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FIELDABLE PLATFORM FOR LARGE-SCALE DEPOSITION OF CONCRETE STRUCTURES

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Abstract

Oak Ridge National Laboratory's Manufacturing Demonstration Facility is developing a novel, large-scale additive manufacturing, or 3D printing, system. The Sky Big Area Additive Manufacturing (SkyBAAM) system will ultimately be a fieldable concrete deposition machine with pick and place abilities that will allow for full-scale, automated construction of buildings. The system will be implemented with existing construction equipment meaning conventional cranes will be used to suspend the print head. SkyBAAM will be cable-driven by four base stations and suspended from a single crane. The elimination of a gantry system, found commonly in large-scale additive manufacturing systems, will enable SkyBAAM to be quickly set up with minimal site preparation. The medium-scale version of SkyBAAM is currently in development. The system design, cable stiffness analysis, and tactics for freezing rotational degrees-of-freedom (DOF), detailed in this paper, will provide a basis for the final, large-scale version of the SkyBAAM system.

Introduction

Additive manufacturing (AM) has the potential to revolutionize and revitalize American manufacturing. Most conventional methods of AM are currently only practical to produce small, high-value, and low-volume components. This leads to applications such as aerospace and biomedical. More recently, AM has been used to fabricate tooling for a broad range of applications. [1] This includes tooling for automotive and other high-volume applications.

However, this scope excludes one of the largest sectors of the U.S. economy, namely the construction industry. New construction in the U.S. is projected to grow to $1.4 trillion by the year 2021. [2] This is roughly 6% of the U.S.'s gross domestic product (GDP). AM fabrication of structures or buildings has the potential to revolutionize this market, saving labor and material cost and shortening construction time.

The idea of AM for construction has been around for decades; although, it is currently far from becoming a real-world application. In the framework presented below, structures are deposited by an extruder, one layer at a time, with a highly-viscous, low-slump concrete. This eliminates the need for costly formwork. Ideally, as the building is deposited, pick and place systems will lay components for the plumbing and electrical systems of the building in channels

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that have been left for this purpose. Rebar and other reinforcing components can also be laid in with pick and place systems. Without the need for formwork, new geometries, impossible with conventional methods, can be realized. This makes new, energy-efficient structures possible.

Construction waste reduction is also a possibility with AM. Waste from new construction in the U.S. in 2014 was 28.9 million tons. [3] With AM, material is only placed where it is needed; therefore, AM is inherently low waste. There is no need for traditional cutting or machining of stock parts and throwing out the waste. There is also no need for temporary structures, such as formwork, that are later discarded. Large-scale penetration of AM into the construction industry has the potential to greatly reduce construction waste.

The end vision for construction-scale AM is grand. It is easy to envision energy efficient [4], aesthetically pleasing buildings constructed with less waste using automated processes that reduce labor. The potential effect on the economy could be profound. Take the following example. Currently, houses cost more than the average yearly income of the residents who buy them. Yet automobiles, which are massively more complex than houses, cost only around a tenth of what housing costs. Part of the reason for this is that automobiles are produced with the benefits of large-scale automation. This is not true with construction, which is a manual, labor intensive industry. The application of automation to construction through AM has the potential to make housing drastically more affordable. Similar benefits could be seen with commercial construction, where lower building costs could lead to increased ease of expansion of businesses and the creation of jobs. Unfortunately, the realization of this vision is still a long way off and requires much more research.

Research on concrete AM started as early as the 1990s; although, the idea was not widely accepted. Randall Lind, a researcher at Oak Ridge National Laboratory (ORNL), first recorded the idea in 1993, and presented work in this field in 2009. [5] Several years after Lind's initial conception of the idea, Khoshnevis [6] started work on what is now known as Contour Crafting.

In recent years, concrete AM has been gaining traction, and there have been continued advances in this field, including advances in materials and extrusion techniques. However, concrete AM is still mostly explored and used in a laboratory setting and has not been seen in industry. Unfortunately, the scale necessary for effective use in construction remains elusive. A large reason for this is because motion platforms used for deposition are highly inadequate for the needs of the construction industry, as will be explored below. This paper aims to examine the possibility of using cable-driven robots for deposition of concrete in the construction industry as a means of making concrete AM a commercially feasible process.

State of the Art: Problems and Alternatives

As mentioned above, work on concrete AM for construction is not new. In fact, there is much prior work in the field. This will be briefly surveyed. However, there is a significant lack of solutions that are practical for use on a real-world jobsite.

Current Additive Manufacturing of Concrete Structures

AM of concrete for construction has been a popular area of research in recent years because this process promises to benefit the construction industry in many ways. Biernacki et. al. have explored some of these possible benefits, such as safety, efficiency, and the ability to fabricate new types of structures. [7] Khoshnevis and the Contour Crafting group are old players in the field. [8] They have been successfully 3D printing with concrete for many years and have proposed many applications for the technology. The U.S. Army Corps of Engineers is researching concrete AM as well, with an interest in printing barracks and forward operating bases. [9] Another player in this area is WinSun, a Chinese company that is perusing the commercialization of concrete AM. Their work includes the printing of an office building in Dubai among other projects. The growing number of groups working in the field of concrete AM has been noted by Bos et. al. [10]

Figure 1: a) US - Army Corp of Eng., b) Russia - Apis Cor, c) China – Winsun

Many of the underlying fundamental material and extrusion problems associated with AM of concrete have also been examined. For example, work has been done to study the mechanical properties of additively manufactured cement [11], [12] as well as the printability of different concrete mixes. [13]

The success of many of the players in the concrete AM realm led the authors to conclude that AM of cement structures is a problem that is well on its way to being solved. The big question that remains pertains to the practicality of 3D printing concrete structures. Can concrete AM be effectively implemented on the jobsite? This paper aims to answer that question in the affirmative by presenting a concept for a fieldable deposition platform.

The Impracticality of Gantry Based Deposition for Construction

While the deposition of concrete for AM structures has been effective, concerns arise when considering the current motion platforms within this context. Nearly all material extrusion (ME) AM systems use a gantry-based motion platform, and large-scale systems for deposition of structures are no exception.

Scaling gantry systems to a sufficient size to manufacture buildings while making the systems fieldable creates problems. Gantry systems, when produced on this scale, become expensive. Furthermore, fielding gantry systems is quite difficult. Since the structure is printed within the gantry itself, it must be larger than the structure. For large buildings, this requires very large machinery that must be transported to the jobsite and installed, likely at a very high cost. The time required to set up a gantry on the jobsite would also likely be significant. Once on the jobsite, the gantry would have to be placed on level ground. This limits the terrain a gantry could be deployed on. Even on relatively level ground, there would be an added cost to get the site level within the accuracy required for a gantry system to operate. Overall, there are significant challenges and costs associated with deploying a gantry system to a jobsite.

Cable-Driven Robots

It is desirable to have a fieldable AM system that can be deployed with ease on a jobsite, allowing a structure to be printed on site. Gantry robots are unlikely to provide this at an economical cost for reasons discussed above. Thus, it is desirable to find another type of motion platform that can be used for this application.

Apis Cor has proposed an alternative to a Cartesian gantry-based system by using a polar style robot. [14] This approach has also been used by Neri Oxman's team at MIT. [15] While this eliminates some of the disadvantages of a traditional gantry system, it has fundamental size and stiffness limitations. A good motion system for deposition is still needed.

An alternative solution can be found with cable-driven robots. Cable-driven robots or cable-driven parallel manipulators (CDPMs) are becoming increasingly popular. They provide potentially large workspaces with relatively light equipment. [16] By using cables, workspaces much larger than the machinery itself can be achieved. This is different from gantry robots, where the machinery must be larger than the workspace.

Cable-driven robots have been used in numerous applications. One notable example is the Skycam, which uses cables to suspend a camera over a sports arena and moves the camera to follow play. [17] Full six degree-of-freedom (DOF) robots have also been developed. [18] A notable example is the National Institute of Standards and Technology (NIST) robocrane, [19] which has spawned large area variants. [20] CDPMs have also been used in large telescopes, which further demonstrate the large-scale at which they can be used. [21]

Cable-driven robots are a potentially suitable replacement for very large-scale AM applications for several reasons. Most importantly, they easily achieve large workspaces without requiring massive equipment and machinery. Additionally, cable-driven robots do not require the same level of site preparation as gantry robots. With a CPDM based system, cable winders can be placed at several base stations around the worksite. This would not require leveling of the site and could be implemented on a wider variety of terrain. Furthermore, these base stations would be small in comparison with the workspace, leading to a lower machinery cost for a given build volume. In the remainder of this paper, a scheme for a fieldable, cable-driven robot for large-scale AM is examined.

SkyBAAM Deposition Platform

Sky Big Area Additive Manufacturing (SkyBAAM) is a proposed cable-driven motion platform that is designed specifically around the requirements for the deposition of large-scale AM structures. These specific objectives will the explained below. Large-scale AM with cable-driven platforms is not a new idea. [22] Bruckmann et. al have also proposed laying bricks with cable-based systems [23], while Vukorep has realized a cable-driven system that places foam blocks. [24] However, the SkyBAAM system proposes a radically different cable architecture from these systems. The SkyBAAM cable system is designed to be easily fieldable at a jobsite with as much conventional equipment as possible. The cable architecture was inspired by the Hangprinter created by Torbjørn Ludvigsen. [25] However, the requirements of the SkyBAAM system are different than the Hangprinter, so there have been significant departures from the original Hangprinter.

SkyBAAM Objective

The overall objective of SkyBAAM is to create a cable-driven motion platform that is easily fieldable for the additive manufacturing of large structures. Furthermore, it is also designed to integrate with existing construction equipment. An initial conceptual design is shown in Figure 2.

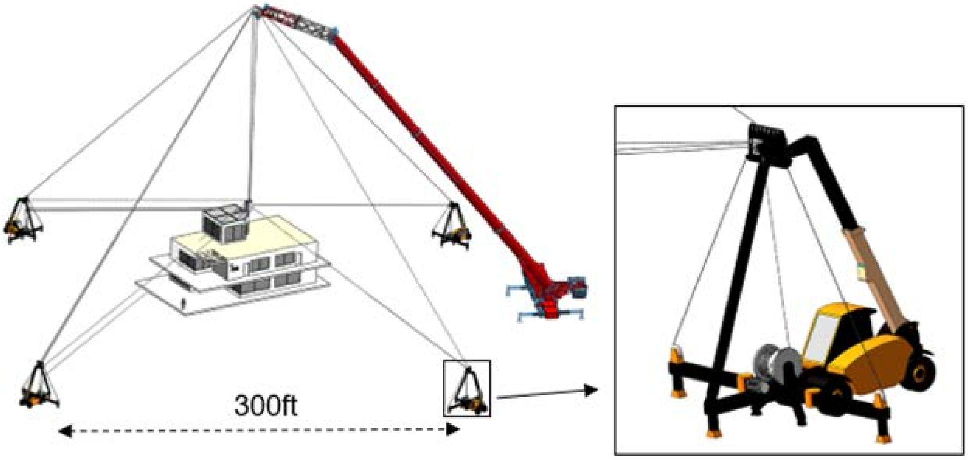

Figure 2: SkyBAAM concept

Single Lift Point

Most cable-driven robots have cable winders at multiple aerial points. In a situation where the robot is permanently installed in a building or high-bay, this is not a problem as these winders can be affixed to a large frame or to the building it is housed by. However, in an outdoor fieldable platform this is less practical. Bruckman et. al. [23] proposed the erection of a large frame around the area where the structure will be fabricated to provide cable attachment points. However, this approach would require significant time and labor to erect a frame that is both large and stiff enough. It is desirable to eliminate the need for such a structure, which increases the ease of fieldability and reduces the amount of time required to set up the system on site.

The best solution is to have a single aerial winding point or platform that can be suspended by a mobile crane. To integrate this system with existing construction equipment, the crane must not be part of the motion system. Instead, it simply acts as a static hoist point for a winder, which is integrated into the motion control. Because the crane merely provides a hoist point for the system, it allows the SkyBAAM system to be integrated with any crane that meets the necessary height and load requirements.

It is also desirable to keep the total number of winders and cable anchor points to a minimum to reduce the number of pieces of equipment required. Furthermore, by concentrating cable winding points and anchor points together, the system can be split into a handful of base stations for deployment in the field. These base stations can be integrated into a truck or trailer that can be driven onto the site.

Constraint and Degrees-of-Freedom

Any object in 3D space has six DOF. To fully constrain the end effector, most cable-driven systems control all six DOF. However, this requires six independently controlled winders. For most AM, only three DOF control is needed. Linear translation is necessary in all three directions, however, the three rotational DOF are not needed. Instead of controlling the rotational DOF, it is more appropriate to fix them and only control the linear translation. This can be achieved, by carefully choosing the cable geometry and controlling multiple cables from one winder. By only controlling the three linear DOF, it is possible to make a simpler system. This, in turn, aids in the ease of fieldability.

Over-constraint is also a problem that must be avoided. If there are more cables than necessary to fully constrain the system, it becomes over-constrained. In an over-constrained system, forces can easily get larger than would otherwise be the case, and the demands on the control system are much greater. Thus, it is desirable to have an exactly constrained system.

Cable Configuration

The cable configuration was chosen to meet the constraints already mentioned. In summary these are:

1. Single aerial winder that can be held by a standard crane
2. Concentrate cable winders and anchor points into several base stations
3. Fully and exactly constrain the end-effector
4. Freeze all rotational DOF

While meeting these requirements, the stiffness of the system must be kept high to maintain good print quality. The importance of high stiffness is addressed in further detail below.

Figure 3 shows the initial cable configuration. The red body represents the print head. Three vertical “z-cables” suspend the print head and control the vertical motion. These three cables all spooled on one winder to ensure their lengths are equal. This keeps the print head from tilting, which fixes two rotational DOF. This winder is located on the yellow platform, which is held up by the crane. Six stay cables, shown in blue, prevent this platform from moving.

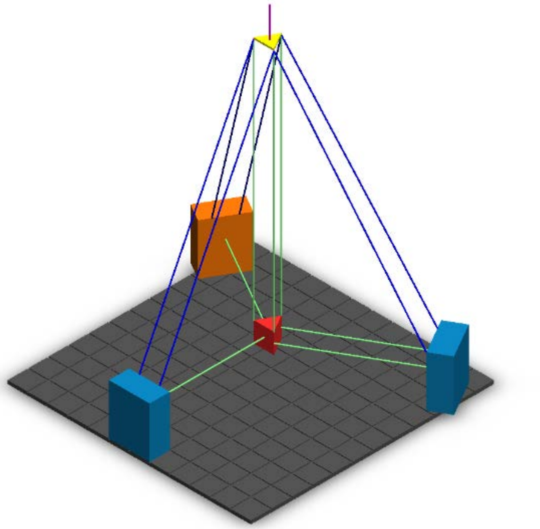

Figure 3: Initial cable configuration for SkyBAAM

Motion in the horizontal plane is controlled by the three cables wound on the blue motion control stations. One of these stations has two equal length cables. This fixes the third rotational DOF.

A cable from the orange station provides tension only. The purpose of this tension cable is to provide a nesting force that keeps all the cables under tension. It does not contribute to the motion. Thus, this extra cable does not cause the system to be over-constrained.

Figure 4 shows the final cable configuration. This configuration has several advantages in comparison to the previous configuration.

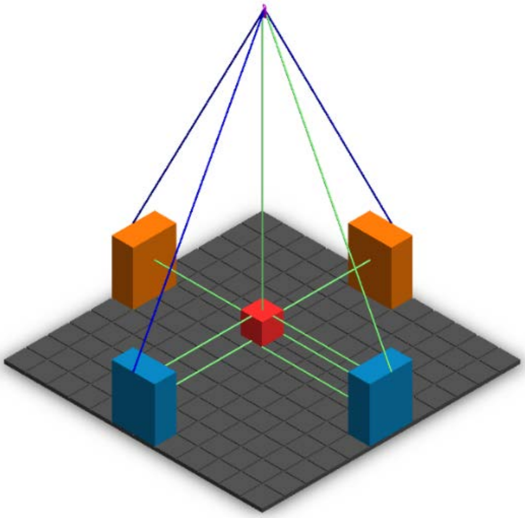

Figure 4: Final cable configuration for SkyBAAM

The two extra cables in the vertical direction in the initial configuration are brought down to the horizontal plane in this configuration. This still freezes all the rotational DOF but offers several more advantages. First, by putting more of the cables in the horizontal plane, the stiffness is increased in the horizontal plane. This does sacrifice some of the vertical stiffness, but the horizontal stiffness is more important in this system because most of the movement will be in the horizontal plane. The only vertical movement will be between layers when the print head is raised by a small increment after each layer.

This change also simplifies the system by eliminating the upper platform. With only one vertical cable, it is possible to run this cable over a pulley and down to a winder located on a ground base station. This pulley is still held up by the crane, but it is possible to hold it stationary with only three stay cables rather than six.

The final change was to add a second cable to provide tension. Both the tension stations are shown in orange in the figure. The net force required to keep the other cables in tension is the vector sum of the tension in these two cables. By adjusting the tension of the two cables, the net tension vector can by adjusted to some degree to optimize the system. The importance of this will be discussed in a later section.

Layout and Deployment in the Field

As noted before, an objective of this system is to be easily fieldable. The four base stations could be contained on individual trailers. These trailers could drive into the correct positions on site. The overhead point can be suspended by a crane. After this, the cables would be attached to the print head, and the machine would go through a calibration routine. Then it would be ready to print.

Material must be delivered to the head during deposition. A simple way to achieve this is to have a hopper on board the print head. This hopper will be periodically refilled as it uses material. This introduces some control challenges because the weight of the print head will be constantly changing. A better possible method would be to continuously supply material to the print head as deposition is taking place. This could be done with a concrete pumping truck. The boom of the pumping truck would extend above the system. A flexible hose would then run all the way from the extended boom to the print head and provide a continuous flow of material for deposition.

Design Challenges

So far, this paper has explained the objective and the general architecture of the SkyBAAM. A scaled-down, operational system is currently in development at ORNL's Manufacturing Demonstration Facility. The remainder of this paper will discuss some of the design challenges that must be addressed to make SkyBAAM a reality. The purpose is not to present a fully-developed design but to examine some of the important challenges and how they are being solved.

Stiffness

A major concern in the design of SkyBAAM is the effective stiffness of the end-effector. The stiffness will affect both the quality of prints and the speed at which deposition can occur. In a stiffer system, the end-effector will deflect less under dynamic loads, leading to a more accurate and repeatable system. Furthermore, a stiffer system leads to higher natural frequencies, which makes control of the system easier.

As mentioned in a previous section, the cable layout of the system was chosen specifically to increase the stiffness of the system in the x-y plane, as this is the plane in which most of the motion occurs.

Stiffness is a driving factor in the design of the whole SkyBAAM system. Not only was the cable configuration selected based on stiffness requirements, but throughout the whole design process, stiffness was a driving consideration.

Cable Selection and Catenary Effects

Cable selection is important for the SkyBAAM because high stiffness is desirable for this system. Cable selection and cable tension play significantly into the stiffness of the system. In selecting a cable and the required tension, the effects of catenary sag must be considered.

A cable span under gravity sags in a well-known and well-studied shape called the catenary. [26] The amount of sag is dependent upon the amount of tension in the cable as well as its weight and length. Catenary effects result in significant non-linearities in the stiffness of cables. [27]

The authors combined the non-linear stiffness produced by catenary sag with the elastic stiffness of the cable to produce a composite stiffness value that is dependent upon cable tension. The mathematical derivation for this will be detailed in a following publication. An example of this for a 17ft long segment of 1/8-inch 7x19 steel wire is plotted in Figure 5.

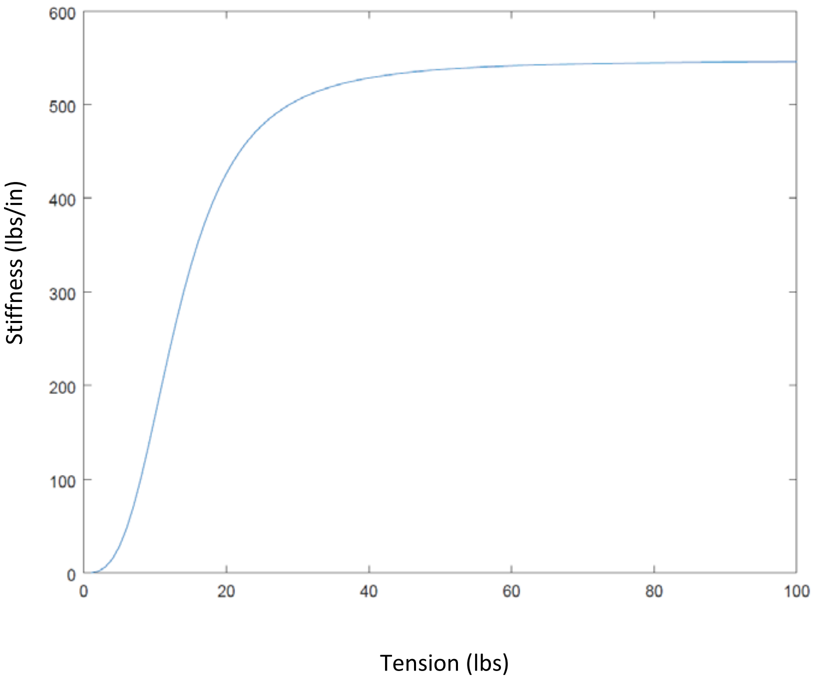

Figure 5. Stiffness of 1/8” 7x19 steel wire rope 17’ long varying with tension

As shown in Figure 5, there is a point where the contribution of the sag to the stiffness becomes negligible, and the stiffness remains essentially constant with increasing tension. This observation is consistent across different cable types and sizes, while the exact shape of the graph changes. This makes it possible to classify cable stiffness into a non-linear range and a linear range.

It is desirable to operate in the linear range for several reasons. First, this is the highest stiffness range of the cable. As stiffness is a priority, this alone provides significant motivation to be in this region. Furthermore, analysis and control of linear systems is significantly easier when compared to non-linear systems. For these reasons, it was decided that the cables of the SkyBAAM should operate in the linear region.

The amount of tension required to reach the linear stiffness region of a cable as well as the value of the stiffness within the linear region are determined by the cable itself. The elastic stiffness, weight, and length of the cable play a significant role in the amount of tension required. To complicate things further, the elastic stiffness of the cable is affected not only by the material, but also by the way the fibers are woven within the cable. The interplay of these factors and their effect on the overall system make the selection of cable an important factor in the system design.

Cable Tensioning Scheme

As mentioned in the previous section, it is important that cables operate within the linear range of stiffness. To achieve this, all the cables must be kept at a certain minimum tension for a given cable type and length.

There are two tensioning cables that keep all the cables in tension. As noted above, this allows for some control of the net tension vector. Tension control in cable-driven robots has been proposed by others. [28] [29] Here, we use the control of tension to keep all the cables above the minimum tension required for operation in their linear stiffness region. However, there is more than one solution that meets this requirement. The set of all possible solutions is found in the null space of the static equilibrium matrix. This method will be detailed in a later paper. Some of the solutions may involve tensions in a few of the cables that are well above the minimum tension. However, it is not desirable to tension cables more than required. This produces no benefit; over-tensioning cables only serves to increase the required motor power and the required strength of the components. Thus, the solution that keeps all the cables above their minimum required tension and has the lowest maximum tension is chosen. The required force in the tensioner cables will vary as the end-effector traverses the workspace.

Motion Tracking

Another important consideration in the design of the SkyBAAM is how to track the location of the end-effector through 3D space. It is also imperative to know the location of the winders to solve the inverse kinematics. Both issues will be addressed with a laser-based time-of-flight sensor. A Leica laser tracker will be used to locate and track the end-effector during deposition. It will also be used to locate the winders and base stations for initial calibration of the system.

In addition to the use of laser-based time-of-flight sensors, the use of relative GPS will be examined. Relative GPS can be used to obtain accurate relative positions but do not require line of sight like a laser-based system would.

System Fabrication & Next Steps

Currently, a detailed design is being completed for a mid-scale SkyBAAM system at ORNL, and fabrication of that system has started. Assembly and testing are currently ongoing over the summer and fall of 2018. There are also plans to design and fabricate a full-scale prototype system with industrial partners that will then be tested in real-world scenarios.

Conclusion

This paper presents the concept for a large-scale, cable-driven system for the deposition of structures from cementitious material. While recognizing the existence of prior art in large-scale AM for construction using cable-driven platforms, this system is designed to be easily fieldable for use on a jobsite. A proposed cable configuration is chosen to achieve this objective, and associated design challenges are examined.

This system is aimed at overcoming one of the major challenges in the AM of structures, namely the current lack of a fieldable motion platform. The development of a practically fieldable platform promises to be another step toward the goal of automated fabrication of structures with AM methods.

The SkyBAAM system has been designed around needs specific to AM in the construction industry. This paper presents the overall design and layout of the SkyBAAM system. Currently, a mid-scale prototype is being designed and built at ORNL. This prototype is the next step toward a full-sized system, which if successful, will be an important step toward realizing practical additive manufacturing of structures.

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