Infrastructure Scale Additive Manufacturing

Oak Ridge National Laboratory
FY19-FY21

Dr. Brian K. Post, Oak Ridge National Laboratory

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Overview

Project Title: Infrastructure Scale Additive Manufacturing

Timeline:

Project Start Date: 10/01/2019

Budget Period End Date: 09/30/2019

Project End Date: 09/30/2021

Barriers and Challenges:

- Very little automation exists in current construction practices
- Current AM systems are not scalable or adaptable to onsite construction without significant site preparation
- Limitations in control of existing AM systems are not expandable to extremely large workspaces
- Significant site preparation is required with most proposed on site construction AM systems
- Scalable solutions are required to enable construction of different structures
- New materials are required to enable the AM of concrete in the field; print dynamics, set dynamics, and structural performance must be understood

AMO MYPP Connection:

- Advanced Materials Manufacturing
- Additive Manufacturing

Project Budget and Costs:

Budget	DOE Share	Cost Share	Total	Cost Share %
Overall Budget	$6,000,000	$1,200,000	$7,200,000	20%
Approved Budget (BP-1&2)	$1,224,375	TBD	$1,029,122	TBD
Costs as of 4/30/19	$1,046,466	TBD	$1,046,466	TBD

Project Team and Roles:

- **Brian Post** – Robotics and Control Systems, Program Lead
- **Phillip Chesser** – Mechanical Design Engineer
- **Randall Lind** – Machine Design Expert
- **Alex Roschli** – Toolpath Planning for AM
- **Catherine Mattus** – Concrete Chemist
- **Yann Lepape** – Structural Concrete Analysis
- **Elena Tajuelo-Rodriguez** – Advanced Concrete Characterization
- **Charles Carnal** – Controls Engineer
- **Peter Lloyd** – Elecrical Design Engineer

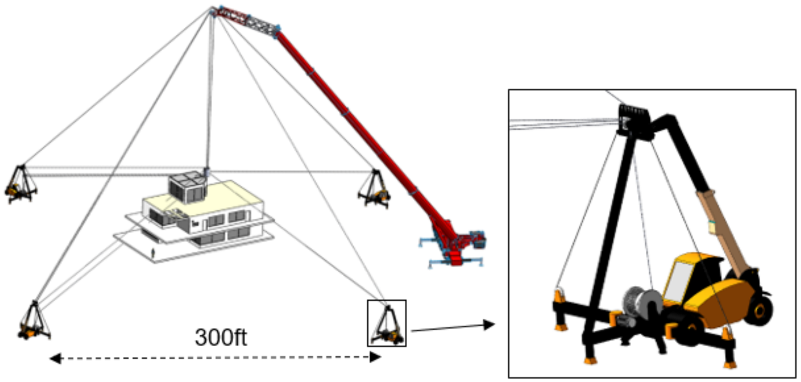
Project Objective(s)

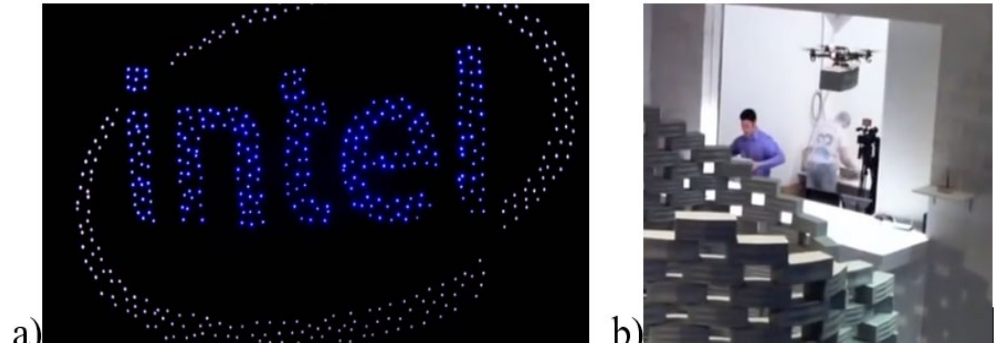
- Construction is the United State's largest single industry ($1.5T)
- 534 million tons of construction debris are created through traditional construction practices (2x all other municipal waste)
- Construction is responsible for $1/5^{th}$ of all workplace fatalities
- AM has been shown to improve the quality, reduce human errors, and material waste
- Structural optimization and robotic precision can improve the structural performance of structures using less material when compared to cast-in-place concrete
- Cable driven robots offer large workspaces without the erection of very large gantry systems
- **Objective:** To dramatically expand the scale and portability of AM systems that are capable of processing low-cost material so that the construction industry can access the benefits of AM.

Technical Innovation

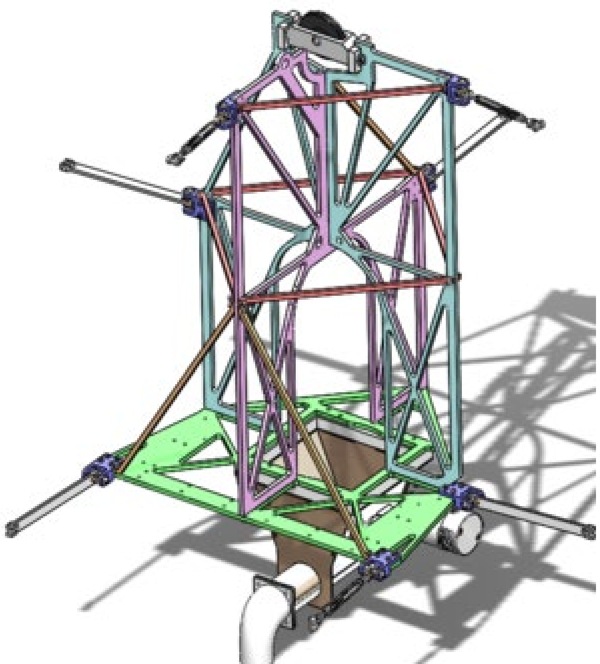
- Current construction practices are wasteful and inefficient
- New additive manufacturing system will enable rapidly fieldable (set up in under 1 hour) AM of building structures with concrete materials
- Development of new materials will enable the greater construction industry to employ this process with numerous solutions in system architectures, i.e. gantry systems, mobile robots, and macro/micro manipulators
- Novel cable arrangement offers a distinct advantage in in-plane stiffness (important for AM) when compared with traditional cable driven robots
- Early investigation of multi-agent systems impacts and potential offer high-risk & high-reward opportunities to enable massively parallel, unbounded AM on site for large infrastructure scale structures (e.g. bridges, dams, wind towers, etc.)

Technical Approach





Inspirations for multi-agent AM approaches



Design concepts for a cable driven large format AM system for the production of construction scale structures

Materials Development: Development of extrudable thixotropic concrete materials which exhibit sufficient structural performance and processing characteristics which are beneficial for system performance (i.e. low slump, pumpable, quick set time, high early strength)

Robotic Systems Development: Development of a novel cable driven motion platform for accurate placement of concrete materials. Inverse kinematics derived for rapid calibration and stiffness analysis to influence controls development.

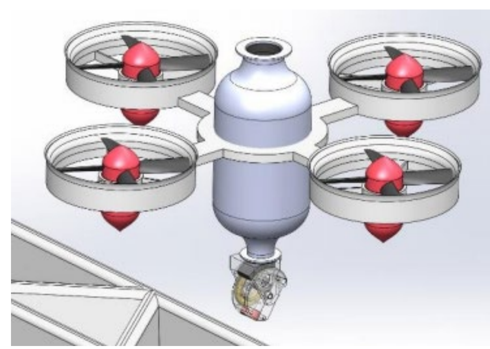
Deposition System Development: Development of equipment necessary to process materials and form geometry conducive to the large format AM process (i.e. metering pump, orientable nozzles, and set accelerant pumps)

Multi-Agent Strategies: Investigate the efficacy of multi-agent approaches to infrastructure scale AM

Results and Accomplishments

- Literature review of cable driven robots, concrete 3D printing, and multi-agent printing completed
- Complete dynamic model of system enables stiffness evaluation of mid scale and full scale system performance
- Mid-scale research robotic positioning testbed has been designed, fabricated and tested (SkyBAAM)
- Extrusion head (metering pump) concepts have been fabricated and tested
- Approaches for closed loop end effector error compensation have been developed
- Orientable nozzle developed and fabricated to improve surface finish and deposition accuracy
- Continuous mixing and pumping strategies have been evaluated for delivering material to the extrusion head
- Concepts for multi-agent drone jetting strategies have been developed
- Deposition of a large object >9000lb completed in March of 2019






Concepts and hardware have been developed to evaluate the efficacy of low cost AM for the construction of infrastructure scale structures

Results and Accomplishments

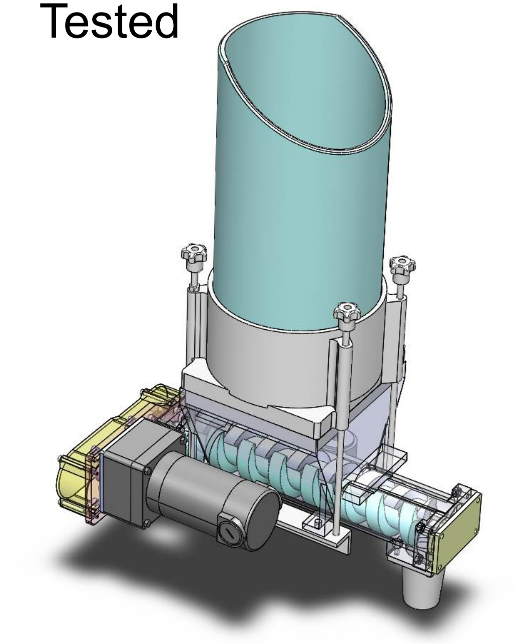
- Development of concrete materials to satisfy performance constraints:
- UHPC
- Materials:
  - Sand – Fine, med, coarse
  - Type III Cement (fast cure)
  - Blast Furnace Slag
  - Silica Fume
  - High-range Water Reducing Agents
  - Steel Fiber, Set Accelerators, Internal Curing Agents tested

Materials (kg/m3)	1000 kg	kg/m3	$/kg	$/m3	$/m3	$/m3	$/m3
Cost Portand cement	216.1	**566**	0.075	42.47	42.47	42.47	42.47
Cost BFS	108	**283**	0.0625	17.69	17.69	17.69	17.69
Cost Silica fumes	36	**94**	0.250	23.58	23.58	23.58	23.58
Cost sand	540.6	**1416**	0.005	7.08	7.08	7.08	7.08
cost steel fibers			3.854	151.09	302.17	453.255	604.340
steel vol%				**0.5**	**1**	**1.5**	**2**
cost HWRA	1.93	**5.06**	3.99	20.16	20.16	20.16	20.16
cost water (free)	97.3	**255**					
Total Wt (kg)	999.93	**2620**					
total vol m3 =	0.381653	**1**					
			Cost $/m3	262	413	564	715

Results and Accomplishments

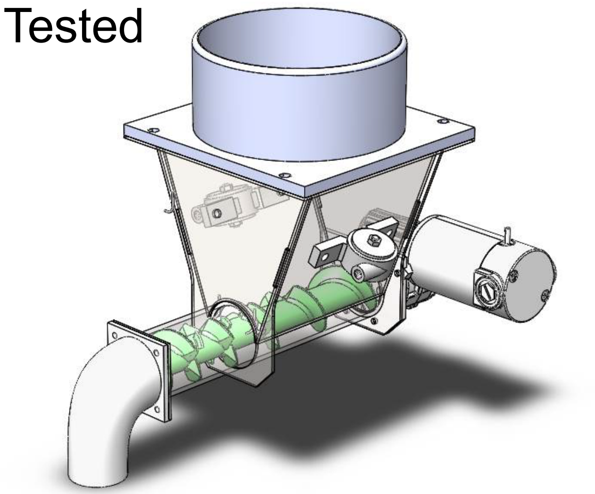
- Development of concrete metering extruders for precision deposition

Fabricated and Tested



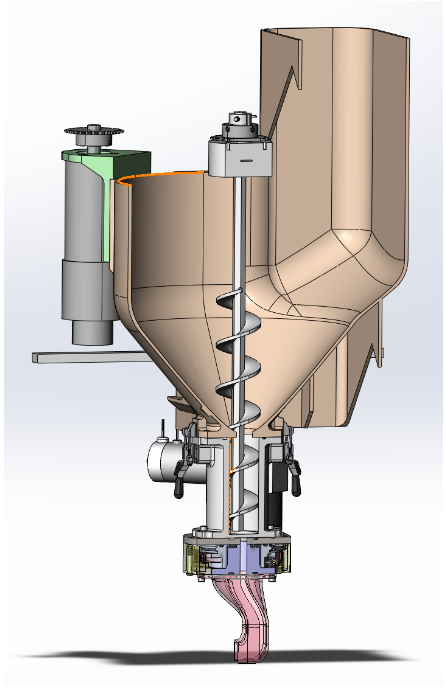
Twin Screw
- Positive Displacement
- <1mm aggregate

Fabricated and Tested



Single Screw
- < 4mm aggregate

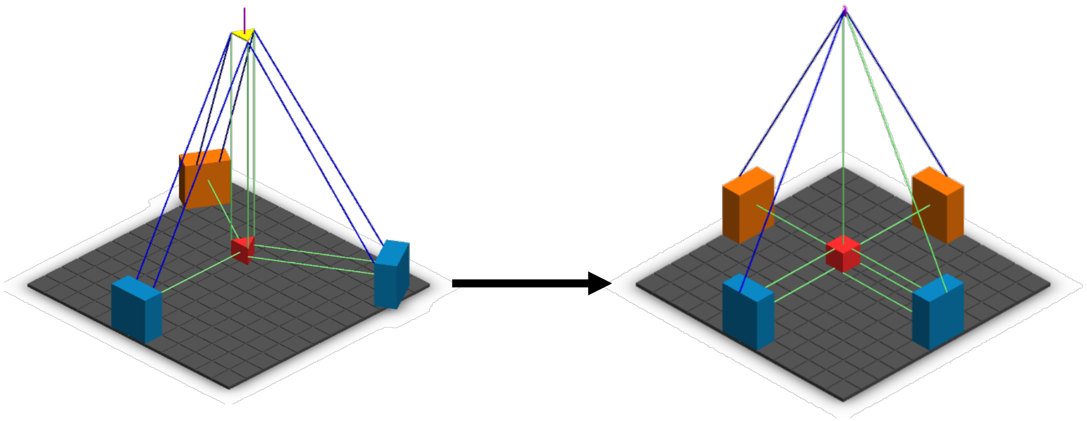
In Fabrication



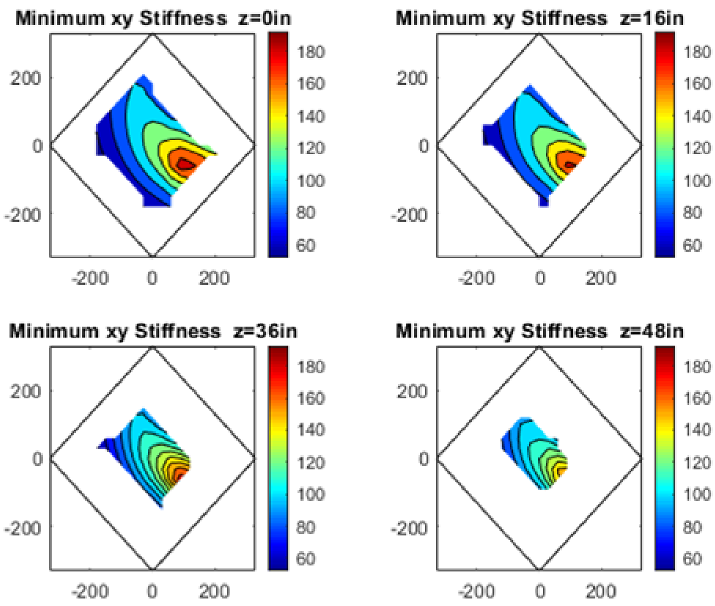
Vertical Extruder
- < 4mm aggregate
- Rotary Nozzle

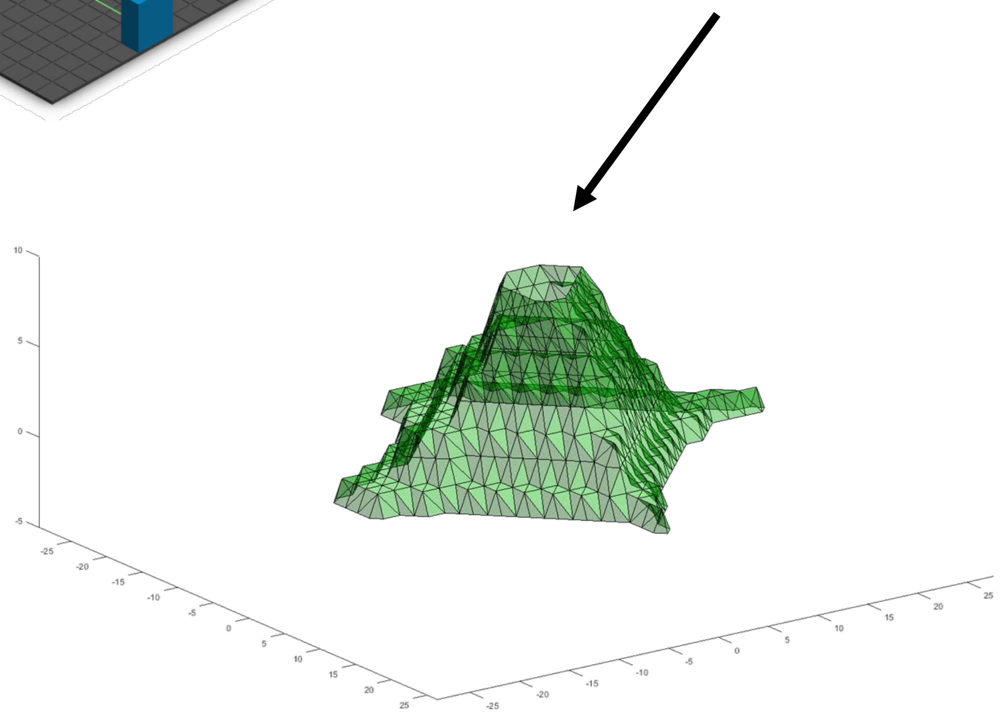
Results and Accomplishments

- Development of mathematical models for analyzing operational stiffness and workspace



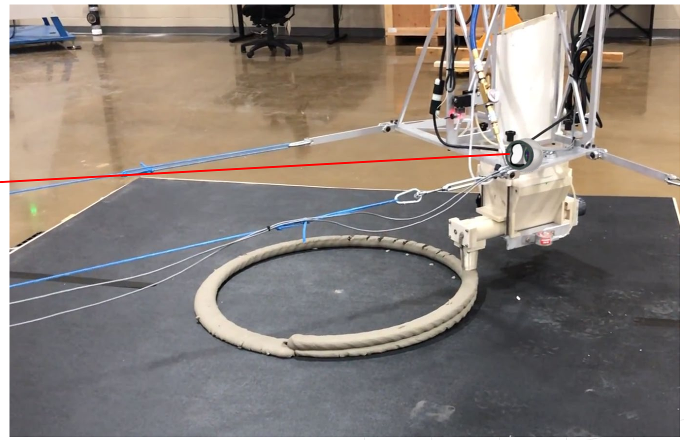
Printable Workspace:
- All Cables in Tension
- Optimal In-Plane Stiffness
- High Degree of Manipulator Dexterity



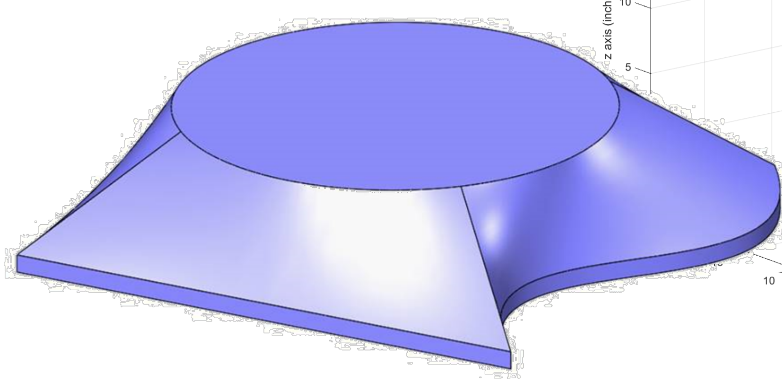


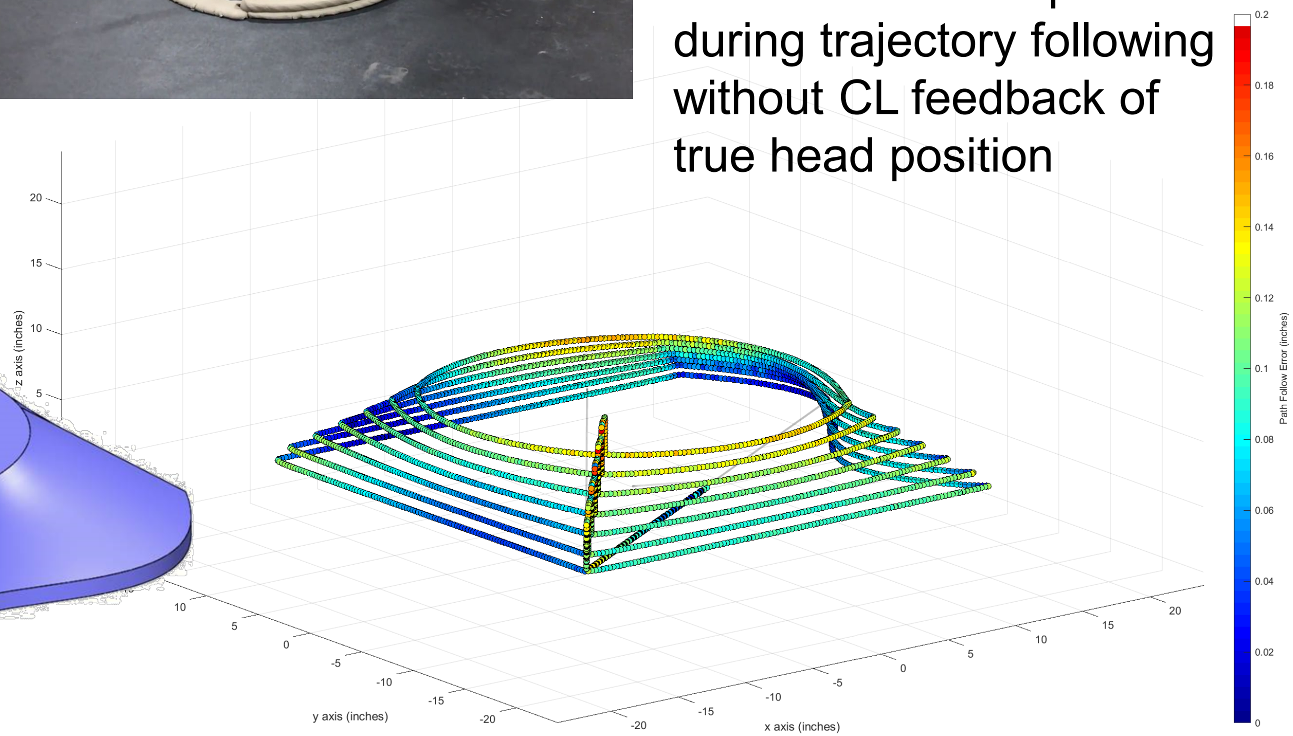
Results and Accomplishments

- Evaluation of dynamic positional accuracy



<0.2in max error over most of the workspace during trajectory following without CL feedback of true head position





Results and Accomplishments

Transition (beyond DOE assistance)

- Commercialization by industrial partner for system development
  - **Oshkosh Truck** – Commercialization of the SkyBAAM system (current active CRADA for extrusion head development)
  - **GE Renewables** – Commercialization of application in on site wind tower manufacturing, i.e. printing pedestals to enable tall wind and lessen transportation logistics and cost (current Active CRADA)
  - **Quikrete** – development of materials for AM which could be distributed nationwide to all 130 production plants to enable the AM construction industry (Developing CRADA proposal)
- DOD – US Army Corp of Engineers and Marine Corps are actively pursuing AM to solve logistics challenges in forward deployed applications (Barracks and Bridges, etc.)
- NASA – The NASA Habitat challenge continues to be the largest funding source for concrete AM. Their aim is to solve the colonization challenge for the moon and mars using locally sourced materials