Workshop Report

NSF Workshop on Additive Manufacturing (3D Printing) for Civil Infrastructure Design and Construction

July 13-14, 2017

Arlington, Virginia

Organizing Committee

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Summary of Research Recommendations

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1. Address knowledge gaps and knowledge transfer

- Explore the advantages of additive manufacturing for next generation civil infrastructure construction and design, particularly for creating new civil infrastructure components and structures with multifunctional properties, biomimicry design, functionally graded components, topology optimization, and other performance attributes.
- Bridge the knowledge gaps in transferring the state-of-art additive manufacturing technologies for civil infrastructure design and construction.
- Investigate the sustainability of civil infrastructure constructed through additive manufacturing processes through life-cycle assessment.
- Invent new additive manufacturing technologies needed for civil infrastructure design and construction (such as new mobile printing devices and robotics)
- Identify and resolve the challenges in scaling up state-of-the-art additive manufacturing for civil infrastructure construction, e.g.,
  - Discovery and implementation of new construction materials for use in additive manufacturing,
  - Implementation of conventional construction materials for use in additive manufacturing,
  - Ability to print full-scale components and structures for prefabrication and/or at construction site,
  - New metrology approaches for material properties and on-site construction,
  - Properties of printed products (e.g., interfacing bonding, rheological properties, and engineering performance properties), and
  - Printing composite materials, e.g., reinforced concrete and fiber reinforced concrete

2. Promote research in additive manufacturing for civil infrastructure

- Foster collaborative research to encourage multidisciplinary team work.
- Organize seminars and sessions at relevant conferences to share research findings.
- Hold grantee conferences for researchers to network (e.g., include research projects funded by various government agencies).
- Organize workshops (national and international) to provide platforms for researchers from different disciplines to identify emerging research frontiers.

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1. Introduction

Additive manufacturing (AM) is defined as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [1]. In 2015, AM had grown into a $5.165 billion industry [2]. Major application areas of AM include industrial businesses and machines (20%), aerospace (17%), motor vehicles (14%), consumer products/electronics (13%), medical/dental (12%), and academic institutions (11%) [2]. Architecture and the construction industry account for merely 3.1% of the total AM applications [2].

The U.S. construction industry is a significant contributor to the national economy. In 2016, the construction industry accounted for 4.3% of the total national employment [3]. Moreover, it was one of the leading contributors to the economic growth in the first quarter of 2016 [4]. However, the construction industry also faces challenges in safety and productivity. In 2016, the U.S. construction industry accounted for more than 15% of the total national occupational fatalities [5]. It is estimated that 25% to 40% of work-related deaths in industrialized countries occur at construction sites even though the industry employs only 6% to 10% of the workforce [6]. Widespread applications of AM in architecture and construction industry can potentially revolutionize the industry, increasing both safety and productivity.

The NSF Workshop on Additive Manufacturing (3D Printing) for Civil Infrastructure Design and Construction was held on July 13-14, 2017, in Arlington, Virginia. More than 170 people from the U.S., New Zealand, China, Switzerland, Denmark, and Netherlands, representing academia, government, and industry, attended the workshop. These participants represented more than 100 institutions and organizations. Figures 1 and 2 show percentages of participants from each sector (academia, government, and industry) and numbers of participants from each country, respectively. U.S. Federal entities represented at the workshop included: Army Corps of Engineers Construction Engineering Research Laboratory, Army Engineer Research & Development Center, Army Medical Research and Materiel Command, Department of Defense (DoD), Department of Energy (DoE), Marine Corps, National Aeronautics and Space Administration (NASA), National Institute of Standards and Technology (NIST), National Science Foundation (NSF), Naval Facilities Engineering Command (NAVFAC), Navy, and Oak Ridge National Laboratory.

The workshop had the following objectives:

- Review of the state-of-the-art in the field;
- Examination of future prospects of AM for civil infrastructure design and construction;
- Sharing perspectives of federal agencies on the role of AM in civil infrastructure design and construction;
- Identification of knowledge gaps and challenges in the field; and
- Formulation of recommendations for research initiatives.

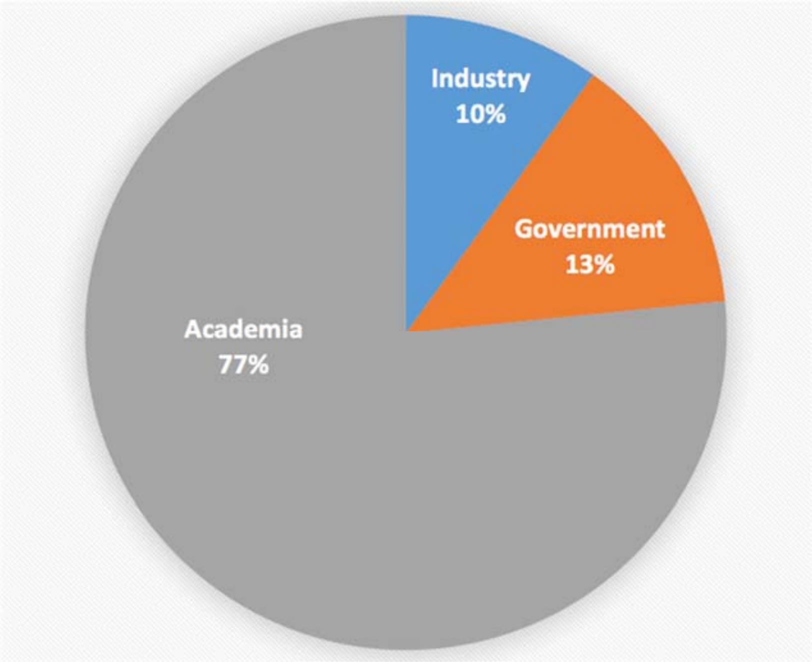

Figure 1: Workshop participants categorized by sector (academia, government, and industry)

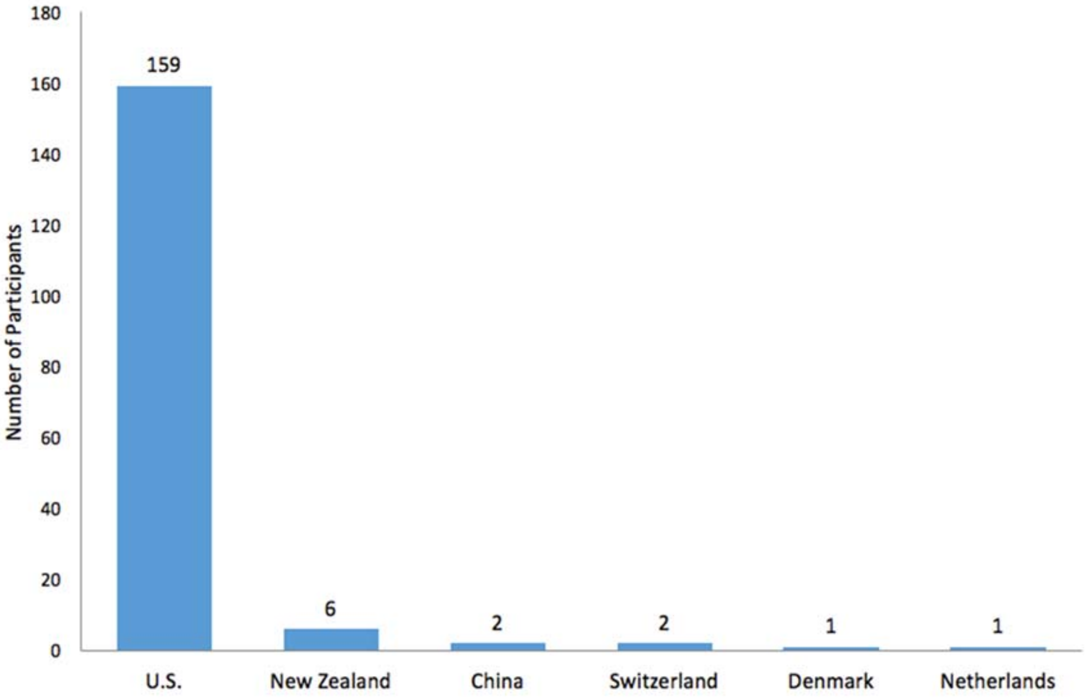

Figure 2: Number of participants from each country

The workshop was one and a half days long. It had five plenary sessions, and each session was comprised of presentations by four invited speakers followed by a 30-minute panel discussion. In addition to these invited presentations, nine participants also delivered idea presentations to highlight various potential applications of AM in civil infrastructure design and construction. Each of these idea presentations was 7 minutes long. The titles and speakers of the invited presentations and idea presentations are listed in Appendix A.

Based on the information shared at the workshop, this report summarizes the current state of the field, gaps, and recommendations. Table 1 summarizes the various AM processes, materials used in these AM processes, and potential applications of AM in infrastructure construction that were discussed during the workshop.

This report is organized as follows. Sections 2 to 5 discuss current AM processes used in the architecture and construction industry as well as gaps associated with each process. Section 6 discusses general gaps and research needs. Section 7 presents recommendations based on workshop discussions.

Table 1: AM processes, materials, and potential applications in infrastructure construction

AM Process	***Material***	***Potential Application***
Concrete Extrusion Printing [7–11]	Concrete	Formwork, structures
Slip Form Casting (Slipforming) [12]	Concrete	Columns
Mesh Mold Metal [12]	Metal (steel wires)	Formwork and reinforcement
Digital Construction Platform (DCP) [13]	Polyurethane foam	Formwork
Flow-based Fabrication [13]	Hydrogel	Structures
Selective Separation Shaping (SSS) [7]	Ceramics	Ceramic structures
Big Area Additive Manufacturing (BAAM) [14]	Polymers (such as ABS)	Large-scale tools, structures
Polymer Extrusion Printing [15]	Polymer (such as ABS with glass-fiber or carbon-fiber reinforcement)	Walls, structures

2. Concrete Extrusion Printing Process

One concrete extrusion printing process is Contour Crafting (CC). It has been demonstrated [16] on a large scale. The CC extruder head is mounted on a crane system capable of moving along the three axes. The mortar is extruded from the head and deposited as per the design file. After printing a layer, the extruder nozzle is raised by an amount equal to the height of the deposited layer and the process is repeated until the final design is achieved. The flow of the extruded wet material is controlled through the use of vertical and horizontal trowels [17]. As these trowels pass over the extruded wet material, they also flatten the surface thereby leading to a smoother finish. The angle and orientation of the horizontal trowel are dynamically controlled as per the surface features of the design. CC enables faster deposition rates by using a larger extrusion nozzle and thicker extruded layers compared to most other AM processes [18]. The print resolution in terms of layer thickness for CC is approximately 13 mm [16]. A 3 m tall concrete wall could be fabricated using a pour rate of 13 cm/hour (or less) without using special high-strength form materials [19]. Additionally, a 2000 square foot house can be constructed in less than 24 hours [20]. It is important to note that, in CC, the mortar is deposited to form a mold of the design. The inside of the mold is later filled with concrete mix.

Using a variety of feed materials (such as mortar, ceramics, and plaster compound), studies have been undertaken to improve the process by analyzing parameters such as print speed, nozzle design, and material composition [16, 21, 22]. Different nozzles (with square and elliptical orifices) have been studied [22]. The square orifice exhibited better adhesion between layers and fewer defects such as surface cracks. The mortar (comprising of Type II hydraulic plaster Portland cement, sand, plasticizer, and water) developed for this process demonstrated adequate compressive strengths for a structural component [16]. Additionally, new materials for this process were developed by changing the aggregate to cement ratio as well as the aggregate size [23]. Sulphur concrete has also been printed successfully using CC [24]. To demonstrate reinforcement, custom U-shaped tie rods were inserted manually into a wall structure during CC printing [17]. The horizontal distance between these tie rods were 305 mm whereas the vertical distance between them was 127 mm [17]. In addition, reinforcement of CC printed structures was also demonstrated using metal coils [25]. This procedure comprised of extruding fresh layers of material over a metal coil. Initial examination of cross-sections of such structures showed reasonable adhesion between layers [25].

Researchers at University of Southern California printed a concrete wall using CC [16]. This demonstration required creating a new mortar mix that would result in printed concrete with sufficient compressive strength. Each extruded layer was 19 mm wide and 13 mm tall. Using this layering method, a wall with dimensions of 1.5 m (L) X 0.6 m (H) X 0.15 m (W) was constructed [16].

Another concrete extrusion printing process is direct ink writing. It was developed by researchers at Purdue University to study the ability of architectured materials (via AM) to control the mechanical properties of cement-based materials [11]. This study was guided by knowledge gained from the research on biologically-inspired materials [11, 26]. Certain natural composite materials (such as those found in exoskeletons of arthropods, bones, and seashells) achieve higher toughness without sacrificing stiffness and strength [11]. Knowledge on how nature employs these strategies is useful in using direct ink printing to print architectured cementitious materials [54].

Another concrete extrusion printing process was developed by researchers at Loughborough University called concrete printing [27]. During its data preparation step, similar to other AM processes, a CAD design file is first converted into an STL format for each layer, and, then, a G-code is generated for printing. This printing process also includes an optimization step to reduce non-printing movements of the nozzle in order to reduce material and time losses [27]. The prepared material is deposited as per the design file. The prototype printer developed for this process has a build envelope of 5.4 m (L) X 4.4 m (W) X 5.4 m (H) and consists of a print head capable of moving in all three directions [27]. No trowels were used in this case, and hence, the surface is ribbed [18]. In terms of print resolution, concrete printing has a layer height of 4-6 mm [18]. This, coupled with the smaller diameter extruder nozzle, accounts for a slower build rate as compared to CC.

For concrete printing, two critical parameters of material being extruded are *Extrudability* and *Buildability* [28]. *Extrudability* refers to the capacity of the material to pass through the feed system and the print head [28]. *Buildability* was defined as the capacity to print a certain number of layers [28]. This is an important parameter since layers of deposited material should exhibit negligible distortion under the weight of subsequent layers. Currently, research on reinforcement strategies for concrete printing is being conducted [8]. In their research on reinforcement of concrete structures, researchers at TU Eindhoven conducted experiments to control the orientation of steel fibers in freshly printed concrete using a magnetic field [8, 29]. Their results indicated an approximate proportionality between the energy absorption capacity of the test specimen and the number of well-oriented fibers [29].

Concrete printing was successfully demonstrated by constructing a "Wonder Bench" with dimensions of 2 m (L) X 0.9 m (W) X 0.8 m (H) [28]. It consisted of 127 layers and each layer was 6 mm thick. The average print time per layer was 20 minutes [18]. The extruded material had a 3:2 sand-binder ratio with the binder comprising of 70% cement, 20% fly ash, 10% silica fume by weight of dry mixture and 1.2 kg/m^3 of 12/0.18 (length/diameter) of polypropylene fibers [28]. The "Wonder Bench" consisted of 12 through holes referred to as "voids" by the researchers. These through holes were used for post-placement of reinforcement bars that were post-tensioned and grouted [27].

While much work has been done in printing concrete structures [7–12, 30–33], significant research efforts are required to develop fundamental understanding of material chemistry, hydration, setting, drying shrinkage, and rheology of materials in order to regulate material flow as well as to avoid clogging and segregation [6, 8, 28].

Another gap is related to reinforcement of 3D printed concrete. The tensile strength of concrete is too low for many applications without reinforcement. No presentations at the workshop reported any examples of incorporating steel reinforcement bars in concrete extrusion printing. Moreover, for reinforcement of AM structures, 3D printing of reinforcement bars/cages presents challenges such as selection of material for reinforcement, economic justification for AM of reinforcement bars, and ascertaining efficient reinforcement configurations [33]. Development of multi-material printing processes would simplify parallel printing of reinforcements as well as the final structure. Such a multi-material printing process could enable inclusion of all manner of co-printed reinforcements and control of reinforcement-matrix interfaces [31]. Research on nozzle designs for multi-material printing and associated effects on build quality is limited [10]. An alternate option to improve structural performance is the development of composite materials that eliminate the need for reinforcement [9]. Furthermore, application of pre- and post-tensioning of synthetic and natural fiber reinforcement can also facilitate structural integrity [34]. Additional gaps in this field include: methods to extend yield stress range [10], new economical and durable materials for reinforcement [33], and analysis of effects of orientation and intersection of reinforcement in these structures on mechanical properties and structural integrity [33].

The unique ability of AM to print with high degree of accuracy can enable the building of complex materials with improved mechanical performance by controlling their internal architecture. These complex materials synergistically employ geometry and material combinations to achieve mechanical properties that are unachievable by other fabrication means [26]. Control of the internal architecture of these complex materials will require mathematical and mechanics tools to create quantitative information and design guidelines for these synthetic materials [11, 31]. These mathematical tools can be bottom-up approaches following unit structures built from simple building blocks or top-down approaches such as topology optimization [26]. In this way, mechanically optimized lightweight and stiff/strong lattice structures or functional graded materials can be designed. However, mathematical foundations for toughness and strength optimization are still limited by current computational approaches.

Currently, no relationships between rheological properties of material, process parameters (such as print speed and curing time), and print quality of structures have been reported [10]. Furthermore, research from a measurements science perspective would be essential for evaluating critical material properties and ensuring field performance of AM processes [10]. Additional gaps include localized control of material chemistry [31], control of fiber orientation in composites [10], understanding of fiber-material rheology and setting time [35]. Currently, these research problems in materials and processes are tackled from an empirical perspective [31]. Development of (accurate) computational models would supplement physical experiments [31, 36, 37]. Research is needed to improve knowledge of materials, structures, and processes [11, 31, 37, 38].

3. Slip Form Casting (Slipforming)

Researchers at ETH Zurich developed Smart Dynamic Casting (SDC) – a robotic slipforming process [39]. In this process, concrete mix with an accelerator is pumped into a small formwork that is attached to a robotic arm. The formwork is moved at a speed determined by the feedback system based on the setting and hardening characteristics of the feed material in order to ensure that the formed structure is self-supporting after the formwork is removed. It is important to note that the formwork is significantly smaller than the final structure printed. The robotic arm is capable of 6-axis motion and velocity and movement of the formwork can be controlled [39].

SDC relies on the fundamental understanding of the dynamic relationship between material properties and process parameters (such as curing time required for a column to be self-supporting and additional load-bearing capacity of the column on removal of the formwork) to achieve desired shapes of printed structures. To develop this understanding, empirical studies were carried out [39]. Additionally, a feedback process monitoring system was set up for heavily retarded fiber reinforced concrete. This feedback system is comprised of a digital penetrometer attached to a digitally controlled tri-axial table [39]. It enabled the real-time measurement of material properties and aided the adjustment of the velocity of the slipping formwork to enable successful construction. In addition, researchers also carried out compression tests to determine material strength. While high velocities of slipping of the formwork were associated with creep, low velocities led to failure through increased friction [39]. Hydration control of the mixture was achieved using chemical admixtures [12].

An early demonstration of SDC was done by printing an elliptical column with a rotation of 180 degrees along its height of 1800 mm. The formwork used for this design was elliptical with dimensions of 125 mm X 80 mm and a height of 60 mm. This approach enabled vertical build rates of 1m/h [40]. While traditional slipforming can fabricate components several m^2 in cross-sectional area, SDC products have cross-sectional area limitations of the order of cm^2.

It is important to note that, for SDC, small disparities in material composition along with room temperature variation can have a significant impact on the outcome. Deployment of this process in real-world applications might not be successful without process knowledge necessary to control rheology and hydration of feed material in dynamic conditions [12]. Furthermore, there are no reports on durability assessment of structures printed by SDC. There are no reports on reinforcement of structures printed by SDC [12].

4. Mesh Mold Metal

Construction of complicated concrete structures requires the use of custom formworks. These formworks made of wood or foam are intended for a single use. Moreover, these formworks and reinforcement processes represent the most labor and cost intensive practices in concrete construction [41]. An alternative to these practices is the use of stay-in-place formworks [40]. The mesh mold metal process developed at ETH Zurich [12, 40, 42] is an example of this approach. In this case, an industrial robot bends and welds metal wires to create a 3D mesh. Fresh concrete mix is infilled following the mesh fabrication. The mesh structure serves a two-fold purpose. First, the mesh acts as a stay in place formwork for the material; and second, it performs the role of reinforcement on setting [40, 42, 43].

5. Non-concrete AM Processes

These processes include digital construction platform, big area additive manufacturing, Flow-based fabrication, fused deposition of polymers, and selective separation shaping.

Researchers at MIT have developed a digital construction platform (DCP) [13]. The DCP is a mobile autonomous construction system that relies on real-time environment data for process control. The mobility of the DCP was facilitated through a track system while the robotic arm system consisted of a hydraulic arm with 4-DOF and a smaller electric arm with 6-DOF. This design was inspired by the kinematic structure of the human arm and hand [44]. The system also incorporated a photovoltaic panel to power the battery for the electrical arm. This process can be used to create formwork for cast concrete structures. In addition, the DCP system is designed to be material independent [44].

This process was demonstrated by printing an open dome-like structure measuring 14.6 m in diameter and 3.5 m in height. The structure was printed over a duration of 13.5 hours [44]. A two-part polyurethane foam was used to print the formwork. Furthermore, the DCP was also successful in printing overhangs at various angles including horizontal overhangs. Similar to most other printing processes, the surface of DCP printed structures was striated [44].

Researchers at the Oak Ridge National Laboratory (ORNL) have developed capabilities for large-scale printing of thermoplastics and composites [45]. This process relies on melt extrusion of industry standard materials such as polymer pellets. The deposition head comprised of a single-screw extruder. This extruder was designed to accomplish melting and deposition of the polymer pellets at a specific rate. A multi-axis robotic arm was used to control the positioning and movement of the deposition head. The material was deposited as thick oval beads along a specific toolpath on a heated platform [46]. Since filament is not used as the feedstock, researchers were able to achieve great control over the print composition while extruding composites. Moreover, the use of pellets reduced the cost of the feed materials by a factor of 20 [46].

Recent experimental studies on BAAM by researchers at ORNL could accommodate a build volume of 6 m (L) X 2.4 m (W) X 1.8 m (H). Using a nozzle with a circular orifice, researchers deposited oval beads having a thickness of 4 mm and a width of 8.4 mm [46]. Build parameters such as extrusion temperature and material flow rate were found to have significant effects on build quality [46]. In August 2016, the Guinness World Record for printing the largest solid 3D printed item was awarded to Boeing (working in collaboration with ORNL). The carbon fiber reinforced ABS plastic part (a wing trim tool) was 5.33 m (L) X 1.68 m (W) X 0.46 m (H) in size and was printed over a duration of 30 hours [47].

Efforts by Branch Technology [15] in the U.S. relied on the fused deposition of free-standing polymer (generally ABS with carbon fiber or glass fiber reinforcement) structures. Prefabricated modular wall sections were extruded and filled with conventional construction materials [48]. In addition to facilitating construction of complex designs, these modular wall sections were 3-4 times stronger than wood framing [15]. These polymer structures have also been used to fabricate walls with gypsum interiors and glass fiber reinforced concrete exterior. Demonstrations of this process include the Pavilion printed using composites for Design Miami in collaboration with Oak Ridge National Laboratory (ORNL) [14, 15].

D-Shape is a powder deposition process for the construction of large-scale artifacts [18]. This process is initiated by the deposition of fine sand as a base layer having a thickness of 5 mm [49]. Thereafter, an inorganic binder is selectively deposited on the base layer by a deposition head mounted on a gantry. This procedure of adding layers of sand followed by deposition of binder is carried out continuously until the final structure is constructed. Using this process, researchers printed a 2 m tall Radiolaria structure made of sandstone rejects. It is important to note that this structure required a week of finishing by hand [50].

Researchers at MIT's Media Lab developed the Flow-based fabrication process [51]. This process was used to print human-scale objects using polysaccharide hydrogels. Researchers developed a workflow for achieving the complexity of multi-scale and multi-material interactions via AM [13, 51]. The computation model used the material, platform, and design information. The results from the computational model were used to deliver fabrication instructions for coordinating deposition and positioning platforms [51]. The pneumatic tool head developed was able to deposit materials ranging from 500-50000 cPs in viscosity. These materials were cured slowly at room temperature after deposition. The prints exhibited spatial and material complexity through structurally patterned lightweight shells that spanned 10 feet in dimension [51].

Researchers at the University of Southern California developed a powder sintering process for AM construction using ceramics [7]. This process, referred to as selective separation shaping (SSS), relied on the use of two kinds of powder: B-powder (that constituted the final part) and S-powder (that acted as a separator) [52]. The S-powder had a higher sintering temperature than the B-powder. During the printing process, S-powder was selectively deposited over a bed of B-powder using a nozzle and a vibrating piezoelectric disk. This disk facilitated the flow control of the powder [52]. Thereafter, sintering was carried out at a temperature higher than the sintering temperature of the B-powder, but lower than that of the S-powder. On completion, the part could be easily removed from the powder bed. This process was demonstrated using a lunar regolith simulant material and an in-situ separator powder to manufacture ceramic tiles [7, 52].

In the field of autonomous construction platforms, no reports are available on fully-autonomous systems that utilize locally available materials for construction [13]. This concept of using local materials is also referred to as "In-situ Resource Utilization" and would be critical to space colonization programs [53]. Additional research gaps for non-concrete AM processes include the control of residual stress and distortion, and development of graded structures via multi-material printing [14]. With major strides in materials knowledge, it would be interesting if new uses of novel materials can be found [34]. Moreover, metal structures are an integral part of the infrastructure industry. No studies have been reported regarding large scale printing for metals [14].

6. General Gaps and Research Needs

In addition to the process-specific gaps discussed in the above sections, there exist general gaps common to several AM processes and their applications in the construction industry. These gaps span a broad spectrum of research topics including materials, designs, standards, and economics.

There are no reports on studies devoted to identifying, designing, and deploying new, tailored materials using experimental, computational, and data informatics approaches [10, 31, 37, 54]. The Materials Genome Initiative [36] would be a vital resource for researchers in the field of material development [37]. New materials for construction would be tailored to meet requirements from the new process technology, satisfy design constraints, and meet structural integrity criteria.

For example, the development of innovative binding materials for new concrete systems (such as plastic fiber concrete [35]) should be instrumental in enhancing the mechanical performance of structures [35]. Moreover, development of a "greener," sustainable concrete continues to remain a challenge [31]. In addition to developing new materials, studies should be undertaken to understand the chemistry and hydration of cementitious materials so they can be utilized in AM.

The layer-by-layer nature of AM makes it uniquely capable to construct functional designs. An example would be self-sensing concrete with added carbon materials (graphene, carbon nanotubes, and graphene nanoplatelets) [35]. Another example would be 3D printed building skins that have temperature sensitive pores. On detecting higher temperatures inside the building, these pores could open up to facilitate air circulation [55]. The use of smart materials that respond to certain stimuli can facilitate achievement of functionality [55]. There are not many reports on studies devoted to functional architecture built by AM [11].

New codes and standards for applications of AM in construction can be useful in ensuring safety of 3D printed structures. However, it is important to keep in mind that codes and standards can inhibit innovation in some cases. Furthermore, current standards for concrete formulation are prescriptive (for example, mix components A, B, and C in X, Y, and Z proportions) and may not be relevant to AM processes [10]. Performance-based standards, for example, "feed material must have X property or its Y property should be greater (or less) than Z" [10], would be less constraining and can facilitate innovation [10]. For various metal AM processes, test artifacts have been used to evaluate printability of certain design features [10]. However, for AM processes used in civil infrastructure applications, no such test artifacts exist [10, 13]. Currently, there are no standards to evaluate the durability of structures printed using AM [12].

Economic justification is necessary for successful deployment of AM processes in the infrastructure construction industry. Currently, no detailed economic justification of AM processes for civil infrastructure design and construction has been reported. Moreover, economic effects of AM processes on various aspects of the construction industry such as supply chain logistics remains unknown. Deployment of AM processes for construction will require rethinking the approach to supply chain logistics [56]. With increased automation, construction can be carried out 24 hours a day and 7 days a week. This will impact the supply chain economics. Moreover, the introduction of new materials would require a new approach to construction and logistics. Industry participation would be a critical requirement for these economic studies [31].

7. Recommendations

7.1 Addressing research gaps and knowledge transfer

Applications of AM processes in civil infrastructure design and construction can facilitate the creation of infrastructure with multifunctional properties, biomimicry design, and functionally graded components. Moreover, the AM construction process could also be automated through the use of robotics [13]. In order to realize the potential of these emerging AM processes, it is vital to develop process knowledge/scale-up and facilitate knowledge transfer to the construction industry.

In order to develop process knowledge, it is imperative to pursue research in materials, design and technology. For example, research is needed on both new materials and conventional cementitious materials. Emergence of AM processes will also require rethinking of the way structures are designed. The freedom of shape provided by AM processes will facilitate designs that minimize the need for reinforcements by minimizing tensile loads in the structure. In order to facilitate faster progress in research of materials and technologies, development of accurate computational models that span over various time and length scales is recommended [31]. Multi-material printing technology also needs to be developed to enable parallel printing of the reinforcement and the structure. The use of measurement science knowledge in these research efforts would be critical to the success of AM processes.

Scale-up of these AM processes from laboratory to real-world applications would require new codes and standards to ensure the performance of emerging AM processes and verify the safety of AM structures. Furthermore, a reinforcement strategy for AM processes needs to be developed to ensure AM structures comply with safety standards. Furthermore, research is required to provide economic justification for using AM processes in civil infrastructure design and construction. Industry participation would be vital in this endeavor.

7.2 Promote research in AM for civil infrastructure

Collaborative, multidisciplinary research studies would be key to accelerating research in the field of AM construction. These collaborations could be further enhanced through various seminars and sessions at relevant conferences to share research findings. An example of this could be a grantee conference where participants could learn more about research projects funded by various government agencies. Additionally, national and international workshops could facilitate multidisciplinary research collaboration to identify emerging research frontiers.

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APPENDIX A

Workshop Format and Agenda

The workshop had three types of activities:

(1) Invited talks (each was 20 minutes long including Q&As). These talks were given by experts who presented inspiring examples of 3D printing in various applications (including, but not limited to, architecture, structures, construction, materials and design); and by individuals from government agencies who presented their agency's perspectives on 3D printing for civil infrastructure design and construction.

(2) Panel discussions (each was 30 minutes long). A group of four speakers served as panelists for each of these panel discussions.

(3) Idea presentations (each was 7 minutes long). These short presentations were given by participants who had ideas about potential 3D printing's applications in civil infrastructure design and construction.

Day 1

8:00-8:20 Introduction and opening remarks

Introduction and opening remarks
Moderator: *Stephanie Paal*

Welcome by workshop organizing committee
Welcome by *Deborah Goodings* (NSF CMMI Division Director)

8:20-9:40 Invited talks (4)

R. Platt Boyd IV, Branch Technology
Cellular Fabrication – 3D Printing at Architectural Scale

Kristy Pottol, US Army Medical Materiel Development Activity
Frontiers of Additive Manufacturing in Military Medicine

Rob Gorham, America Makes
America Makes – A Consortium Approach to AM for Infrastructure Design and Construction

Kaleb Steinhauer, Genesis Dimensions
Bringing Additive Manufacturing to the Construction Site

9:40-10:10 Panel discussion
Moderator: *Brennan Grignon* (DoD)

10:10-10:40 Coffee break

10:40-11:40 Invited talks (4)

Berok Khoshnevis, University of South California
Large-scale 3D Printing: Past, Present and Future Projection

Zofia Rybkowski (with *Negar Kalantar*), Texas A&M University
Performative 3D Printed Building Skins: Towards an Adaptable Built Environment

Pablo D. Zavattieri, Purdue University
Material Architecture Inspired by Nature: Harnessing the Role of Interfaces and Uncovering Hidden Possibilities

Brian K. Post, Oak Ridge National Laboratory
Breaking Barriers with BAAM: Large Scale Additive Manufacturing Applications in Infrastructure

11:40-12:10 Panel discussion
Moderator: *John Vickers* (NASA)

12:10-13:30 Lunch break (lunch will not be provided by the workshop)

13:30-14:50 Invited talks (4)

Neri Oxman (with *Julian Leland*), MIT
Towards A Material Ecology

TAM (Theo) Salet, Eindhoven University of Technology, Netherlands
3D Concrete Printing – A Journey with Destination Unknown

Philip F. Yuan, Tongji University, China
Robotic Additive Manufacture in Architectural Industry

Florence Sanchez, Vanderbilt University
3D Printing: A New Promising Avenue for Concrete and the Construction Industry

14:50-15:20 Panel discussion
Moderator: *Chiara (Clarissa) Ferraris* (NIST)

15:20-15:50 Coffee break (coffee and refreshments will be provided by the workshop)

15:50-17:00 Idea presentations (9)
Moderator: *Ralph Resnick* (NCDMM)

Hunain Alkhateb, The University of Mississippi

Mars Habitation: Mission, Vision, and Current State of Art

Christopher Carroll, Saint Louis University
3D Printed Reinforcing Cages for Concrete Columns

Patricia Clayton, University of Texas at Austin
Additive Manufacturing in the Construction Industry: Getting Beyond the Hype

Qingli Dai, Michigan Technological University
Plastic Fiber Concrete Design and 3D Printing Techniques

Mo Ehsani, QuakeWrap, Inc.
Onsite-Manufactured Continuous Pipe

Johan Potgieter, Massey University, New Zealand
Solving the Good and the Bad of Small Scale Resolution for Large Format Printing

Wil Srubar III, University of Colorado Boulder
Structural Plastics: Polymer Additive Manufacturing in Civil Engineering Research and Education

Ross Stevens, Victoria University of Wellington, New Zealand
Recreating Earthquake Prone Historic Buildings with 3D Printing

Hongyu Zhou, University of Alabama – Huntsville
Self-adaptive Building Facade Enabled via 3D Printed Metamaterials: Harnessing Geometry Complexity for Performance

17:00 Adjourn

Day 2

8:00-8:10 Introduction and announcements

8:10-9:30 Invited talks (4)

Sarat Singamneni, Auckland University of Technology, New Zealand
Ceramic 3D Printing for Additive Solutions in Civil Construction

Simon Fraser, Victoria University of Wellington, New Zealand
Scaling Up: Novel Design Inspired Applications of 3D Printing

Didier Lootens, Sika Technology AG – Central Research, Switzerland
Industrialization of the Construction: Local Producing with 3D Printing

Timothy Wangler, ETH Zürich, Institute for Building Materials, Switzerland
Materials Challenges in Digital Fabrication with Concrete

9:30-10:00 Panel discussions
Moderator: *Frank W. Gayle* (AMNPO)

10:00-10:30 Coffee break (coffee and refreshments will be provided by the workshop)

10:30-11:50 Invited talks

Deborah Goodings, NSF
NSF Perspectives on Additive Manufacturing for Civil Infrastructure Design and Construction

Frank W. Gayle, Advanced Manufacturing National Program Office (AMNPO)
Manufacturing USA – the National Network for Manufacturing Innovation

Scott Z. Jones, National Institute of Standards and Technology (NIST)
NIST Perspectives on Additive Manufacturing for Civil Infrastructure Design and Construction

Michael Case (with *Megan Kreiger*), US Army
Automated Construction of Expeditionary Structures

11:50-12:20 Panel discussion
Moderator: *John A. Barton* (Texas A&M)

12:20-12:30 Wrap-up
NSF program director *Joy Pauschke*

12:30 Adjourn

APPENDIX B

Workshop Organizing Committee

The workshop organizing committee was responsible for logistics of the workshop, dissemination of workshop results, and travel reimbursement for participants. It is consisted of following people at Texas A&M University:

ZJ Pei, Professor in the Department of Industrial and Systems Engineering.
Satish Bukkapatnam, Professor in the Department of Industrial and Systems Engineering.
Li Zeng, Assistant Professor in the Department of Industrial and Systems Engineering.
John Mander, Professor in the Department of Civil Engineering.
Stephanie Paal, Assistant Professor in the Department of Civil Engineering.

ZJ Pei served as an organizer of the NSF CAREER Proposal Writing Workshop every year from 2004 to 2012. He served as an NSF coordinator for the workshop from 2013 to 2016, while serving as a program director at NSF. During his 4 years as a program director at NSF, his program supported more than 10 workshops on various topics. He worked closely with organizers of these workshops. He also served on the organizing committee and the steering committee for the NIST/NSF Workshop Measurement Science Roadmap for Polymer-Based Additive Manufacturing, Gaithersburg, Maryland, June 9-10, 2016.

Satish Bukkapatnam has been a PI for one and Co-PI for two earlier NSF workshops in manufacturing, and has served as an invited participant in five different NSF workshops. Additionally, he currently serves as a Rockwell International Professor of Industrial and Systems Engineering (with a joint appointment in Biomedical and Mechanical Engineering) at Texas A&M University (TAMU), College Station, TX, and Director of the Texas A&M Engineering Experimentation Station Institute for Manufacturing Systems (TEES-IMS), a state agency. TEES-IMS would provide institutional support for the proposed workshop.

Li Zeng received her MS degree in Statistics and PhD in Industrial Engineering from the University of Wisconsin-Madison. Her research interests are additive manufacturing for health, quality control in manufacturing and healthcare delivery systems, and system informatics. Her research is supported by NSF, Air Force, American Heart Association and the University of Texas System. She is leading an NSF project, starting September 2016, to create a 3D printing-based meniscus transplantation system. She was a participant of the 2016 NSF Workshop on Additive Manufacturing for Health.

John Mander received his BE (Hons) and Ph.D. degrees from the University of Canterbury, New Zealand. His primary research interests are in developing new and enduring large-scale structural systems that are modular to construct (and de-construct) that also follow the precepts he pioneered on Damage Avoidance Design for shock, earthquake and impact loading. With this work, he developed the next generation of seismic resistant buildings and bridge piers that are now part of the rebuilding inventory following the 2010-2011 Canterbury Earthquake Sequence; and more recently, two distinct bridge types for short and long-span girder bridges. His research has been supported by Federal Highway Administration, Texas Department of Transportation, the New Zealand Government, NSF via N/MCEER (in the 1990s), and various private sector companies.

Stephanie Paal received her MS and Ph.D. in Civil Engineering from the Georgia Institute of Technology. Her research interests are infrastructure condition assessment, computing technologies and visualization in civil engineering, sensing and data collection for civil infrastructure and system of systems resiliency.

APPENDIX C

Workshop Steering Committee

The steering committee was responsible for the technical content of the workshop, identification and invitation of speakers, and recruitment of attendees. Members of the steering committee are as follows:

- **John A. Barton** (Assistant Vice Chancellor for Strategic Initiatives, Texas A&M University)

  John Barton is a Professor of Practice in the Zachry Department of Civil Engineering at Texas A&M University, an Associate Vice Chancellor for the Texas A&M University System, and the Executive Director of The TAMUS RELLIS Campus as well as the TAMUS Center for Infrastructure Renewal. In these roles John directs all activities related to the development and operation of the new TAMUS RELLIS Campus and directs the operations, research, innovation, education and workforce development activities of the new Center for Infrastructure Renewal. John retired as the Deputy Executive Director of the Texas Department of Transportation (TxDOT) in 2015 where he provided executive control and oversight of all TxDOT operations and the management and operation of the state's transportation system. He held a variety of positions with TxDOT during his 30 years of state service. John graduated with honors with a Bachelor of Science Degree in Civil Engineering from Texas A&M University in 1986. He received the Distinguished Graduate Award of the Zachry Department of Civil Engineering from his alma mater, the AASHTO President's Special Award of Merit, and the FHWA Administrator's Public Service Award; and was honored as the inaugural recipient of the Governor Rick Perry Leadership in Transportation Award. John has served on the Board of Directors of the Intelligent Transportation Society of American, the Board of Directors of the National Operations Center of Excellence, the Safety Advisory Board for Uber Technologies, Inc., and the Advisory Board for the Southwest Research Institute; and as the Chairman of AASHTO's Subcommittee of Traffic Engineering.

- **Dr. Chiara (Clarissa) Ferraris** (Group Leader, The Inorganic Materials Group, The Materials and Structural Systems Division, Engineering Laboratory, National Institute for Standards and Technology)

  Dr. Ferraris' research is concentrated in developing test methods for measuring the rheological properties of cementitious materials. She developed a Bingham Standard Reference Material (SRM), containing particles as large as 10 mm, for calibration of rheometers for paste to concrete. She is chairing the American Concrete Institute (ACI) committee on Grouting and was past chair of various committees both at ASTM and ACI. She is the author of numerous papers related to the rheological properties of cement paste and concrete. In 2017, she received the ACI Philleo Award for her leadership and advancement of the rheology of cementitious materials. She is a Fellow of ACI and of ASTM.

- **Frank W. Gayle** (Deputy Director, Advanced Manufacturing National Program Office; Deputy Director, NIST Office of Advanced Manufacturing, National Institute of Standards and Technology)

Dr. Frank W. Gayle is the Deputy Director of the Office of Advanced Manufacturing at the National Institute of Standards and Technology (NIST). NIST's Office of Advanced Manufacturing is responsible for extramural advanced manufacturing programs and serves as a liaison to industry and academia. The interagency Advanced Manufacturing National Program Office coordinates Federal activities in advanced manufacturing, and is the Congressionally-designated National Program Office for Manufacturing USA – the National Network for Manufacturing Innovation. Frank spent 11 years in the aerospace industry before joining NIST. As Division Chief of the NIST Metallurgy Division, Frank developed programs in energy, microelectronics, and mechanical properties, focusing on measurement needs for industry. Frank also led the team of technical experts on the forensics of structural steel in the Congressionally mandated NIST investigation of the World Trade Center disaster on September 11, 2001. Frank earned an Sc.D. in Materials Science from MIT, and degrees in Civil and Mechanical Engineering from Duke University.

- **Brennan Grignon** (Senior Advisor, Office of the Assistant Secretary of Defense for Manufacturing and Industrial Base Policy, Department of Defense)

  Brennan currently serves as senior advisor in the Office of the Assistant Secretary of Defense for Manufacturing and Industrial Base Policy (ODASD MIBP). She strategically coordinates efforts among the fourteen Manufacturing USA institutes, with Department of Defense (DoD) counterparts, and with other government agencies to create a holistic strategy for education and workforce development efforts in manufacturing. She leads engagement between the DoD and industry, facilitating dialogue to support a communicative and collaborative relationship between small, medium, and large defense industrial base companies and the Department. Brennan also leads efforts regarding strategic use of additive manufacturing (AM; aka 3d printing) throughout the DoD. Prior to her role at MIBP, Brennan was the program manager of LMI's Research Institute, managing a multi-million-dollar R&D budget and coordinating over 40 internal and external R&D projects on a variety of technologies. Brennan also supported government clients (civilian and defense) in strategic planning, communications, change management, technology transfer and implementation, competency management, and workforce development efforts. She served as LMI's additive manufacturing lead. Brennan's early career was as a financial advisor and retirement plan analyst, managing large personal estates and retirement plans for individuals, companies, and private equity firms. She earned her master's in history and bachelors in history and biology, all from American University.

- **Ralph Resnick** (President and Executive Director, NCDMM; Founding Director, America Makes, the National Additive Manufacturing Innovation Institute)

  Mr. Resnick joined NCDMM in September 2008 as Vice President, and became President and Executive Director in May 2011. In 2012, he led NCDMM to winning the competitive National Additive Manufacturing Innovation Institute contract. Upon award, he also assumed the role of Acting Director of the Institute until February 2013 upon appointing a new director. Prior to joining NCDMM, Mr. Resnick served as Chief Technology Officer for both The ExOne Company and Extrude Hone Corporation where he was a major contributor in establishing both organizations as leaders in advanced manufacturing, including such areas as additive manufacturing, process research, and technology transition to the world's factory floors. He holds several patents in manufacturing processes and metrology. Mr. Resnick serves on numerous Boards, including the Association for Manufacturing Technology (AMT), the Louisiana Center for Manufacturing Sciences (LCMS); the NIST Smart Machining Consortium; the Navy Metalworking Center's (NMC) Industry Advisory Board; and the MTConnect® Institute. He is also a member of DoD's JDMTP Metals Subpanel and Advanced Manufacturing Enterprise (AME) Subpanel and participates actively in the National Science Foundation (NSF) proposal reviews and technical events. Mr. Resnick is an active member of the NDIA Manufacturing Division; Industry Advisor for the Eastern Westmoreland Career and Technology Center; founder of the recently formed Mission Ready Sustainability Initiative (MRSI); and is an associate member of the prestigious International Institution for Production Engineering Research (CIRP). He also is a former Board member of the Navy's Electro Optic Center (EOC); a past Chairman of the AMT's Technology Issues Committee; and past President of the NAMRI/SME. Currently, Mr. Resnick is a Fellow of SME and the Chairman of SME's International Awards and Recognition Committee. In 2010, he received the NAMRI/SME "Outstanding Lifetime Service Award."

- **John Vickers** (Principal Technologist, Space Technology Mission Directorate, National Aeronautics and Space Administration (NASA))

  John Vickers is currently the NASA principal technologist in the area of advanced materials and manufacturing. He also serves as the Associate Director of the Materials and Processes Laboratory at NASA's Marshall Space Flight Center and as the Manager of the NASA National Center for Advanced Manufacturing with operations in Huntsville, Alabama and New Orleans, Louisiana. He has over 30 years of experience in materials and manufacturing — research and development, engineering, and production operations for propulsion, spacecraft, and scientific systems. As principal technologist, he leads the nationwide NASA team to develop advanced manufacturing technology strategies to achieve the goals of NASA's missions. In this role, he represents the Agency supporting the President's National Manufacturing Initiative and the Interagency Advanced Manufacturing National Program Office, which includes participation by the National Institute of Standards and Technology (NIST), the Department of Defense, the Department of Energy, NASA, the National Science Foundation, the Department of Education, and other agencies. He also leads the NASA Technology Roadmap effort for "Materials, Structures, Mechanisms and Manufacturing." He is a Fellow of SME. He holds a Bachelor of Science in Engineering from the University of Alabama in Huntsville.

APPENDIX D

Sponsors

This workshop is supported by NSF Award 1713983 through the following NSF programs in the Civil, Mechanical and Manufacturing Innovation (CMMI) Division:

- **Engineering for Natural Hazards (ENH)**
  (Joy M. Pauschke and Richard J. Fragaszy)
- **Manufacturing Machines and Equipment (MME)**
  (Steven R. Schmid and Brigid A. Mullany)
- **Structural and Architectural Engineering and Materials (SAEM)**
  (Yick G. Hsuan)

APPENDIX E

Diversity of participants of NSF Workshop on Additive Manufacturing for Civil Infrastructure Design and Construction

	Total Number	Number of Women	Percentage
Organizing committee and steering committee	11	4	36%
Invited speakers	23	7	30%
Idea Presenters	9	3	33%

APPENDIX F

Participants of NSF Workshop on Additive Manufacturing for Civil Infrastructure Design and Construction

First Name	*Last Name*	*Organization*
Mohamed	Abdel-Raheem	University of Texas Rio Grande Valley
Timothy O.	Adekunle	University of Hartford
Hunain	Alkhateb	University of Mississippi
Mohammed	Alnaggar	Rensselaer Polytechnic Institute
Hossein	Ataei	Syracuse University
Sez	Atamturktur	Clemson University
Amarnath	Banerjee	Texas A&M University
Miki	Banu	University of Michigan
John	Barton	Texas A&M University
Sarah	Bates	National Science Foundation
Amir	Behzadan	Texas A&M University
Dale	Bentz	National Institute of Standards and Technology
Michelle	Bernhardt	University of Arkansas
Abhinav	Bhardwaj	Texas A&M University
Onur	Bilgen	Old Dominion University
Ian	Black	Lehigh University
Marisol	Bonnet	Department of Energy
Platt	Boyd	Branch Technology
Julia	Carroll	Johns Hopkins University
Chris	Carroll	Saint Louis University
Michael	Case	U.S. Army Corps of Engineers Construction Engineering Research Laboratory
Eduardo	Castillo	University of Central Florida

First Name	***Last Name***	***Organization***
K.	Chandrashekhara	Missouri University of Science and Technology
Yanling	Chang	Texas A&M University
An	Chen	Iowa State University
Changqing	Cheng	Binghamton University
Huanyu	Cheng	Pennsylvania State University
Nancy	Cheng	University of Oregon
Patricia	Clayton	University of Texas at Austin
Eric	Compton	Genesis Dimensions, LLC
Khershed	Cooper	National Science Foundation
Denis	Cormier	Rochester Institute of Technology
Jason	Cotrell	RCAM Technologies
Steve	Cranford	Northeastern University
Qingli	Dai	Michigan Technological University
Nicholas	D'Angelo	Lehigh University
Edward	Davis	Auburn University
Karnika	De Silva	University of Auckland, New Zealand
Manish	Dixit	Texas A&M University
Mo	Ehsani	QuakeWrap, Inc.
Mohamed	ElGawady	Missouri University of Science and Technology
Alaa	Elwany	Texas A&M University
Yaghoob	Farnam	Drexel University
Chiara	Ferraris	National Institute of Standards and Technology
Evgueni	Filipov	University of Michigan
Simon	Fraser	Victoria University of Wellington, New Zealand
Matthew	Friedell	U.S. Marine Corps / DoD
Andre	Fuqua	Columbia University

First Name	***Last Name***	***Organization***
Yong	Gan	Cal Poly Pomona
Xin-Lin	Gao	Southern Methodist University
Frank	Gayle	National Institute of Standards and Technology
Ali	Ghahremaninezhad	University of Miami
Deborah	Goodings	National Science Foundation
Rob	Gorham	America Makes
Brennan	Grignon	Department of Defense
Qiang	Gui	University of Tennessee Knoxville
Gary	Halada	Stony Brook University
Suyun	Ham	University of Texas at Arlington
Julie	Hammett	Texas A&M University
Christopher	Hansen	University of Massachusetts Lowell
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Weiling	He	College of Architecture, Texas A&M University
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