The Mobile Gantry: A Robotic Architecture for 3D Printing Structures on Mars

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Abstract

The additive manufacturing of habitable structures on Mars from in-situ resources will enable the low-cost development of Martian infrastructure in preparation for a large-scale human presence. To realize this potential, significant obstacles must be overcome across many aspects of additive manufacturing technology. In this research, a new robotic architecture for the 3D printing of habitats is proposed. This architecture, the Mobile Gantry, improves upon previous approaches in that it is capable of producing larger, stronger, and more capable structures. This architecture has the potential to outperform other common robotic architectures and opens the possibility of exciting new capabilities.

Keywords

3D Printing; Sulfur Concrete; Habitat; Robot; Mars

Introduction

In recent years the space industry has undergone dramatic change. The development of reusable launch systems has opened the possibility of much more complex and bold missions beyond Earth. These systems are opening the door to the possibility of colonies of people living and working on other planetary bodies.

Sustaining workers in such hostile environments requires structures in which they can live and work. Relying on prefabricated structures manufactured on Earth quickly becomes cost prohibitive as populations increase. Moreover, launch requirements constrain these structures to be compact and lightweight, offering limited internal volume and poor radiation protection. As a result, there is a transition point when building structures in-situ will be a better option than delivering them from Earth.

In preparation for this, many researchers have been exploring 3D printing of structures using resources available on the Moon or Mars. Research into print materials [1], print techniques [2], autonomy [3], and building architectures [4] are just a few examples of the wide-ranging work. Researchers have also explored robotic architectures capable of efficiently and effectively manufacturing structures. These architectures can generally be grouped into three families: fixed base radial arm robots (FBRA), mobile robots and gantry robots.

Several groups [5], [6] have explored the possibility of building structures using the FBRA architecture (Figure 1).

Figure 1 - Apis Cor's "Frank" robot is an example of the Fixed Base Radial Arm architecture (Photo courtesy of Apis Cor)

In this approach, a long robotic arm is used to manipulate the extrusion nozzle while the base of the arm remains fixed during the print. These concepts 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 printed structures are generally small 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.

To avoid these problems, [7],[8] envision the use of a team of mobile robots that maneuver in and around the structure while it is being built, coordinating the motion of the robot base with the manipulator to move the print head along the desired path. 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 of the mobile robot architecture is much greater than FBRA because robots must be able to maneuver within the structure, mobility paths must be coordinated, 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 discontinuities in the path, which yields a weaker structure and limits the utility of reinforcing fibers. 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.

The third architecture is the robotic gantry [9], [10]. This is a single robot, positioned on rails, which spans the work area. This approach has the advantage of being able to print from above, simplifying control and allowing 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. Building sequential structures requires repositioning the rails, and the size of the built structure is limited by the size of the robot.

In this work, a hybrid of the mobile robot and gantry robot architectures is proposed. The *Mobile Gantry* architecture benefits from many of the positive characteristics of each, eliminates some of the most difficult negative aspects, and introduces exciting new capabilities: self-scaffolding, sequential builds and parallel construction.

3. Mobile Gantry

The mobile gantry architecture is a gantry without rails. Figure 2 illustrates an example of this architecture.

Figure 2 - The Mobile Gantry architecture rolls directly on the planetary surface. (J. Miles)

The robot maneuvers directly on the planetary surface using wheels. Large scale, low precision motion is achieved through a combination of the mobility subsystem and two additional coarse degrees of freedom. The combination of these coarse degrees of freedom position the print head in close proximity to the desired print path. Fine positioning of the print head is achieved through a much smaller, more agile manipulation system, which guides the print head along the desired trajectory while isolating it from the coarse motion of the rest of the robot.

Figure 3 – Coarse positioning (Blue) and Fine positioning (Green) work together to allow precision printing over workspaces spanning 10’s or even 100’s of meters

Coarse Positioning

Figure 3 illustrates an example configuration of the coarse positioning degrees of freedom. (Blue arrows) X-axis motion is achieved by rolling along the planetary surface. Rolling along the surface means that no rails, or rail placement, are required. It also means that the X-axis length of printed structures is not bounded by the physical size of the robot or rails–allowing for very long structures. In this example, coarse Y and Z-axis motion are achieved using prismatic joints which position the fine positioning degrees of freedom and print head.

The mobility system is primarily designed for long straight print paths but allows more complex maneuvering of the robot between prints, enabling the printing of additional structures or expansion of existing structures.

The introduction of additional degrees of freedom that allow the leveling of the gantry in response to uneven terrain allows the system to print on unprepared surfaces. This terrain compensation also plays a significant role in the self-scaffolding capability.

Fine Positioning

Figure 3 also illustrates an example configuration of the fine positioning degrees of freedom. The fine degrees of freedom (Green arrows) must be capable of moving the print head along the print path (position and velocity) while isolating the print head motion from the motion of the coarse degrees of freedom. The combination of coarse and fine positioning systems allows for relatively simple isolation of the print path from the influence of complex terrain.

The workspace of the fine positioning system includes the area in front of the wheels, enabling the robot to build habitat walls that can subsequently be driven on. This self–scaffolding capability is detailed in Section 4 – Advantages of the Mobile Gantry.

Localization

As the mobility system traverses the surface, slip and interaction with terrain features will introduce error into dead reckoning location estimates. Therefore, the architecture employs a local positioning system to determine the position, orientation and velocity of the print head and mobility system in the world frame. This system must be wireless, update at a high rate, and have high precision to ensure quality prints.

Employing the localization system for sensing the position and orientation of the print head relaxes a constraint typical of gantry robots. To minimize positioning error, most gantry robots are very stiff, and therefore massive. Measuring the print head position directly in the world frame means that high precision print paths can be maintained despite any external disturbances to the robot. As a result, robots of this architecture can be much more flexible without incurring additional positioning error, which translates to larger robots with longer spans and lower mass.

Concept of Operations

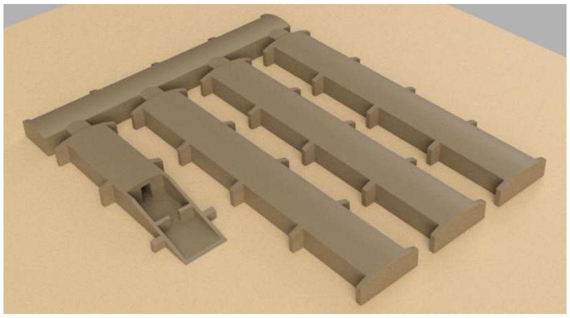

Figure 4 – Facility concept in which a long “backbone” hallway is printed first. Wings can be printed off of this connecting hallway and commissioned over time.

A Mobile Gantry robot is envisioned to be a member of a larger team of robots working together to build structures. Such teams would include multiple mobile gantries, cable management robots, material hauling robots and mining robots.

The mobile gantry robots roll along the planetary surface printing structures. A reel on the printing robot lays and picks up the power cable as the robot traverses the print area, minimizing dragging and damage to the cable. When a print is complete, the robot traverses to a new print area with the aid of a cable management robot. When the printing robot runs low on materials it rolls out of the print area and a material hauling robot delivers printing materials. Upon refill, the printing robot re-enters the print area and resumes construction.

The mobile gantry robot architecture is flexible in the types and organization of the structures it can build. One possible facility design is illustrated in Figure 4. In this illustration a long "backbone" hallway with tapered interfaces for additional wings was printed first. This hallway serves as the connector between different areas of the structure that can be built at later times. Pressure doors are built into the core hallway, allowing parts of the facility to be used while others are still under construction. When a new wing print is completed and post processing (sealing & finishing operations) are finished, it is pressurized and added to the habitable volume while the robots move to the next tapered interface and begin printing another wing. Facilities like very long greenhouses, pressurized garages for performing maintenance on rovers and radiation bunkers are all possible using this architecture.

4. Advantages of the Mobile Gantry

The mobile gantry architecture benefits from many of the best characteristics of the mobile robot and gantry robot architectures while eliminating some negative aspects. Table 1 illustrates the advantages of the mobile gantry architecture when compared to the three traditional architectures.

In addition to this, the mobile gantry architecture enables new and/or improved functionalities that distinguish it from existing architectures.

Self-Scaffolding

The mobile gantry architecture is capable of efficiently printing structures taller than itself, structures that are not limited by the size of the robot. The ability of the robot to roll across unprepared planetary surfaces means that it can also roll on the surfaces it is printing. To achieve this, the robot prints structures with walls and internal dividers that are aligned with the wheel base. Figure 5 shows a mobile gantry printing while traversing already printed layers. Note that the structure is tapered to the ground at one end to allow the system to descend for restocking materials and at the completion of the print.

Parameter	Description	Fixed Base Radial Arm	Mobile	Gantry	Mobile Gantry
Mobility Control Complexity	Complexity of maneuvering base and manipulator	Simple, no base motion and no robot coordination during print	Complex, robot maneuvers around / in structures, coordinates with other robots	Simple, motion only on rails	Simple, motion only on virtual rails
Print Head Control Complexity	Complexity of print head motion control and planning	Simple, location of fixed base is static during print, print head suspended above print	Complex, location of mobile base changes during print, Print head maneuvered around structure	Simple, location of gantry is well known during print, print head suspended above print	Simple, location of gantry is well known during print, print head suspended above print
Sequential Builds	System capability to build structures sequentially, connecting them together into a single facility	Poor, printing tapered junctions to connect prints negatively impacts structure internal volume	Excellent, robot mobility enables tapered junctions in any direction without limiting internal volume	Poor, requires repositioning of rail infrastructure to allow additional builds.	Good, X mobility enables tapered junctions without limiting internal volume
Robot Size	Relationship of structure dims to robot size	Robot size constrains all structure dimensions	Robot size only constrains structure height	Robot size constrains all structure dimensions	Robot size only constrains structure width
Parallel Construction	Robots can work on a single structure simultaneously	No, A single robot prints in a single area	Yes	No, A single robot prints in a single area	Yes
Continuity of print	System can create continuous print paths for increased structural strength	Yes	No, Complex robot mobility paths and coordination limit continuity	Yes	Yes
Power Supply	Location of robot power source	Remote – Cable supplies power from power station	Onboard – Robot must carry power source, limits operational time	Remote – Cable supplies power from power station	Remote – Cable supplies power from power station

Table 1 – Comparison of key parameters of robotic architectures for 3d printing of habitable structures.

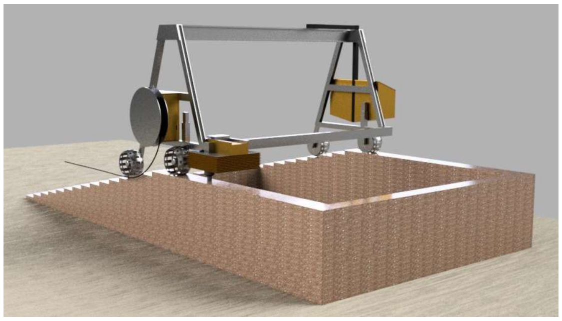

Figure 5 – The self-scaffolding capability allows the mobile gantry to roll on the structure it is building and enables the construction of structures taller than the robot.

Sequential Builds

The ability of the mobile gantry to print very long structures opens the possibility of facilities with vast internal volumes. Printing such structures using the traditional bottom-up approach (in which the entire first layer of the facility is printed prior to starting the second layer) means that a structure is unusable until the entire facility is complete.

The mobile gantry architecture introduces the possibility of efficient sequential builds in which sections of the facility can be built and completed with tapered junctions ready for extending the facility. Using this approach, parts of a structure can be used while other parts are still under construction.

Parallel Construction

The mobile gantry can perform efficient and low complexity parallel construction of facilities. Robots of this architecture can work on the same structure at the same time as illustrated in Figure 6. This parallel work dramatically reduces the time to complete construction.

Although the FBRA and mobile robot architectures can also perform parallel construction, doing so yields high complexity coordinated print paths and low workspace efficiency.

5. Prototype

A first-generation mobile gantry prototype called Mud Dauber has been developed and is currently undergoing testing at Taylor University. [11] This prototype, shown in Figure 6, includes mobility, terrain compensation, fine positioning and printing subsystems. The mobility system allows the robot to traverse the test terrain. Terrain compensation has been included to allow the robot to print while traversing uneven and irregular surfaces. A 3 degree-of-freedom Cartesian positioning system allows the robot to precisely position and maneuver the print head and isolate the motion of the head from the motion of the robot. A sulfur concrete print head is used to extrude a slurry of sulfur concrete during testing.

Figure 6 – Mud Dauber is a first generation prototype of the mobile gantry architecture.

6. Conclusion

The mobile gantry architecture is a gantry without rails. When compared to the three common robotic architectures for 3D printing structures, the mobile gantry benefits from several key advantages. Lower control complexity allows for simple, low risk control, increased print speeds and improved print quality. The architecture allows for the printing of structures larger than itself in both length and height, translating to larger structural volumes and greater flexibility in structure design. The ability of multiple robots to operate in parallel on a single structure with minimal increase in print complexity means prints can be completed much faster with higher quality. The architecture's method of positioning the print head from above means that print paths can be continuous, yielding higher strength structures. Finally, simple mobility paths during printing enable the architecture to operate on tethered power which allows continuous operation and reduces structure build times. The mobile gantry architecture will enable higher quality prints of more diverse structural designs in less time.

7. 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 faculty, staff and students. Special thanks to: R. Cartwright, H. Childs, J. Conejero, S. Dalcher, C. Deckard, N. Eshuis, M. Jacques, K. King, C. Lehrian, L. Mason, N. Reisler, J. Richey, M. Schlenker, M. Shearer, S. Wozniak. Illustrations by Jamie Miles.

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