanooga, TN (\$250,000)
- Second Place: Penn State, State College, PA (\$150,000)

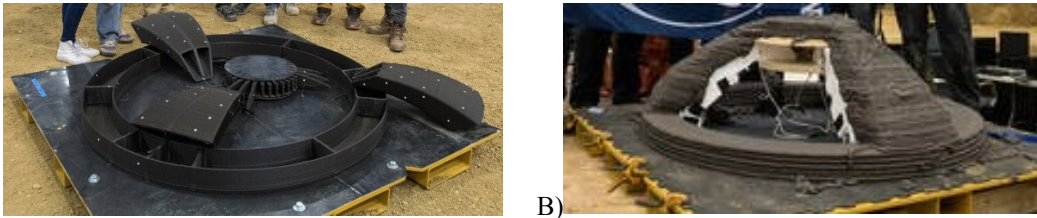


Figure 4. A) Winning dome structure printed by Foster+Partners and Branch Technology. B) Second place structure printed by the team from Penn State.

Phase 3 competition was kicked-off on November 7, 2017, and there will be five levels of competition in a period of 1.5 years to culminate in a final Level 5 head-to-head competition on April 29, 2019 on the Caterpillar Edwards Facility. The total prize purse for Phase 3 is \$2 million. Listed below are the 5 Levels of competition, the associated submission date and the prize purse:

- Level 1: Virtual Construction BIM 60% Design, May 16, 2018, \$100,000 Prize Purse
- Level 2: Construct Foundation, July 11, 2018, \$400,000 Prize Purse
- Level 3: Construct Hydrostatic Test, December 5, 2018, \$600,000 Prize Purse
- Level 4: Virtual Construction BIM 100% Design, January 16, 2019, \$100,000 Prize Purse
- Level 5: Construct Subscale Habitat, April 29 - May 4, 2019, \$800,000 Prize Purse

4. Outcomes

- **Technology:** There have been significant observed 3D-print construction material technology advancements in Phase 2. Team Branch Technology worked with a company to develop a new feedstock for their printer. There has also been great progress in materials and additive construction technology development in Phase 2. Branch Technology is a company that is already working in this technology area, but the competition pushed them toward new materials that they may continue to use in their construction applications and use of a larger scale robotic system, which was needed to build the dome in Phase 2: Level 3. Branch also used finite element analysis to inform their material deposition and deposit more material exactly where it was needed based on the load. Branch's material formulation, developed by Techmer, represented an advancement in development of high strength feedstock for 3D printing. Branch Technology worked closely with Techmer to experiment and produce pelletized feedstock with the optimal combination of crushed basalt igneous rock and polyethylene terephthalate glycol to obtain high scores for competition. This material combined with the print system was able to print strong and complex structures. The material factor of 10 was the highest possible allowed taking into consideration indigenous and recyclable material. The ability to process rock-based material and combine it with polymeric materials into a pelletized form represents a great advancement in 3D printing feedstock materials development that has been furthered through this competition.
- **Mars Cement:** There has been significant advancement in the demonstration of cement production from Mars indigenous materials. Challenge team CTL (Concrete Test Lab) Groups' desire to use cementitious concrete and be competitive under the indigenous material rules for Phase 2 drove them to a proof of concept

for a simulated Portland Cement mixture produced from indigenous Mars materials. CTL produced cement that was basalt (Crushed Basalt Indigenous, 3DP Factor 10) and limestone (Carbonaceous Sedimentary Rocks, 3DP Factor 6), both materials indigenous to Mars. The basalt/limestone mixture was first calcined at elevated temperatures to remove the carbon dioxide from the limestone. After calcining, the material was then clinkered (fusing without melting). The clinkers (fused basalt/limestone particles) were then ground with some gypsum (gypsum, sand, and siliceous sedimentary rocks, 3DP Factor 8) to make sample ‘Mars’ Portland cement. With this strong effort and proof of concept, CTL Group earned the right and was allowed by the judges to use Portland cement for the competition with a positive 3DP Factor defined by the indigenous factors instead of the negative penalty due for Portland cement. This demonstration also showed that if needed, Portland cement can be produced on Mars with some processing.

- **3D Printer Feed System Technology:** There were significant observed 3D printer feed system technology advancements in Phase 2. There were two approaches to printing systems in the Phase 2 competition. Branch and Penn State used 6-degree-of-freedom robotic arm systems (effectively placing the extruder on the end of an industrial robot), while MoonX used a gantry style system. Penn State also had inline mixing of their dry mix with water, which was necessitated by the challenge rules for autonomous operation of the system.
- **Autonomous Operations:** Penn State’s autonomous removal of the supports they used to print the dome was also novel and a technique they might not otherwise have developed outside the framework of this competition. Although the removal of supports by Penn State required significant attention and needed refinement to be considered autonomous, these types of mechanisms sets the stage for Phase 3 and will allow more complex structures to be fabricated without human intervention to advance autonomous technologies. Overall significant advancements in materials, systems and autonomy for both planetary and terrestrial construction were on display at the head-to-head competition.
- **ISS In-Space Manufacturing (ISM) Technology Demo:** The ISM Project at NASA Marshall Space Flight Center (MSFC) is pursuing printing with regolith-based materials in orbit. After learning about the feedstock used by Branch Technology during the Phase 2 Structural Member competition, the ISM Project reached out to Techmer to see if the company could provide a regolith-based plastic polymer filament feedstock. The material Techmer developed for competition in the 3D-Printed Habitat Challenge produced high-strength cylinders, beams and domes by Branch Technology and in some ways had advantages over concrete. Branch Technology used the feedstock material in pellet form, but ISM will need it in a filament feedstock form that will work with the existing 3D printer by Made in Space currently on ISS. If Techmer can provide the filament feedstock in the right size and at the required temperature for the nozzle, the final print of the first-ever 3D printer on the ISS and in space will be printing with polymer-based concrete.
- **Lunar Habitat Construction Technology:** NASA Kennedy Space Center procured material from Techmer and is working with pelletized regolith and plastic material to develop lunar regolith 3D printer. This technology is very applicable toward lunar habitat construction. With some of the ideas and concepts observed during the competition and with ready-made material from Techmer, our subject matter experts can evaluate the usefulness and applicability of the technology toward space exploration.

B. Cube Quest Challenge

1. Objective

Advancements in small-spacecraft capabilities will provide benefits to future missions and may enable new mission scenarios, including lunar exploration precursor missions, in-situ resource investigation and data communications networks for lunar missions and beyond. If capabilities typically associated with larger spacecraft can be achieved in the smaller platform of CubeSats, a dramatic improvement in the affordability of space missions will result, greatly increasing human exploration and science possibilities.

The goal of the Cube Quest Challenge, managed by NASA Ames Research Center, is to stimulate the advancement of CubeSats with capabilities needed for deep-space mission operations through prize awards to non-government teams with the best designs. The top three teams are also awarded free integration and launch of their CubeSat on NASA’s EM-1 mission. From there, they will demonstrate their superior CubeSat performance at the Moon (‘Lunar Derby’) or well beyond (‘Deep Space Derby’) by achieving several prizes challenges with specified goals for advanced navigation, propulsion, longevity, and long-distance/high-bandwidth communications.

2. Structure

Up to a total of \$1,500,000 in cash prizes will be awarded to and shared between registered competitor teams that meet or exceed technical objectives for communication from at least 4,000,000 kilometers from Earth during the Deep Space Derby. Up to a total of \$3,000,000 in cash prizes will be awarded to and shared between registered competitor teams that are able to meet or exceed technical objectives for propulsion and communication from lunar orbit during the Lunar Derby.

A series of four Ground Tournaments (GTs) were conducted prior to both the Deep Space Derby and Lunar Derby. Any registered competitor teams – regardless of whether they intend to compete for launch on EM-1 or obtain their own launch – had to participate in any or all of the GTs. Up to a total of \$1,000,000 in cash prizes was available in the complete GT series.

Competitor teams may utilize more than one CubeSat for either or both in-space Prizes, but the combined payload volume and mass must be no larger than the equivalent of one 6U volume and mass and must be deployed from a single 6U dispenser.

Start dates for the In-space Prizes begin at the deployment time from the respective launch vehicles, SLS or otherwise. In-space Prize activity ends for each Competitor Team 365 calendar days after their respective CubeSat space deployment date, regardless of the launch vehicle used, but is no later than 365 calendar days after the EM-1 CubeSat deployment date – whichever occurs first. The results of all competitor teams will be considered at the end of the in-space Prizes to determine the winner(s). Data transmissions outside of the 365 calendar days will only be considered for the longevity prizes, regardless of burst rate and volume. No transmissions after Cube Quest Challenge conclusion (EM-1 plus 365 calendar days) will be considered for any prize.

All competitors will be judged using the same criteria in the Ground Tournaments and In-space Prizes, regardless of the launch vehicle used.

A competitor team may only be awarded first or second in any prize, but not both.

Deep Space Derby Prizes:

Judges must verify that competing CubeSats have reached the minimum required distance from Earth (4,000,000 kilometers, as defined in the rules). While maintaining at least this distance for prize eligibility, competitor teams will perform communications and longevity achievements.

Judges score Competitor Team performances and NASA will award the following Deep Space Derby Prizes:

1. Best Burst Data Rate: \$225,000 will be awarded to the Competitor Team that receives the largest, and \$25,000 will be awarded to the Competitor Team that receives the second largest volume of error-free data from their CubeSat over a 30-minute period.

2. Largest Aggregate Data Volume Sustained Over Time: \$675,000 will be awarded to the Competitor Team that receives the largest, and \$75,000 will be awarded to the Competitor Team that receives the second largest, cumulative volume of error free data from their CubeSat over a continuous 28-day (calendar days) period.

3. Spacecraft Longevity: \$225,000 will be awarded to the Competitor Team with the longest elapsed number of calendar days, and \$25,000 will be awarded to the Competitor Team with the second longest elapsed number of calendar days between the first and the last confirmed reception of data from their CubeSat.

4. Farthest Communication Distance from Earth: \$225,000 will be awarded to the Competitor Team that receives at least one, error-free, CubeSat generated data block from the greatest distance and \$25,000 will be awarded to the Competitor Team with the second greatest distance. Distance must also meet minimum Challenge requirement.

Lunar Derby Prizes

Judges verify that competing CubeSats first achieve a verifiable lunar orbit to win an equal share of the Lunar Derby Prize. While maintaining a verifiable lunar orbit, competitor teams will acquire as much error-free data from their CubeSat within single continuous 30-minute periods, and as much error-free data within any 28-day (calendar day) period.

Judges score Competitor Team performances according to the Rules. NASA will award the following Lunar Derby Prizes (refer to the Rules for details and constraints):

1. Lunar Propulsion: \$1,500,000 will be divided equally between all competitor teams that achieve at least one verifiable lunar orbit, with a maximum of \$1,000,000 to any one Competitor Team.

2. Best Burst Data Rate: \$225,000 will be awarded to the Competitor Team that receives the largest, and \$25,000 will be awarded to the Competitor Team that receives the second largest, cumulative volume of error-free data from their CubeSat over a 30-minute period.

3. Largest Aggregate Data Volume Sustained Over Time: \$675,000 will be awarded to the Competitor Team that receives the largest, and \$75,000 will be awarded to the Competitor Team that receives the second largest, cumulative volume of error free data from their CubeSat over a contiguous 28-day (calendar) period.

4. Spacecraft Longevity: \$450,000 will be awarded to the Competitor Team that achieves the longest elapsed number of calendar days, and \$50,000 will be awarded to the Competitor Team that achieves the second longest elapsed number of calendar days, between the first and last confirmed reception of data from their CubeSat.

3. *Competition and Results*

The ground-based phase of the Cube Quest competition culminated in the June 2017 Ground Tournament (GT) No. 4, at which the teams judged as the top three competitors were awarded the \$20,000 prize purse and a free launch on NASA's EM-1 mission around the Moon. These winners were chosen from an initial field that included: 13 teams in GT-1, August 2015; 10 teams in GT-2, March 2016; 8 teams in GT-3, October 2016; and 5 teams in GT-4, June 2017.

4. *Outcomes*

- **Successful finale of Ground Tournaments:** More than 125 members of the interested public and representatives of STMD leadership attended the GT-4 SmallSat – Deep Space event in June 2017, co-sponsored with the STMD Small Spacecraft Systems Virtual Institute.
- **Agency's first-ever in-space competition:** The in-space phase of Cube Quest will start after the 2019 launch of EM-1 and lasts 365 days. Teams may also elect to procure their own non-EM-1 launch for the in-space competition. Two Ground Tournament teams that did not secure a space on EM-1, and two new teams that did not compete in the Ground Tournaments, have each stated that they intend to procure non-EM-1 launches to compete during the in-space phase or else to demonstrate their technologies in other missions or tests.
- **New technologies developed:** Several novel technologies to enable CubeSats to explore the moon and beyond have been developed by Cube Quest teams to date. Results include:
- **Water-based propulsion:** CisLunar Explorers (Cornell University) is creating a novel water-based propulsion system using the 'greenest' of green propellants, to achieve lunar orbit. Using off-the-shelf fluid control components, the Explorers electrolyze water to form hydrogen and oxygen for fuel and oxidation. Electrolysis of water for fuel for propulsion has never been demonstrated in a small spacecraft. The thrusters are custom designed and are manufactured out of 3D-printed titanium.
- **Thruster technology:** Team Miles (Tampa, FL) is creating their own propulsion unit as well, along with radiation tolerant flight computers. Team Miles' ConstantQ thruster has already garnered attention within industry, and the Cube Quest launch will be a major highlight in their product development. The cis-lunar environment is also beneficial as a test bed for their low-cost radiation-tolerant flight computers.
- **Antenna array:** CU-E3 (University of Colorado at Boulder) is designing a large reflect-array antenna intended for high-volume lunar-distance communications. A reflect-array antenna design may be demonstrated by the Small Spacecraft Technology Program (SSTP) Integrated Solar Array and Reflectarray Antenna (ISARA) Mission in 2018 in LEO; however, CU-E3's design's reflect-array antenna will be demonstrated for the first time at cis-lunar distances and provides a stepping stone to further antenna development in that regime.
- **Commercial partnerships:** Team Miles has developed partnerships with other commercial industries that have led to the formation of Miles Space, a commercial endeavor to further develop the technology and intellectual property for spacecraft propulsion and communications that has come out of their CubeSat design process.
- **Camera navigation:** Cornell's CisLunar Explorers have devised their own method of finding their way in space. Since the satellite spins at a relatively high rate, traditional star tracks would be ineffective. Instead, the Explorers have mounted three small cameras (and the Raspberry Pi camera module) to take pictures of the Earth, Sun and Moon. These camera measurements can generate a transformation matrix from the Spacecraft Body Frame to an inertial frame. Coupled with knowledge of which face of the satellite is facing

the sun (by recording the current on the various solar panels), and a gyroscope, the Explorers can generate the spin axes of the spacecraft body, which can then be transformed into an inertial frame.

- **New partnerships/award:** Ragnarok has teamed up with Georgia Tech and their attitude control experts to create a custom, 3D-printed cold-gas thruster system. Ragnarok also partnered with a team of Radio Amateurs from Maryland for a proposal submitted to the 2017 NASA CubeSat Launch Initiative and was selected for award.
- **Youth engagement:** Team Ragnarok partnered with Emergent Space Technologies to offer mentors and materials to a group of young aspiring satellite developers at Thomas Jefferson High School for Science and Technology in Northern Virginia. The educational mission gives students the opportunity to develop and fly a CubeSat mission.
- **Mono-propellant system:** One of the explicit goals of the University of California San Diego's (UCSD's) TRITERA satellite is to prove the concept of 3D-printed thrusters in space. UCSD's approach to propulsion is an in-house designed hydrogen peroxide monopropellant system, made entirely from 3D-printed Inconel 716. Two propellant tanks, plus all the required plumbing, take up around half of TRITERA's volume. The system is expected to generate reasonably large thrust and delta-V.
- **Combining forces:** The Massachusetts Institute of Technology (MIT) KitCube team members learned of a high school team in La Cañada Flintridge, California, that was also a Cube Quest challenger in the first ground tournament. They invited the La Cañada Flintridge team to join forces with them, and the high school team accepted. The joined team competed through GT-2 and GT-3.

C. Space Robotics Challenge

1. Objective

The SRC was organized through NASA's Centennial Challenges Program in conjunction with the Game Changing Development program, both of which are part of NASA's Space Technology Mission Directorate. To-date, there are two phases of the Space Robotics Challenge. Phase 1 was completed in June of 2017 and will be discussed in further detail in the body of this paper. Phase 2 is currently in development and seeking feedback through a Request for Information posted to www.fbo.gov.

For the Allied Organization, Centennial Challenges collaborated with Space Center Houston, the official visitors' center of NASA's Johnson Space Center in Houston, Texas. NineSigma, a company with experience in prize-based innovation challenges, worked with Space Center Houston as the sponsor of the competition.

The goal of Phase 1 of the Space Robotics Challenge was to foster innovations in robotics technology to advance robotic autonomy in manipulation and perception in humanoid robots, specifically NASA's Robonaut 5 (also known as R5 and Valkyrie). Autonomy is critical for space flight missions to Mars and beyond due to the time it takes to send and receive commands from Earth; communication signals travel at the speed of light, which means it can take between 3 and 22 minutes for the information to reach its destination. There are also potential Earth applications for autonomous capabilities, including disaster relief and clean-up and/or maintenance of areas with conditions hazardous to humans. This Challenge focused on not only engaging the existing robotics research community, but also those in the public interested in solving these challenges who may not usually be represented in said community. The public-at-large could provide NASA with innovative solutions that deliver the robotics capabilities NASA needs for future space missions to Mars. To reach out to the public, Centennial Challenges and the allied organization provided social media platforms for publicizing the event and for engagement of the community at large. The competition culminated in a public event at Space Center Houston to award the top four teams with prizes, which consist of monetary awards and the chance to test their winning solutions on one of the three R5 prototypes in the United States. NASA desires to infuse any successful software solutions into current and future robotic platforms for use in future missions and technology development programs.

2. Structure

Phase 1 of the Space Robotics Challenge was divided into the following three levels:

- **Level 1—Open Registration:** The Challenge opened for Registration in August of 2016, with over 400 teams from around the world signing up to compete. Once teams submitted their initial interest, they were asked

to complete additional challenge forms in order to complete their registration and move on to the Qualification Round.

- **Level 2–Qualification Round**

- Ninety-three (93) teams completed their registration and competed in the Qualification Round.
- These registered participants attempted to qualify for the Final Virtual Challenge by demonstrating a simple technological advancement. Each team was required to complete two qualification tasks. The qualification tasks were run independently at each team’s site. Two simulation log files were submitted, one for each qualification task. Challenge officials evaluated the log files. Instructions on how to complete the qualification tasks and submit log files were provided to registrants upon confirmation of completion of the registration paperwork. Teams were allowed to attempt the qualifying tasks any number of times and submitted only their best results – one file for each of two tasks.
 - **Task 1:** The first qualification task required teams to find a series of lights on a panel. R5 stood in front of a textured panel containing a number of colored lights. One at a time, the lights illuminated in a random pattern, and each remained on for a fixed period between 5 and 20 seconds. The light pattern began once simulation ran and continued until simulation was complete. Successful completion of Qualification Task 1 entailed:
 - Correctly identifying 10 lights in a row
 - Light identification consisted of an RGB value and position in R5’s head frame (*Both the RGB and position values allowed a specified error tolerance*)
 - **Task 2:** The second task required teams to press a button opening a door, then walk through a doorway. R5 started in front of the wall, pressed a brightly colored, textured button opening the door, and walked through a doorway located next to the button. Successful completion of Qualification Task 2 entailed:
 - Pushing the button
 - Walking through the doorway, where R5 must walk one meter beyond the door without falling
- Teams were scored on their demonstration performance, with twenty (20) teams advancing to the final level.

- **Level 3–Final Virtual Competition**

- The 20 teams that advanced to the final competition were asked to complete three tasks set in a simulation environment. These tasks were designed to simulate what a robot may be required to do while assisting a NASA mission to Mars, whether in a preparatory capacity before astronauts arrive or alongside astronauts.
- The virtual competition used a simulation of R5 in a virtual Mars environment. This simulation environment was provided by Gazebo [gazebo.org], a tool maintained by Open Robotics. The robot also used a Robot Operating System (ROS) environment [http://www.ros.org/], which is an open-source suite of tools and interfaces that allow for interaction with robots. The simulation provided to competitors included walking and balancing control software, provided by the Florida Institute of Human and Machine Cognition (IHMC), and is identical to the software currently controlling the R5 robot [https://ihmrobotics.github.io/].
- Teams were given a “Practice Phase” where variants of the final simulation environments were provided with the purpose of giving the teams a chance to test their code in a model of the final competition arena. These arenas were representative of the final arenas in that they reflected the same tasks and approximately the same configuration. However, parameters in the final arenas were altered from those of the practice arenas such that the exact figuration, fixture sizes and geometries, friction coefficients, the communications parameters and a variety of other minor adjustments would not be known in advance.
- The competitors were also given a period of time to participate in a dry-run one week before the final competition. The purpose of the dry-run was to give the competitors a chance to experience the arena and practice a full run of all of the tasks. This was also a test for the competition arena to ensure that any and all major bugs were worked out and fixed before the final competition.
- The Final Virtual Competition began on June 13, 2017 and concluded on June 16, 2017.

3. Competition and Results

The following scenario served as a backdrop for developing coding advancements for these humanoid robots:

In the not too distant future, R5 has arrived on Mars, along with supplies, ahead of a human mission. Overnight, a dust storm damaged the habitat and solar array and caused the primary communication antenna to become misaligned. R5 must now repair an air leak in the habitat, deploy a new solar panel and align the communication antenna.

Teams used software to control a simulated R5 in order to resolve the problems caused by the dust storm. The competition arena contained a rover, solar panels, communication dish and a habitat on a Martian plain. Each component was within eyesight and walking distance of each other. Each team was provided 300 Amazon Web Services (AWS) Cloud hours to complete the Virtual Competition tasks and were permitted to compete at any time during the open competition period. Challenge Staff was on-hand during the entire final competition and could be contacted directly by the competitors if they encountered any problems with the software.

Teams had to complete three tasks in the Final Virtual Competition that were aimed to simulate what a robot may be required to do while assisting a NASA mission to Mars, whether in a preparatory capacity before astronauts arrive or alongside astronauts. The first task involved aligning a communications array. The second task involved repairing a broken solar array. The third task involved identifying and repairing a habitat leak. Winners received scores based on their ability to complete tasks and the time it took for completion. Each task consisted of multiple checkpoints described in the following paragraphs. Teams were not awarded points for skipped checkpoints. When a checkpoint was skipped, the environment was automatically altered to reflect completion of the checkpoint. Skipping a checkpoint allowed teams to solve a subset of checkpoints.

Simulation Time Limits Per Run:

- Task 1: 30 minutes,
- Task 2: 1 hour,
- Task 3: 2 hours

For each of the three (3) tasks, teams were to perform five (5) runs, for a total of fifteen (15) tasks:

- **Task 1: Communications Dish:** In the first task, R5 began near a communication dish that was aligned incorrectly. R5 was required to walk a short distance to the communication dish and locate two handles: One to adjust pitch and another to adjust yaw. R5 was provided the current dish orientation and desired orientation. A tolerance of five degrees in pitch and yaw was allowed. A message was sent to R5 when the dish was correctly aligned.
- **Task 2: Solar Array:** In the second task, R5 began in the finish box of the previous task and was required to walk to a rover and retrieve a new solar panel. After acquiring the new solar panel, R5 walked to the solar array and deployed the new panel within reach of the power cable. Once deployed, R5 connected the solar panel to the existing array. The solar panel had a handle for R5 to grasp and carry. Deployment of the solar panel consisted of placing the solar panel on the ground and pressing a button on top of the solar panel. An existing power cable, located on the ground near the solar array, had to be picked up by R5 and plugged into the newly deployed solar panel.
- **Task 3: Air Leak:** In the third task, R5 started in the finish box of the previous task and was required to walk to the habitat, climb the stairs to the habitat entrance, enter the habitat, find an air leak using a leak detector tool and repair the air leak using a patch tool. Stairs to the habitat entrance had railings on both sides. The habitat entrance consisted of a door with a rotary valve which had to be turned to unlock the door. The door was hinged to swing into the habitat and had to be pushed open by R5. Upon entering the habitat, R5 had to pick up a leak detector device from a table and walk to a designated wall that had a leak. The leak detector tool continuously emitted a message that contained information about the presence or absence of an air leak. By moving the leak detector tool in front of the wall, R5 would need to locate the source of the leak. Once the leak was found, R5 would pick up a leak repair tool from a nearby table and press the tool on the leak location. The act of pressing the leak repair tool on the correct leak location stopped the leak.

The final scoring combined both ranking and judges' subjective scores. Subjective scoring looked for realism of R5 motions (i.e., not taking advantage of simulation physics), limiting of intentional damage to R5 and the environment to complete tasks successfully and other possible subjective measures. Judges' decisions on scores were final.

The top four teams were awarded the following prize money and a code implementation partnership with an R5 Host Team for at least two weeks.

First Place: \$125,000—Coordinated Robotics of Newbury Park, California (also receiving a \$50,000 bonus award for accomplishing a perfect run where they completed all the tasks);

- Second Place: \$100,000—Walk Softly of Niskayuna, NY;
- Third Place: Team Olympus Mons of Barcelona, Spain (International teams can win honors but not eligible for prize money.);
- Fourth Place: \$25,000—ZARJ of St. Paul, Minnesota

The First-Place Winner successfully completed each task of the virtual competition and was awarded a bonus award for a perfect run. This was unexpected due to the difficulty of completing all three tasks successfully. Additionally, most teams completed each task in the challenge with successful coding, allowing for advancement of the technology (Fig. 5).

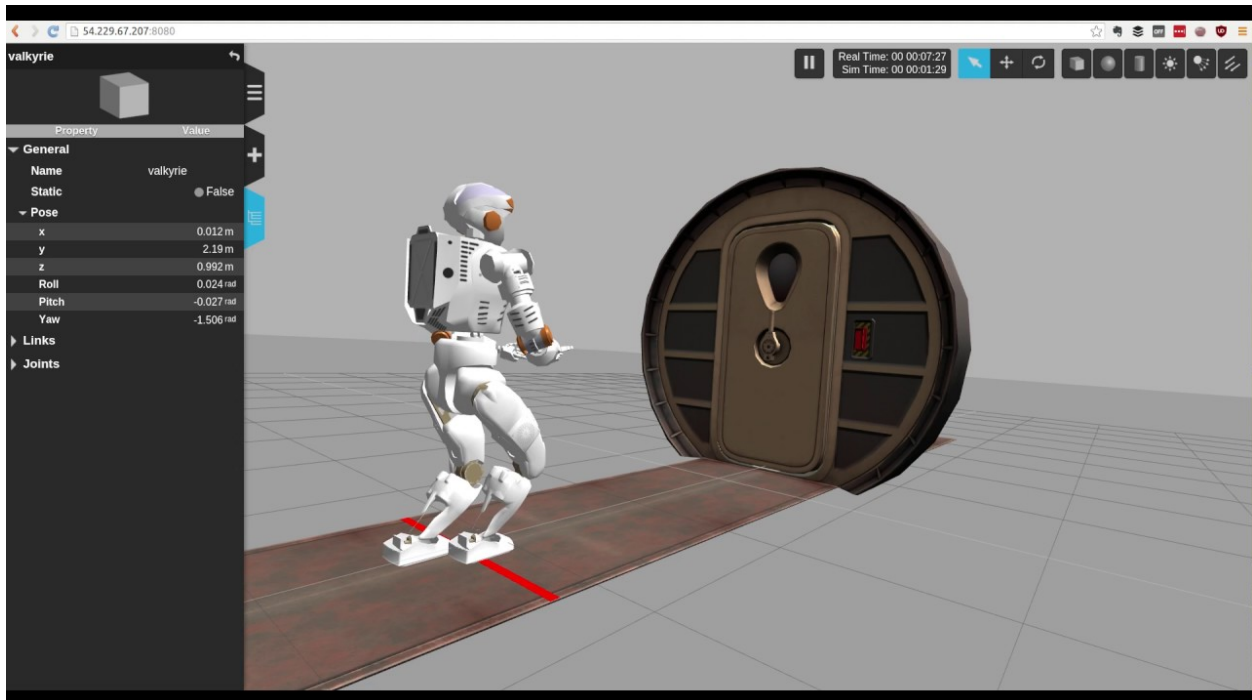


Figure 5. Screenshot of the computer simulation of NASA’s Valkyrie robot which had to successfully complete a series of tasks following code written by Space Robotics Challenge participants.

4. Outcomes

- **Technology Advancement:** One team (out of 20) completed all three virtual tasks in order without stopping. This was an unexpected result, as the NASA team of experts did not think this was possible due to the sheer complexity of the competition. This team was also able to transfer this software from the virtual setting of the competition and successfully infuse it onto the R5 robot. The technology gained through the SRC will enable NASA to further the autonomous abilities of humanoid robots as we aspire to safely explore the deeper regions of space. Solutions provided some levels of higher autonomy, but also fell short of the desired level of autonomy. This challenge showed that more investment is needed in the area of robotic autonomy to enable robotic tasks for future deep-space missions. It was discovered while visiting Northeastern on October 2, 2017 (while the winning team was testing with Northeastern University / University of Massachusetts Lowell), that more autonomous perception software was used on the robot that was not used in the competition. This was because the nature of the competition caused him to use something more reliable and stable than

the perception software he developed. Lesson learned: may need to adjust scoring metrics to reflect taking higher risk on solutions.

Top teams have tested their programs with NASA R5 robots currently hosted by the Massachusetts Institute of Technology (MIT) and NEU. The R5 robots hosted by the universities are supported by a grant with NASA's Space Technology Mission Directorate Game Changing Program. The collaboration between the NASA Centennial Challenges winners and these universities can potentially accelerate the development of robotics systems and can produce benefits both inside and outside of the Agency.

- **Post-Challenge Opportunities for Competitors:** A pool of students with a strong understanding of the NASA R5 robot's technology advancement needs were offered internships at NASA with the SME team continuing advancements in this area. A company recruited a participating team to write a proposal for an upcoming small business innovation research (SBIR) subtopic—potentially transferring the knowledge gained in the competition to the next step—producing a product that can be marketed and used by NASA and others. A small company with a NASA contract actively reached out to the challenge competitors to investigate potential hires with experience in programming NASA's R5. A team licensed software developed under a NASA SBIR for use in the competition, furthering the SBIR objective of increasing commercial opportunities for the small business while also expanding the solution space for existing SBIR products.
- **Opportunities for Challenge Execution Processes:** The main challenge Sponsor, NineSigma, was very impactful in the structure and processes they used to execute the challenge and lead the challenge planning team. As a result, the CC Program is testing the use of vendors that specialize in challenge facilitation through a collaboration with the NASA Center of Excellence for Collaborative Innovation (CoECI). An outcome of this test could be a more streamlined process for managing competitors and increased efficiencies in the execution of the challenge development and planning.
- **Software Advancements:** The coding developed and implemented by Open Robotics for the competition is now offered as open source and can be used and further developed by the general robotics community. Some advancement to the software developed specifically for the SRC were never used before and address known issues in other virtual simulation programs. The advancements in this area have the potential to impact the capabilities of a variety of robotics applications.

D. Vascular Tissue Challenge

1. Objective

NASA's objective for this challenge is to produce technologies capable of creating heart, lung, kidney, liver or muscle tissues that are at least 1 cm thick, that function as the organ should and that possess a vascular (blood vessel) system sufficient to sustain the tissues for at least 30 days. This must be demonstrated three times with >85% survival of the tissues. Once this is achieved, these engineered vascularized tissues can be used to advance research on human physiology, space biology and medicine both on Earth and aboard the International Space Station (ISS). In addition, technology innovations may enable the growth of better tissues and organs in microgravity, which then could more effectively address the risks related to traumatic bodily injury, improve general crew health and enhance crew performance on future, long-duration missions. On Earth and in space, the vascularized tissue could be used in pharmaceutical testing or disease modeling. The challenge also has the potential to accelerate new research and development in the field of organ transplants, as well as provide NASA with solutions and insight into the condition and maintenance of the human body in deep space. In order to achieve these objectives, the NASA Centennial Challenges program has entered into a Space Act Agreement with the Methuselah Foundation for the Vascular Tissue (VT) Challenge. The Methuselah Foundation will use its New Organ Alliance to develop and manage the VT Challenge. This Alliance is dedicated to advancing tissue-engineering capabilities to provide tissue and organs to patients in need. The National Science Foundation is a participating sponsor, the Center for the Advancement of Science in Space is a sponsoring partner, and NASA's Ames Research Center is the specific challenge administrator.

2. Structure

The Vascular Tissue Challenge incorporates a first-to-complete structure, with a \$500,000 prize purse to be divided among the first three U.S. teams to successfully create thick, human vascularized organ tissue in an in vitro

environment while maintaining metabolic functionality similar to their in vivo native cells throughout a 30-calendar day survival period. Teams must demonstrate three successful trials with at least a 75% trial success rate to win an award. The first team to meet the VT challenge requirements will receive an award of \$300,000, while \$100,000 will be awarded to the teams finishing second and third. Tissues developed by participating teams will be evaluated by a Judging Committee of highly qualified, independent and impartial experts. In addition to the in-vitro trials, teams must also submit a Spaceflight Experiment Concept that details how they would further advance an aspect of their tissue vascularization research through a microgravity experiment that could be conducted in the U.S. National Laboratory (ISS-NL) onboard the International Space Station. This Spaceflight Experiment Concept will be used in evaluation for the CASIS Innovations in Space supplemental award but will not have an impact on determining if a team has won the Vascular Tissue Challenge.

3. Competition and Results

The Vascular Tissue challenge was initiated on June 13, 2016 and will conclude on September 30, 2019. Two years into the challenge, no teams have completed all of the challenge requirements. However, significant advances have been made by all of the participating teams, each one leading to a better understanding of tissue vascularization and the requirements for artificial organ development.

4. Outcomes

As of this paper, 10 teams from some of the top tissue engineering laboratories in the world have entered the Vascular Tissue Challenge. Each team has a different plan for creating the required vascularized tissues, along with their own unique problems to overcome. The following is the status of the challenge to date:

- **Innovative approach to tissue growth:** ITEAMS of Stanford University, led by Dr. Yunzhi ‘Peter’ Yang, is using a multi-modular approach to overcome the tradeoff of growing tissues that maintain the tissues’ function, while controlling the growth of capillaries to ensure adequate delivery of nutrients and removal of wastes over the required 30-day interval. This multidisciplinary team has been focused on vascularization for the past five years and considers vascularization to be the greatest challenge in tissue engineering. They are currently working to optimize their biomaterial and fabrication methodologies, with the intent to conduct their VT Challenge trials in 2018. Their most critical current milestone is to demonstrate functional microvasculature (very small blood vessels) at a large scale over a long term.
- **‘Bioprinting’ system to create tissue:** BioPrinter of the Florida Institute of Technology, led by Dr. Kunal Mitra, has developed a bioprinting system that uses a 3D printer to create tissue samples with high resolution and cell viability. The bioprinting project started as a senior year design project for students in biomedical engineering. The project was so successful that Dr. Mitra continued the research. Dr. Mitra presented an update at the Vascular Tissue Challenge Roadmapping Workshop held at Ames Research Park in November 2016. The team is currently working on increasing tissue survival rates, minimizing stress on the cells’ DNA during printing, maintaining the structural integrity of the tissue and more. They are also investigating best practices regarding the maintenance of a sterile environment during the bioprinting process and transference of printed tissue to the bioreactor. Currently, their main focus is developing a custom syringe-based extrusion system that can be retrofitted to most commercial 3D printers to provide a reliable, inexpensive and effective platform for manufacturing cell-embedded 3D extracellular matrix (ECM) environments with enhanced accuracy and reproducibility.
- **3D printing approach to tissue creation:** Team Vital Organs of Rice University, led by Dr. Jordan Miller, is also working on a 3D printing approach, focusing on precision, cell viability and bioactivity and how best to assess the printed tissues. Team Vital Organs’ approach combines microfabrication with molecular imaging to create cultured human cells and more complex living blood vessels and tissues. Their research is evaluating ways to decouple complex relationships between tissue architecture and cell function, engineer intricate branching vascular structures, and fabricate tissue constructs and model disease progression in cancer, thrombosis, and atherosclerosis. Due to his work in biological tissue printing, Dr. Miller has earned two United States patents.
- **Bioreactor development:** Flow, Maize, and Blue of the University of Michigan, led by Dr. Si Ming-Sing, has designed and built a bioreactor that is being optimized for creating customizable tissue and vascular networks. This multidisciplinary team was formed out of a common interest to treat and cure heart failure in children and adults. Their current focus is on the processes for generating vascularized, engineered heart and skeletal muscle tissues. To overcome one of the key issues, Dr. Si and his team plan to work over the next

six months on long-term perfusion of vascular tissues. (Perfusion is the passage of fluid, like blood, through the blood vessels to an organ or tissue usually through a capillary bed).

- **3D printing tissue aboard ISS:** Techshot, led by Dr. Eugene Boland, is using a 3D printing approach aboard a Zero Gravity Corporation aircraft and ISS. Techshot has been pioneering science research in space for nearly 30 years by helping researchers develop science payloads and operate them successfully, first on the Space Shuttle and now on the International Space Station. During the summer of 2016, test tissues comprised of both biological materials and adult stem cells were printed during cycles of zero G and high G in order to evaluate the viability of printing in multiple environments. Techshot is now focusing on bioprinting larger cardiac and vascular structures within a proprietary container that is designed to use physical and electrical stimuli to accelerate cell growth and development. SpaceX launched one set of the Techshot containers to the ISS during August 2017.
- **Microvascularization within cell clusters:** Team Penn State, led by Dr. Ibrahim Ozbolat, has made substantial progress towards microvascularization (the production of small blood vessels) within clusters of cells. This is an important step in the development of tissues and organs. Dr. Ozbolat launched the Biomanufacturing Laboratory at the University of Iowa, where his team mainly focused on 3D-bioprinting of various tissues such as bone, cartilage, blood vessels and pancreas. A major challenge of bioprinting is creating larger sections of viable tissue. To this end, the team has scaled up tissue constructs to a sub-cm³ level and are working on expanding to the cm³ level for the VT Challenge trial. Dr. Ozbolat has released several papers about his biofabrication process, discussing and evaluating a number of challenges learned and exciting future prospects.
- **'Bioink' cell-printing system:** Team WFIRM Bioprinting of Wake Forest University, led by Dr. Anthony Atala, has been focusing on development of their planned bioink systems that would print cells able to mimic the various microenvironments of selected tissues. WFIRM's team is composed of scientists that were the first in the world to successfully implant bioengineered organs into humans. They have successfully printed ear, bone and muscle structures that, in test animals, successfully matured into the right kinds of tissue and also developed a complete system of blood vessels. Current trials are confirming the assumption that tissue-specific bioink environments will more perfectly replicate the cell-cell and matrix-cell communications that accelerate tissue function. Next, the team plans to combine their printed constructs with microvasculature created by endothelial cells and investigate the effects of that microvasculature on cell viability and function. In addition, the team has hosted several open seminars to the science community to help accelerate the development of new medical applications through organ engineering.
- **New teams joining the competition:**
 - Team Asimov is comprised of a collaborative team from Prellis Biologics and 3Scan Inc., two San Francisco companies that are working to improve the way human tissue is imaged and printed inside the body. 3Scan uses proprietary imaging technology to generate maps of vascular systems at less than 1 μ resolution. These images are then converted to printable files. Prellis Biologics uses a proprietary laser-based tissue printing system to recreate native vasculature and tissue structures at ultra-high resolution.
 - Team Cellink is a diverse team of scientists and engineers that focuses on continually commercializing improvements in bioengineering technologies and currently provides several models of 3D bioprinters. The team is focusing on organ engineering of the cardiovascular system, specifically bioprinting the vasculature of the heart and smooth muscle in a collaboration with BIDMC/Harvard.
 - Team IVIVA Medical's goal is to develop autologous tissue constructs as a solution to end-stage kidney disease (ESKD). End-stage kidney disease affects over 500,000 patients in the United States, and despite transplant being the only definitive treatment for ESKD, most will never receive a donor kidney. The team is leveraging emerging complementary technologies in tissue engineering, 3D additive manufacturing and stem cell biology to realize the potential of regenerative medicine to end donor organ shortage. They are developing bioartificial platforms and systems, not only to provide therapies, but to serve as the foundational building blocks for the next generation of engineered functionalized tissues.
- **Vascular Tissue Summit at Ames:** In addition to the progress made by the competing teams, the Methuselah Foundation, NASA, National Institutes of Health (NIH), National Science Foundation (NSF), Veteran Affairs (VA) and Department of Defense (DoD) came together with over 100 scientists and technologists at NASA Ames Research Center to examine the state of the art in thick-tissue vascularization and 3D tissue engineering

and to map out the pathways, milestones and challenges toward ending the organ shortage using these technologies. In addition to the organizations above, attendees included tissue engineering experts from some of the nation's leading universities including Dartmouth, University of California (UC) Berkeley, UC San Francisco (UCSF), Duke, Stanford, UC Los Angeles (UCLA), UC Davis, University of Southern California and University of Toronto. (See <https://neworgan.org/vtc-workshop.php>).

- **Recognition of software:** Recognition of the value of Vessel Generation Analysis (VESGEN) 2D software and its potential application to vascular tissue engineering were among the many results of this workshop. In 2005, NASA began developing the innovative VESGEN software. VESGEN maps and quantifies vascular remodeling. The globally requested VESGEN 2D is acknowledged by numerous NASA and NIH grants, publications and journal covers. The majority of work has been done on the highly vascularized retina of the eye, in part to support space biomedical issues such as visual impairments. Because of the interest of the participating teams at the Workshop, the Centennial Challenge Program provided funds to Dr. Patricia Parsons-Wingerter to determine whether the branching rules for blood vessels that her laboratory had determined for eyes were the same for the other organs of interest for the VT Challenge. The hope is that the branching rules can then be used for generating higher fidelity vascularized tissues, especially by 3D printing, that will be more structurally similar to what happens in the human body. This is pioneering research and will be a novel contribution to the field.

V. Media/Outreach Efforts

Communication and outreach are essential parts of the Centennial Challenges program. Because the success of the competitions depends on the participation of non-traditional solvers, efforts to reach and recruit these communities are important. To achieve this goal, the program uses a broad variety of media and engagement tools.

Externally, the program operates three social media accounts—Twitter, Facebook and Instagram—and an Agency website (www.nasa.gov/winit) and uses each to promote competitions, highlight teams and increase awareness. Combined, the social accounts have more than 321,600 followers. In addition, many Agency-level social media accounts are help promote the challenges on their own channels. The program communications manager creates compelling written, visual and video products to disseminate about each challenge, from shorter animated trailers that attract attention, to in-depth interviews with subject matter experts who can explain the technical aspects.

The program also participates in many public engagement and outreach events each year to seek out competitors and challenge partners and to publicize the competitions. In FY17, program personnel attended mainstream events including South By Southwest, NASA in the Park and the U.S. Science and Engineering Festival help us reach a younger, university demographic, as well as industry conferences such as Space Symposium and various 3D-printing events to touch base with small businesses and citizen inventors. The program utilizes panel participation, exhibit space and guest speaker slots to communicate our message broadly.

The program is also an active participant in the General Service Administration (GSA) Challenge.gov effort. Challenge.gov is a listing of challenge and prize competitions, run by more than 100 agencies across federal government. These problem-solving events include idea, creative, technical and scientific competitions in which U.S. federal agencies invite the public's help to solve perplexing mission-centric problems. This venue provides the program with a way to interact with challenge experts in other government agencies before we launch a challenge, during the launch and after the challenge is completed.

Internally, the program has increased the coordination and collaboration with other NASA Mission Directorates (MD). All the challenges that are in formulation are being coordinated with other MDs, including providing resources needed to support the challenge. From a communications perspective, the more MDs a challenge touches, the better. Each MD has its own team of communicators, social media accounts and subject matter experts. We have made an effort to cross-promote to our own media lists, customers and interest groups, resulting in more competitors, more industry partners and increased public interest.

When challenges conclude, we have taken the action with all current and recently past challenges to keep in touch with teams, encouraging them to reach out to us when they do something noteworthy and keeping eyes out for media mentions. We continue to promote their achievements long after the competition ends. We have begun filming an "After the Challenge" series of videos following up on some of our biggest success stories and hope to keep updates like that going on our website and through social media. In addition, we are collecting mentions of progress and next steps by our teams in a document that we can use to promote them, as appropriate. We also reach out to past teams to encourage them to participate in new competitions that might be in their area of expertise.

Each of these tools and methods helps us to elevate and go beyond the more traditional products, such as press releases and stories, reaching a wider audience and thereby growing our solver community.

Media Resources:

- The main web page for the Centennial Challenges program: <https://www.nasa.gov/winit>
 - 3D-Printed Habitat Challenge: <https://www.nasa.gov/3DPHab>
 - Cube Quest: <https://www.nasa.gov/cubequest>
 - Vascular Tissue: <https://www.nasa.gov/vtchallenge>
 - Space Robotics: <https://www.nasa.gov/spacebot>
- The playlist for the program's video content is at <http://bit.ly/2w86p4C>
- Twitter handle: @NASAPrize
- Instagram handle: nasaprize
- Facebook: www.facebook.com/nasacc

VI. Summary and Conclusions

NASA's Centennial Challenge (CC) program continues to push the boundaries of prizes and competitions. In 2017, the program surpassed its goal of conducting at least three competitions, successfully conducting seven events and awarding prizes at each one. Cube Quest (GT3 and 4), Space Robotics (Qual Phase and Finals) and 3DPH (Phase 2 Level 1, 2 and 3) awarded more prize money than ever before (see Fig. 11). Registration for the challenges has also increased over the past few years (see Fig. 12). The program is reaching out to a larger, more varied demographic. This will hopefully result in more innovative solutions to the technology problems the Agency faces.

Efforts to improve the formulation, design, and execution of competitions have resulted in an increase in the number of teams participating in competitions, steady cadence of challenges, and an increase in prize purse awards. By implementing a continuous assessment of competition formulation and execution results, the CC Program continues to look for ways to increase the benefits to the Agency, the Nation, and the participants. The program has also significantly increased collaborations with other government agencies, industry, and academia. NASA continues to partner with non-profit external entities; one challenge is being executed by NASA alone. Strong support from AO industry sponsors have had a crucial role in the execution of virtual and on-site competitions. The competitions could not have been executed without their support.

Communications and outreach are also an integral part of the program, not only for team and sponsor recruitment but for public awareness and support. In 2017, the program received more than 830 media hits from web, podcast, print, and radio outlets. Coverage appeared in publications including: *TechCrunch*, *LA Times*, *Houston Chronicle*, Fox News, *Robot News*, and many more. The program manages three social media platforms (Twitter, Facebook and Instagram) and, over the course of the year, generated 476 posts, 320,307 account followers, and 21,382 engagements from those followers. The program was also invited to take over the NASA HQ Snapchat account for a day to cover the 3D-Printed Habitat Challenge events, which resulted in more than 230,000 views. In addition, the program worked with NASA 360 to create new video products to promote challenges and to highlight past competitors. NASA 360 also provided live coverage of the 3D-Printed Habitat Challenge Phase 3 events, and the viewership resulted in numbers that were second only to the solar eclipse events for the year. For outreach, the program supported panels and exhibits at events including South by Southwest, Space Apps Challenge, NASA Technology Day on the Hill, American Concrete Institute Conference, the Dr. Who Convention and NASA in the Park (local to Huntsville).

Centennial Challenges is an embodiment of NASA's continuing commitment to technological advancement and innovation through non-traditional programs. This program exemplifies the values that have formed the bedrock of the culture at NASA since the beginning—innovation, imagination and passion for exploration. The challenges create greater leverage for competition-derived technological advancement, while simultaneously enabling contestants to expand their business models and customer base. The CC Program is dedicated to encouraging innovation and imagination through its organic approach to utilizing the great talents this nation has to offer, while also capturing the public imagination, engaging communities, and attracting greater public attention to these endeavors.

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