Habitat Scale Polar Coordinate 3D Printing System

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I. Introduction

Since the advent of 3D printers, building increasingly larger objects has been a significant research challenge, requiring larger and larger scale 3D printers. Generally the printers themselves must occupy a volume larger than the object they are printing. This is true of cartesian printers such as University of Maine's gantry system printer [1] or delta printers such as 3DWASP's 12m system [2]. The exception to this rule are 3D printers based on serially linked robotic arms. Most of these systems have two common disadvantages: workspace and payload. Concurrently, NASA has expressed interest in additive manufacturing on the Lunar surface [3]. FASER's use of the Lightweight Surface Manipulation System (LSMS) [4] initially designed by NASA's Langley Research Center for lunar operations, seeks to address these challenges.

II. The LSMS

The LSMS [5] was initially conceived as a means for unloading prefabricated habitats from landers on the surface of the Moon and Mars and placing them on the surface. As the program evolved, additional mission options involved the LSMS not only deploying payloads but using a regolith scoop to bury habitats as a form of radiation shield [6]. The issue with this mission profile is that while the LSMS is able to make use of materials within its landing region, it must still bring with it entire completed habitats. The LSMS consists of a tendon actuated serial manipulator, standing approximately 4m tall and with an 8m reach. In earth gravity, the LSMS can lift in excess of 200lbs at its end effector, and on the Moon this figure becomes over 2000lbs. To use the LSMS as a 3D printer instead of a manipulator device, special considerations are needed for the following reasons:

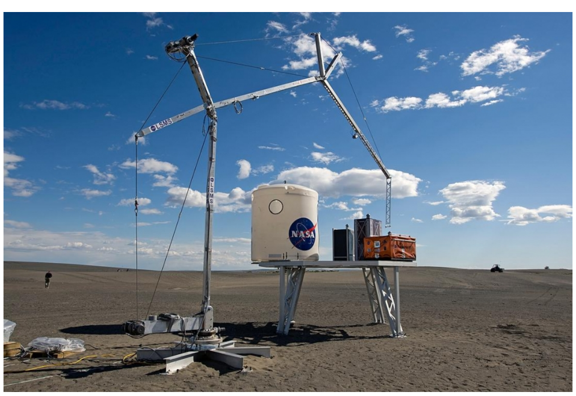

Fig. 1. The LSMS, as built at NASA Langley

- The LSMS's base turntable is not perfectly accurate, so large objects would be printed with less accuracy the farther the end effector is from the base.
- Using the LSMS's end effector as an extrusion system limits the workable volume of the extruder, as the LSMS must be able to point its end effector downward.
- The LSMS is prone to lateral flex and wobble due to its extremely large size and lightweight construction.

Special considerations aside, as a fully functional 3D printing system, the LSMS could make use of a variety of materials such as concrete or plastics. This flexibility would allow the LSMS to aid in the construction of facilities in difficult to reach locations, with different material requirements. On extraplanetary surfaces such as the Moon, where in-situ resource utilization is paramount, research has shown that lunar regolith itself is a viable printing material [7], though additional work is required to reach the structural strengths required for habitat applications.

III. The LSMS as a Gantry Printer

In order to mitigate the problems described above, the conceptual solution is to mount a Stewart platform (SP) to the underside of the 4m forearm link of the LSMS on a sliding gantry system, as shown in Fig. 3. The Stewart platform will serve as the extrusion head, and the mixed serial/parallel system has the following advantages:

- Because the LSMS's shoulder and elbow joints are parallel to each other, the forearm can be raised and lowered level with respect to the ground, and functions as the z axis of the printer. An additional result of this configuration is that the Inverse Kinematics of the whole system are directly calculable. The Forward Kinematics of the system remain an iterative problem because of the presence of the SP.
- The high accuracy of a SP, combined with a form of external metrology allow for the SP to correct for any inaccuracy in the LSMS's joints[1], allowing for consistent printing accuracy at workspace extremes and mitigating one of the main drawbacks of polar 3D printers.

[1] https://www.youtube.com/watch?v=DXPB2JrW9DY

- The SP can also react to error induced by external forces, such as the LSMS being hit by wind on Earth's surface[2].
- The 6 Degree of Freedom (DOF) nature of the SP allows for multi-axis printing, which can increase the overall strength of the structure [8].
- Because the gantry on which the SP travels is suspended underneath the forearm link, the LSMS's primary end effector is left unobstructed, allowing for prefabricated items such as airlocks and windows to be integrated into the 3D printed structure during its construction.

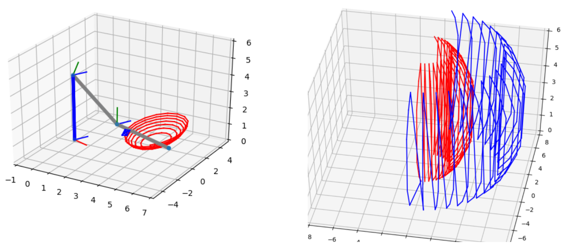

Fig. 2. Left: Simulated LSMS Gantry Constructing a Habitat Shell, Right: Workspace bounds of the LSMS Gantry Printer

The workspace of the LSMS gantry system extends a full 360 degrees around the robot, with a minimum distance from the base of the robot of just over a meter, and a maximum distance of 8m. The workable volume does change with the elevation of the system, and has a constant width at a given Z of slightly over 4m (accounting for the length of the gantry plus the translational abilities of the SP itself). The workspace is shown in Fig. 2 (right), where the red volume represents the inner bound of the workspace, and the blue represents the outerbound. Because it would not be practical in most cases to print toroidal objects with the LSMS in the center, only a semicircular portion of the workspace is shown.

IV. Dynamics

The most significant open research area for this project is to design a system wherein as in Fig. 3, the SP can recognize and counteract unpredicted motions of the LSMS. Situations in which unintended motions may arise include the LSMS abruptly changing direction, being hit by an external actor, or the SP itself. Early simulation efforts have shown that the SP can counteract the LSMS's motion (as shown) but only if the end effector position is known. The degree by which a physical Stewart platform's counteraction efforts would affect the LSMS's movements in a contact event scenario are currently unknown, but are a focus of upcoming hardware testing. Initial tests will use FASER's optitrak system to monitor the desired extrusion location versus the actual position of the LSMS's end effector, and measure the sway in the LSMS induced by the SP moving to counteract the error.

[2]https://www.youtube.com/watch?v=abdg5okcXms

V. Future Hardware Demonstration

The FASERLab at Virginia Tech is currently building a copy of the LSMS arm from NASA Langley which is currently in final assembly and is slated to be completed in December of 2020. A full scale demonstration of the gantry system is slated for May 2021. FASER's primary challenges are designing and mounting the SP system, as well as determining and validating the method of extrusion. Prior to May 2021, FASER will be attempting sub-scale and component testing of the mechanisms required for this demonstration.

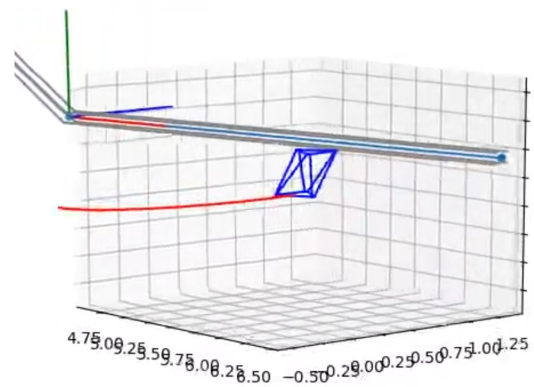

Fig. 3. Underslung Stewart Platform Articulating to Respond to Sway in the LSMS

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