Solid Freeform Fabrication 2019: Proceedings of the 30th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

SKYBAAM LARGE-SCALE FIELDABLE DEPOSITION PLATFORM SYSTEM ARCHITECTURE

Phillip Chesser*, Brian Post*, Randy Lind*, Alex Roschli*, Celeste Atkins*, Alex Boulger*, Paritosh Mhatre*, Pete Lloyd*

*Oak Ridge National Laboratory, Manufacturing Demonstration Facility, 2350 Cherahala Blvd, Knoxville, TN 37932

Abstract

Oak Ridge National Laboratory (ORNL) is currently developing a concrete deposition system for infrastructure-scale printed objects. This system, called SkyBAAM, uses a cable driven motion platform to manipulate the print head. This work focuses on the general aspects of the system architecture, including arrangement of the cable driven platform, general high-level control methodology, and system accuracy, along with concrete deposition methods. Results and demonstration prints will be shown.

Introduction

From the early days of additive manufacturing, visionaries have dreamed of using additive techniques to revolutionize the construction industry by direct printing of buildings and other infrastructure [1] [2]. This has been a popular topic of research in recent years. Oak Ridge National Laboratory (ORNL) has been developing a novel, fieldable system for research in large-scale concrete deposition [3]. This system has been named Sky Big Area Additive Manufacturing, or SkyBAAM.

SkyBAAM is a cable driven motion platform designed for fieldable additive manufacturing (AM) at large scales. A cable driven system has several advantages over a traditional gantry motion platform for this type of scenario. These have been examined in detail in [3]. In summary, large gantries are expensive, difficult to transport and require a high degree of site preparation. On the other hand, SkyBAAM as a cable driven robot has a compact mechanical footprint relative to its build volume, thus it is cheaper and easier to transport than a gantry. It also requires less site preparation and can even operate on non-level ground. This paper will look at the prototype system that has been developed at ORNL. This is an evolving system as research is ongoing.

SkyBAAM System Overview

SkyBAAM is a cable driven parallel manipulator (CDPM). This means that the end effector, or print head, is connected to some number of cables that are wound on fixed cable winders. By paying cable in and out on these winders, the print head can be manipulated through space. A schematic of this is shown in Figure 1. On SkyBAAM there are 8 cables; 6 that control

This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

motion and 2 that keep the system under tension. The exact configuration of these cables is shown in Figure 2. The motion control cables come from the blue base stations, and the tension cables come from the orange stations. One of the motion cables goes over a pulley to provide motion in the vertical dimension. This elevated pulley is held up by a crane or other vertical force. A detailed explanation of the reasoning behind this configuration is presented in [3].

The motion control cables control pseudo x, y and z directions. In actuality, the motion in x, y and z are coupled. However, for the sake of terminology, the cables that are nearest to being parallel with the x direction are termed the x-cables, the cables that are nearest to being parallel with the y direction are termed the y-cables, and the vertical cable is termed the z-cable.

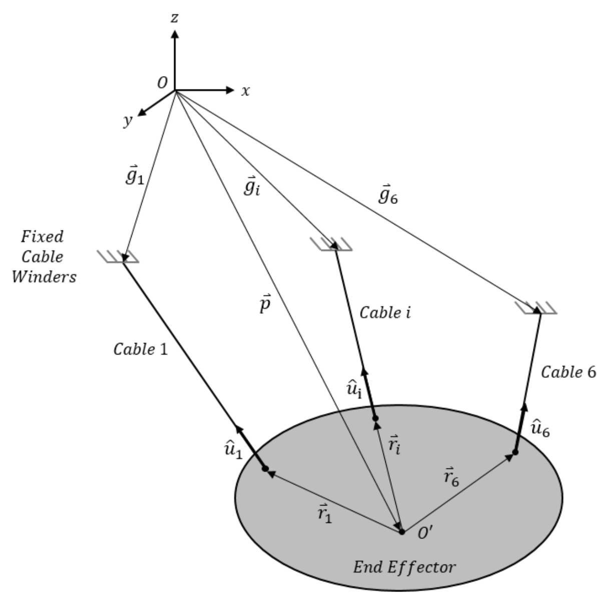

Figure 1. Cable Schematic.

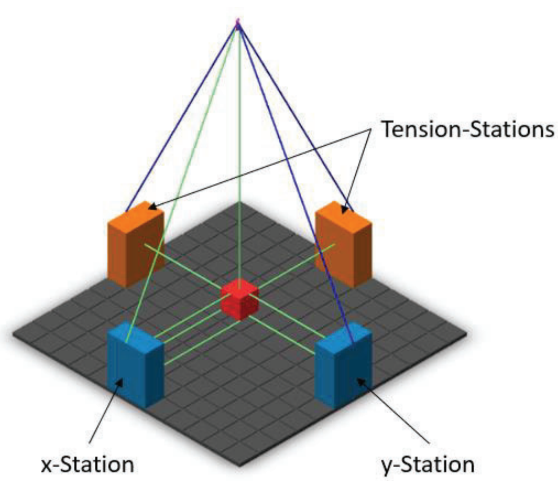

Figure 2. Cable Configuration.

Prototype System at ORNL

A prototype SkyBAAM system has been developed and tested at ORNL. It was designed and built in-house from the ground up. This system has a footprint of roughly 25 feet square and can print objects with a nominal diameter of 10 feet. Due to the flexible nature of the system, exact dimensions of the system and the parts it can print will vary some depending on the placement of the base stations and the height of the crane. It is envisioned that future full-scale system would be able to print objects with a major dimension of 100 feet or larger.

The system is comprised of four base stations, one of which is shown in Figure 3. One base station controls motion in the x direction, one controls motion in the y and z directions, and two control the tension of the system. There is also an apex block that contains the pulley for the z motion. The apex is held up by a crane. This is shown in Figure 4. The total system is shown in Figure 5. The end effector, or print head, can be more clearly seen in Figure 6.

Each motion direction is controlled by a servo motor driven winder drum. Cable is wound onto and off of this drum to control the end effector position. Some of the motion directions have more than one cable that are wound in sync with each other. To do this, multiple cables are wound on the same drum. There are 3 x-cables that are wound together and 2 y-cables that are wound together. There is only one vertical z-cable.

When initially set up, the system used braided Dyneema rope for the cables. Later these were replaced by 7x19 steel wire rope on the motion cables. This was done to achieve a higher stiffness. The tension cables ideally should have a low stiffness, so these were replaced with a low stiffness braided nylon rope.

To calibrate the system, the location of all the base stations and the apex must be measured accurately. This is achieved with a Leica AT960 laser tracker. These measurements are then used in the inverse kinematics to determine the required length of the cables for a given end effector location.

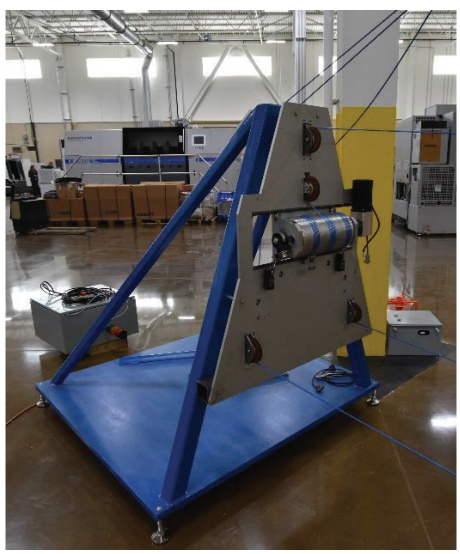

Figure 3. Base Station.

Figure 4. Apex

Figure 5. SkyBAAM System

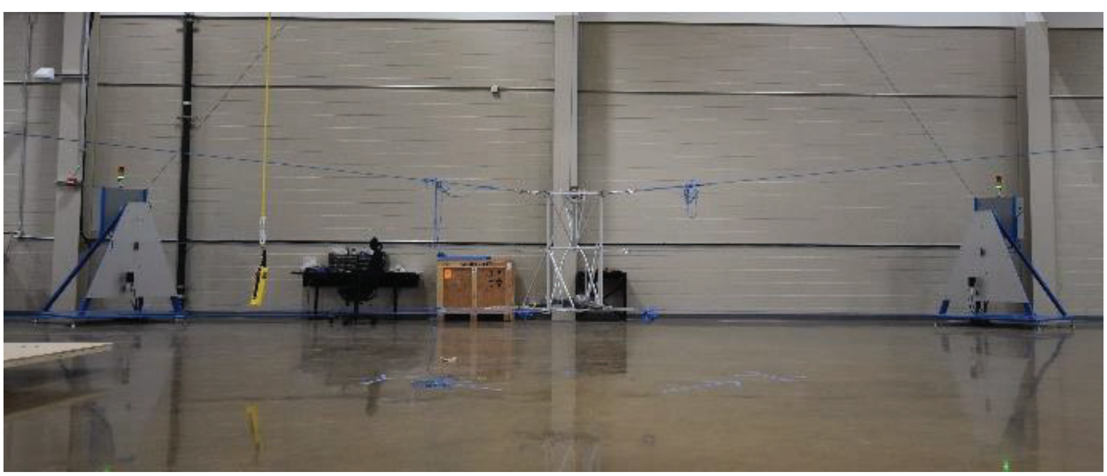

Figure 6. SkyBAAM End Effector

Control Methodology and System Accuracy

The system is run from g-code, as is typical for AM machines and other computer numerically controlled (CNC) machines. A control diagram for the motion control is shown in Figure 7. The g-code is fed into a trajectory planner, which determines an acceleration-limited path for the end effector. The points on this path are then fed into the inverse kinematics for the system. The inverse kinematics determines the length of the x, y and z cables for a given end effector position. These lengths correspond to a position of the x, y and z winding drums. These positions are then used in a feed forward control loop on the drum position. Control of the tension cables is done in a similar manner, but force is being controlled and not position.

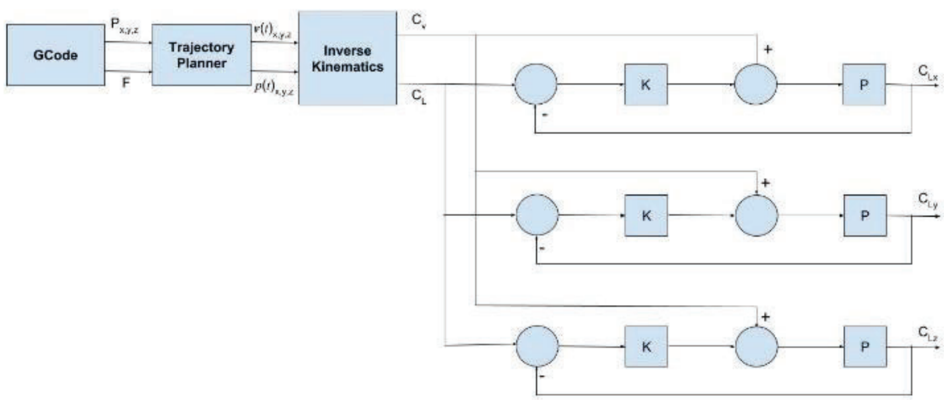

Figure 7. Motion Control Loop.

Currently the system is being run with the end effector position in open loop. In other words, there is no active measuring of the end effector position for control purposes. The winding drum locations are controlled closed loop, but downstream of the drum location there is nothing to correct for error in the system.

With Dyneema cables on the system, the open loop accuracy of the system was measured. An object with straight and curved lines was drawn in the air with the end effector. While doing this, the end effector position was measure with the Leica AT960 laser tracker. This was used to determine path following error over the object. This data is plotted in figure 8.

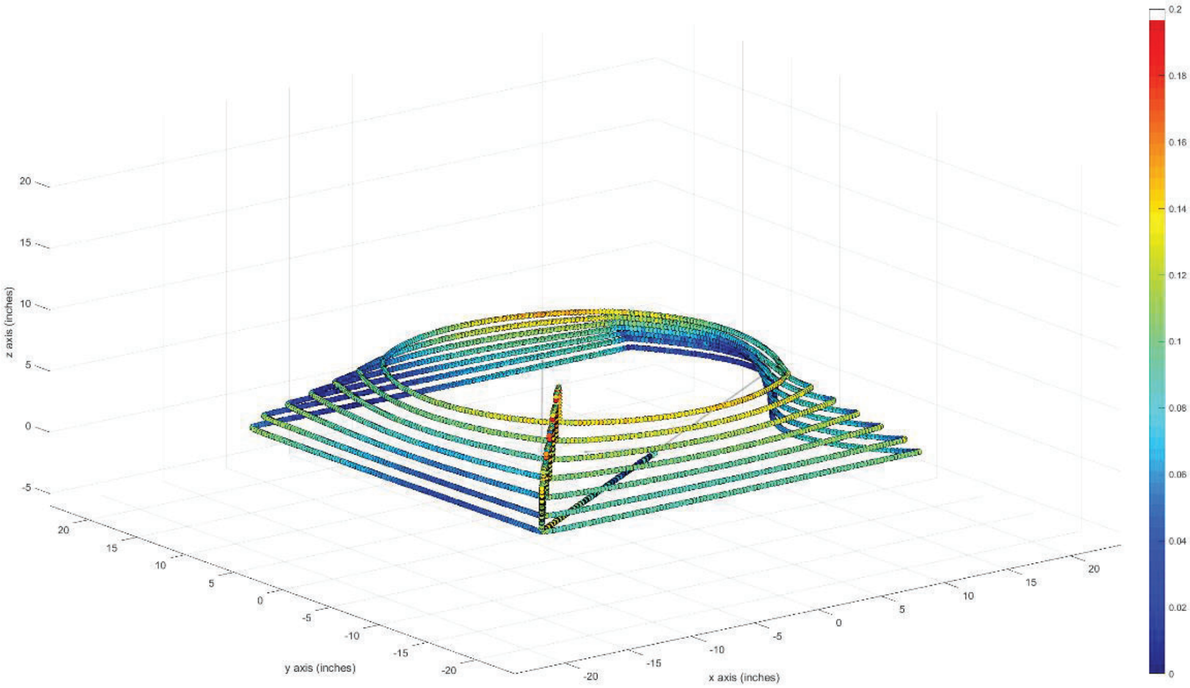

Figure 8. Path Following Error.

Most of the measured error was less than 1/8th of an inch. These measurements were taking in the center of the workspace, and more work is needed to characterize error over the whole workspace. While this is much more error than most AM systems can tolerate, the tolerance requirements for a construction system are not as stringent, and this would be acceptable for some applications. However, future work will encompass using the Leica laser tracker to provide feedback to close the loop on end effector position. This should dramatically improve system accuracy. However, there are challenges to overcome because it will be non-co-located feedback due to the coupled nature of the system.

Concrete Extrusion

In addition to the motion platform, deposition hardware is also being developed. Several concrete extruders were developed. Both augers and positive displacement pumping schemes were used on different designs. Target deposition rate for this system is 2.5 cubic yards per hour with a bead width of 2 inches and a layer height of 1 inch. Figure 9 shows CAD models of two of these designs. One of these is a single crew auger feed and the other is a twin-screw positive displacement feed. The twin screw positive displacement extruder is shown on the SkyBAAM printhead in Figure 10.

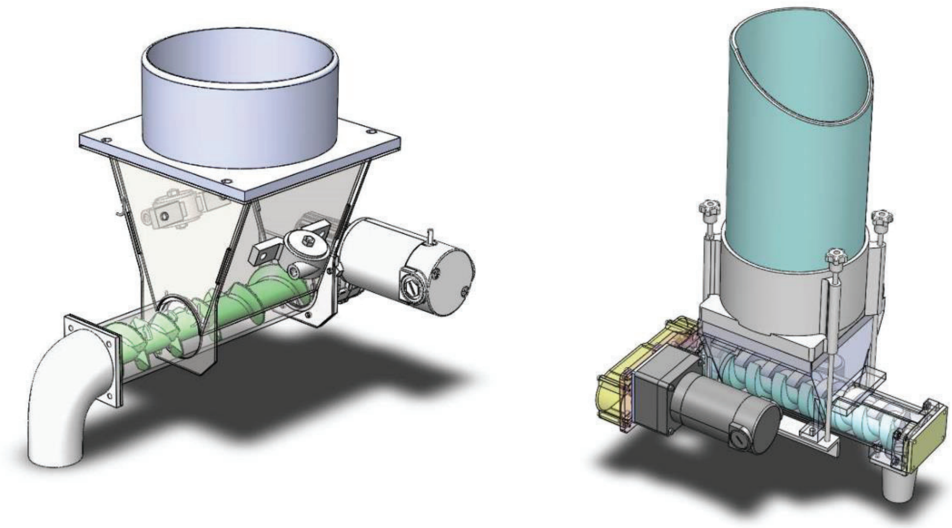

Figure 9. Single-screw extruder design (left) and twin-screw extruder design (right)

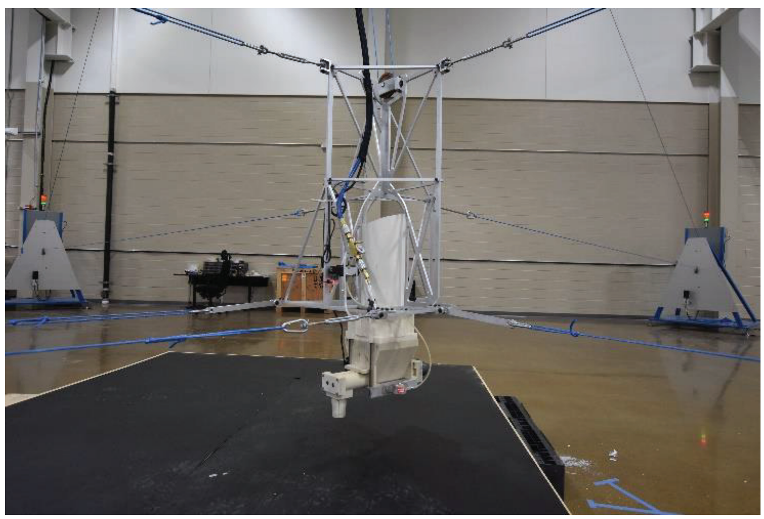

Figure 10. Twin Screw Extruder on SkyBAAM.

After testing the different extruder designs, it was determined that a single screw auger is the best rout because this type of extruder can handle larger aggregate in the concrete than the positive displacement type extruders. Using this method, a more robust extruder with a single vertical auger is currently being fabricated. A CAD image of this extruder on the SkyBAAM printhead is shown in Figure 11.

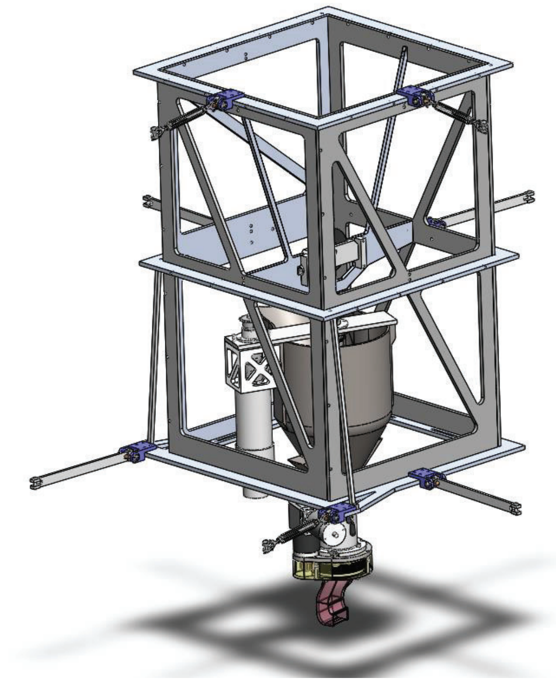

Figure 11. Vertical Single Screw Extruder Design.

SkyBAAM Prints

The first successful print on the SkyBAAM system at ORNL was done on December 14, 2018. This was an eight-layer circle, shown in Figure 12. More objects were printed to calibrate extruder flowrate and improve consistency, and these are shown in Figure 13. The largest object printed to date on SkyBAAM is shown in Figure 14. This print was done over three days.

Figure 12. The first test print of the SkyBAAM system: an eight-layer circle

Figure 13. Concrete bead calibration square (left) and ‘MDF’ printed out of concrete using the SkyBAAM system (right)

Figure 14. Largest Print to Date.

The quality on the last print varies throughout the print because it was difficult to maintain a consistent concrete mix that would give a consistent deposition rate. Future research will include materials research to improve material quality and consistence. This will include not only material development, but also development of mixing hardware.

Conclusion

ORNL has developed a prototype system of a large-scale cable driven platform for AM of infrastructure-scale parts. The prototype system was designed and built at ORNL. This system demonstrates successful printing of concrete from a cable driven motion platform. Future research will work to improve the accuracy of the system, the deposition hardware, and materials development. The aim of this system and the ongoing work is to pave a path to a full-scale cable driven system for AM of large concrete structures.

Acknowledgement

This material is based upon work supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Office of Advanced Manufacturing, under contract number DE-AC05-00OR22725.

References

[1] Lind R. Automated Freeform Construction. In *Proceedings of Solid Freeform Fabrication Symposium*, presentation. Austin, Texas, U.S.A, 2009.

[2] Buswell R. et al. Freeform Construction: Mega-scale Rapid Manufacturing for Construction, Automation in Construction, pages 224-231, volume 16, issue 2, 2007.

[3] Chesser P. et al. Fieldable Platform for Large-Scale Deposition of Concrete Structures. In *Proceedings of Solid Freeform Fabrication Symposium,* Austin, Texas, U.S.A., 2018.