Mud Dauber: Prototype of the Mobile Gantry Architecture

P.J. Staritz[a], J.C. McClurg[a], C.S. Miller[a], M.J. Schlenker[a], S.A. Wozniak[a]

[a] Department of Physics and Engineering, Taylor University, USA
Email: peterstaritz@taylor.edu, josiah_mcclurg@taylor.edu, caleb_miller5@taylor.edu, moriah.schlenker@gmail.com, shanewoz@ymail.com

Abstract

The Mobile Gantry is a robot architecture in which a rail-less gantry rolls directly on the unprepared planetary surface. Mud Dauber is a prototype of this architecture developed to enable testing of the concept and understand the capabilities and limitations of the architecture. This paper describes the major subsystems developed and tested in Mud Dauber: coarse positioning, fine positioning, localization, print head and control.

Keywords

3D Printing; Sulfur Concrete; Mobile Gantry; Robot Architecture; Mars

1 Introduction

Creating a self-sustaining colony on Mars requires the ability to autonomously construct habitable structures using locally available (in-situ) resources. 3D printing is an excellent solution to this problem, and in recent years research into print materials, print techniques, robotic autonomy, and building architectures have examined many aspects of this approach. A growing body of research into robotic 3D-printed construction has primarily explored three robotic architectures: fixed base radial arm, mobile robot and gantry.

In the *fixed base radial arm architecture* [1] a long robotic arm is used to manipulate the print head while the base of the arm remains fixed. Concepts of the type often envision the radial arm mounted to a mobile base to allow the system to move to other locations *between* prints. Because each structure is printed from a single location, the size of the structure is directly related to the size of the robot. The limited reach of this architecture means that the footprint of the printed structures are generally measured in meters and usually self-contained. For example, a winner of the NASA Habitat Challenge, envisions pod-like structures isolated from one another that require pressurized suits when traversing to other habitats. [2]

In the *mobile robot architecture* [3, 4] robots capable of maneuvering during the build process employ shorter, more agile arms to print as they maneuver in and around the structure. This architecture envisions a beehive of activity in which many robots work together to print the structure. In this way, the mobile robot architecture enables much larger and more capable structures. However, this capability comes at a cost, impacting robot control complexity, introducing constraints on habitat design, and requiring frequent recharging. The control complexity is much greater than the other architectures because robots must be able to maneuver within the structure to print internal walls. As a result, mobility paths must be coordinated between robots, and robot manipulator paths must avoid collision with already printed structure and other robots. In addition, because of these various constraints, robots of this architecture cannot ensure continuous extrusions along the print path. This results in frequent discontinuities in the path, which yields a weaker structure and limits the utility of reinforcing fibers. The requirement that the robots must be able to maneuver within the structure also means that the structure must have internal dimensions (doorways, hallways, etc.) large enough to accommodate the robots that are building it. Finally, this architecture requires the robots to be tetherless in order to avoid power cable tangling and damage from other robots rolling over the cables. The need to be tetherless requires portable power sources, for example rechargeable batteries which must be frequently recharged, limiting robot operational time and increasing overall system complexity.

In the *gantry architecture* [5, 6, 7] a single robot, positioned on rails, maneuvers the print head from above, in a manner very similar to a desktop 3D printer. Printing from above, simplifies control and allows for very long continuous print paths. However, only a single robot can work in the workspace at one time, limiting the speed at which large structures can be built. As with the fixed base architecture, the size of the printed structures is directly related to the size of the robot. Thus, the footprint of the building is bounded by the position and length of the rails and the height of the building is bounded by the height of the gantry. When building sequential structures, this architecture requires repositioning of the rails. This repositioning process is complex and would likely require additional robots dedicated to the task.

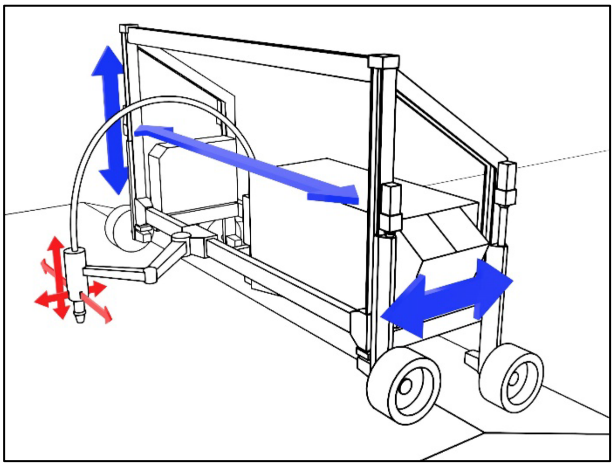

Figure 1. Artist's rendition of the mobile gantry robotic architecture with coarse positioning system (blue) and fine positioning system (red).

This team has developed a hybrid architecture, the *mobile gantry*, which benefits from many of the positive characteristics of the other architectures, eliminates some of the most difficult negative aspects, and introduces new capabilities. The mobile gantry architecture is a gantry without rails. Robots of this architecture maneuver directly on the planetary surface using wheels and can maneuver from print area to print area using their mobility system. During the printing process these robots roll back and forth as though on a set of virtual rails. Figure 1 presents an artist's concept of this architecture. The architecture benefits from simple control and long continuous print paths, enabling the building of structures measuring 10's or even 100's of meters in length. Because robots of this architecture are designed to print while maneuvering on the planetary surface, they are capable of using their printed structures as scaffolding that they can climb using their mobility system. In this way, the mobile gantry architecture is able to build structures taller than the individual robots. Moreover, multiple robots can print on the same structure at the same time, increasing the speed that structures are printed. The paper [8] describes the benefits and tradeoffs of this hybrid architecture in detail. In this work, early prototype results are presented, demonstrating core functionality from the primary subsystems of the Mud Dauber mobile gantry.

2 Mud Dauber Robot

The Mobile Gantry architecture maneuvers directly on the unprepared planetary surface using wheels. To print while moving, these robots isolate the motion of the print head from the motion of the robot body. Large-scale motion is performed using the *coarse positioning system*, consisting of vehicle mobility (X-axis) and two coarse degrees of freedom (Y & Z Axes). The *fine positioning system* is moved in the workspace by the coarse positioning system and provides precision positioning of the print head, allowing it to follow the print path at the required velocity. (Figure 1) A *localization system* is used to measure the print head position in the world frame. The *print head system* enables heating, mixing, and extrusion of a high-quality sulfur concrete slurry. The *control system* commands and coordinates robot actions.

Mud Dauber (Figure 2) is a prototype mobile gantry designed to enable testing of the robotic architecture concept and understand its capabilities. Designed for laboratory testing, it is 2.4m wide, 1.65m tall and 1.75m in length. Through the development of Mud Dauber, the team is developing insights with regard to mobility systems, fine positioning, localization and print head technology.

Figure 2. Mud Dauber is a prototype testbed of the mobile gantry architecture.

2.1 Coarse Positioning System

Mud Dauber's coarse positioning system consists of the robot's frame, wheels and a leg extension module. This system enables the robot to traverse long straight paths in the test area and decouples the length of the building from the size of the robot.

The wheels move the robot along the primary axis of the system (X-axis, see Figure 2) and a leg extension module enables the robot to navigate over obstacles and uneven terrain (Figure 3). This device changes the length of the right rear leg and allows Mud Dauber to bypass obstacles up to 17.5 cm in height. In future iterations of the coarse positioning system the design will include coarse Y and

Z axis degrees of freedom and a leg extension module on each leg. However, to control the scope and cost of this initial prototype these additional degrees of freedom were not implemented.

The addition of Y and Z degrees of freedom will allow the movement of the fine positioning system in 3 axes and enable the printing of structures up to 1.8m wide and 1.3m tall. The addition of the 3 other leg extension modules will allow the traversal of slopes and rough terrain while maintaining the orientation of the robot during printing.

Initial testing of the Mud Dauber has confirmed basic functionality of the coarse positioning system. The robot traverses the X-axis at a maximum velocity of more than 2.5 cm/s. The leg extension module articulates at 0.8 cm/s, can articulate over obstacles and is capable of lifting loads in excess of 110kg. The robot has also demonstrated the ability to climb inclines of more than 25 degrees.

Figure 3. The leg extension mechanism keeps the robot level when traversing obstacles and slopes.

2.2 Fine Positioning System

The fine positioning system isolates the motion of the print head from the coarse motion of the robot. This allows the mobile gantry robot to print precise paths over very long distances. To demonstrate this capability, a 3-axis fine positioning system was developed. This system is capable of moving the print head within a print volume of 30 cm on a side and allows print head positioning to within ±1mm. The system employs an inverted frame that ensures the print head is the lowest component in the print area, preventing collisions with printed structures.

The fine positioning system enables the print head to traverse in all directions at the maximum print velocity of 2.5 cm/s in the world frame regardless of coarse robot motion. This capability allows the robot to position the printing workspace independent of the print head motion, ensuring that the print path remains continuous for the entire printed structure.

Testing of the fine positioning system has confirmed baseline functionality. The X and Y axes traverse at a velocity of more than 5.0 cm/s and with a precision of ±1mm. Z axis motion only occurs during the transition from one printed layer to the next and is limited to 0.1cm/s. The fine positioning system is capable of responding to three-axis position and velocity commands from Mud Dauber's control system.

In future work this version of the fine positioning system will be replaced with a 3 degree of freedom radial manipulator arm. This concept is illustrated in Figure 1 and will enable Mud Dauber to reach in front of and beyond the front wheels of the robot. This capability is critical for the demonstration of self-scaffolding whereby the robot prints the walls of the habitable structure so that it can use the walls as scaffolding. Using this approach, future versions of Mud Dauber will be able to print structures taller than the robot itself.

2.3 Localization System

Because the entire mobile gantry is moving through 3D space, the absolute position of the print head must be determined in the world frame. To enable Mud Dauber to print high quality structures, this system must support an update frequency of at least 30Hz and with an accuracy of 1mm. To accomplish this, a precision wireless localization system is being developed.

In this approach, four transmitters are positioned around the outside of the print envelope at fixed locations in the world frame. Receivers are mounted on the print head and robot frame to provide the position and velocity of both the print head and the robot as a whole. The system measures the distances to the fixed bases and calculates the position and velocity of the robot and print head using multilateration.

Progress has been made on an early low-precision version of the distance estimation using off-the-shelf digital transceivers with wired reference clocks separated by a known phase offset. Additionally, the prototype localization system includes a multilateration estimator running on embedded hardware that is capable of streaming data to Mud Dauber's control system.

In future work, a high-speed wirelessly-synchronized clock reference and a low jitter RF (radio frequency) stack will allow the proposed system to be capable of precise distance measurements at high sample rates.

2.4 Print Head System

Future Martian construction systems will use locally available (in-situ) resources as raw materials. A promising material for 3D printing structures on Mars is sulfur concrete which is made by mixing sulfur and regolith and then heating the mixture above the melting point of sulfur (~113°C). When the slurry cools, the sulfur freezes and acts as a binding agent for the regolith.

Figure 4. The first-generation print head extrudes a mixture of sulfur and sand.

Mud Dauber's print head (Figure 4) is capable of heating, mixing and extruding sulfur concrete. Raw materials are loaded into the mixing hopper (1250 cm^3) where they are heated and mixed. An auger extrudes the slurry through a 2.8cm diameter nozzle at a maximum rate of 18 cm^3/s. The print head is capable of imparting up to 4500W of heat in two independently controllable zones: mixing chamber and extrusion nozzle. Testing has validated mixing performance, extrudate homogeneity, extrusion rates and the impact of extrusion temperature on slump. (Figure 5) These tests revealed problems with the flow of extrudate from the mixing chamber to the extrusion nozzle which is being addressed in a second generation print head.

In future work the print head will be redesigned to enable continuous extrusion, improved efficiency, and better sensing and closed loop control. The new design will allow for continuous operation in which the print head is constantly ingesting, mixing, heating and extruding the sulfur concrete. Eliminating the batch-based design enables continuous extrusions and minimizes discontinuities. The print head will change the heating approach to improve the thermal efficiency of the system and decrease overall print head power consumption. The print head will incorporate improved sensing to allow for higher quality extrusions in a wider range of laboratory conditions.

Figure 5 – Test extrusions from the first-generation print head show the variability in the material slump due to changes in extrusion temperature.

2.5 Control System

Control of Mud Dauber is based on an STM32 microcontroller. The controller coordinates robot mobility, terrain compensation, fine positioning, and print head action. The STM32 communicates with a user interface and issues commands to subsystems which employ microcontrollers for closed loop control.

3 Terrestrial Applications

Today, commercial companies [5, 6] are 3D printing terrestrial structures using robots of the gantry and fixed base architectures. These robots have shown great promise in their ability to build useful structures for human use at low cost. But the printing process still includes substantial involvement from humans during setup, operation and finishing of the structures.

The mobile gantry architecture has the potential to further decrease the cost of commercial terrestrial 3D printed structures by eliminating or reducing the effort associated with setting up and moving robots during the print. For example, the mobile gantry architecture can print a series of structures one after another without ever needing to move a set of rails. This architecture can also increase the size of such structures, leading to longer and taller buildings.

The mobile gantry architecture becomes even more valuable when considering military applications. Structures in forward operating areas must be built quickly, often under threat, with minimal existing infrastructure and support. The mobile gantry architecture requires fewer support personnel (reducing risk), is more easily transported (due to the ability to roll out of the transport container) and only requires site clearing and not extensive site preparation. These factors make the mobile gantry an ideal candidate for future 3D printing of military structures.

Applying this architecture in these areas will require continued advances in the coarse positioning, fine positioning, and localization subsystems as well as the integration of print heads that are relevant in terrestrial applications.

4 Conclusion

Mud Dauber is a prototype of the *mobile gantry architecture*. Robots of this architecture roll directly on the planetary surface but move back and forth as though on a set of virtual rails. These robots are simple to control, generate continuous print paths, and can build structures measuring 10's or even 100's of meters in length. A key new capability of this architecture is the ability to use the robot's printed structures as scaffolding upon which the robot can climb to print taller structures. This capability allows the printing of structures taller than the robots themselves. These capabilities open the door to the construction of complex and capable structures that are taller and longer than those generated by robots of competing architectures and similar size.

Mud Dauber is an early prototype of this architecture, designed to perform 3D printing of test structures while demonstrating key capabilities. This paper detailed the five major subsystems developed for the prototype and reported on early validation testing of these subsystems. Mud Dauber is a first step in the development of more capable 3D printers for construction on Earth, Mars and beyond.

4 Acknowledgement

This research was performed under funding from the Indiana Space Grant Consortium (INSGC) at Taylor University. Prototype development was performed as part of engineering design classes and as such was supported by a large team of undergraduate students. Special thanks to: H. Childs, J. Conejero, C. Deckard, N. Eshuis, C. Gardner, M. Jacques, K. King, C. Lehrian, L. Mason, J Meleski, N. Reisler, J. Richey, M. Shearer, N. Streitmatter, R. Cartwright, and S. Dalcher.

5 References

[1] "Meet Frank and his family" Apis Cor, 2022. Online: https://www.apis-cor.com/technology, Accessed: 2/20/2022

[2] "Architecture on Mars" AI Spacefactory, 2022. Online: https://www.aispacefactory.com/marsha

[3] Yuan X., Zhang J., Zahiri B., and Khoshnevis B. "Performance of Sulfur Concrete in Planetary Applications of Contour Crafting." Additive Manufacturing Conference, Jan. 2016.

[4] Howe A. S. *et al.* "Modular Additive Construction Using Native Materials." *Earth and Space 2014*, St. Louis, Missouri, Jun. 2015, pp. 301–312.

[5] Cesaretti G., Dini E., De Kestelier X., Colla V., and Pambaguian L. "Building components for an outpost on the Lunar soil by means of a novel 3D printing technology." *Acta Astronautica*, vol. 93, pp. 430–450, Jan. 2014.

[6] Khorramshahi M. R. and Mokhtari A. "Automatic Construction by Contour Crafting Technology." Emerg Sci J, vol. 1, no. 1, p. 28, Jul. 2017.

[7] "Meet ICON's next generation Vulcan construction system." https://www.iconbuild.com/vulcan Accessed: 4/24/2022

[8] Staritz P.J., Miller, C.S., and McClurg, J.C. "The Mobile Gantry: A Robotic Architecture for 3D Printing Structures on Mars" Available EngrXiv.org