Transforming Lunar Regolith into a Digital Printable Material. R. Batra[1] and H. Lipson[1], [1]Columbia University, Mechanical Engineering Department, 500 West 120th Street, New York, NY 10027 (richa.batra@columbia.edu and hod.lipson@columbia.edu

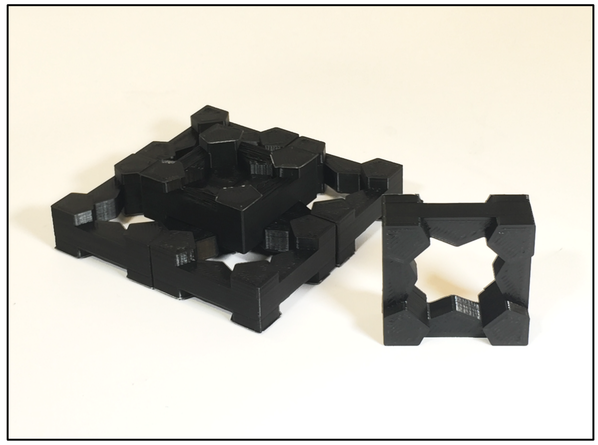
Introduction: The viability of future space travel depends on developing technologies for in-situ resource utilization (ISRU) for life-support necessities, such as infrastructure and consumable products. The use of 3D printing technology for ISRU is an obvious solution, allowing one to manufacture, repair, and replace tools and components on demand. This technology already excels at efficient use of material, situational responsiveness, and minimization of cost, particularly in the manufacturing of small scale, custom parts. However, there are still constraints on 3D printing, specifically when considering multiple materials, scaling of size, and repeatability which are significant considerations for construction of habitats and infrastructure. These issues can be addressed with the introduction of digital printing materials that are comprised of physical, self-aligning units known as voxels. Though virtual voxels have traditionally been used as a graphical data structure for representing 3D geometry, in digital 3D printing framework, voxels allude to fundamental physical structures or shapes to be used in fabrication.

We present here a concept for in-situ production of voxel feed stock from regolith, a proof of concept printhead device for assembly techniques, and a proposed study on the structural integrity of the digital material.

Motivation: Previous studies have looked into creating amorphous structures from lunar and Martian regolith simulant via laser fabrication, geothermite reactions, and binder additives [1][2][3]. While these may provide valuable techniques for manufacturing small, precise parts or customized pieces, the use of additives and localized heating preclude them from scaling up to large structures.

Digital printing allows for perfect replication and zero noise despite using a noisy and inaccurate substrate. Moreover, digital parts are perfectly repeatable with no loss of 3D information over subsequent replications. In comparison to traditional (analog) 3D printing in which material is deposited or solidified in an inherent continuum, digital 3D printing imposes finite resolution: the size of a single unit. Advantages of this 3D digital domain include high dimensional accuracy, perfect repeatability, and the inherent capability of low-temperature co-fabrication using a rich and diverse set of materials [4].

Voxel Design and Fabrication: We define a digital 3D printing voxel as a fundamental unit used for additive manufacturing. In this study we consider voxels with a 3-5mm face length.We studied and evaluated different voxel designs based on their modularity, ease of assembly, diagnosability and reparability, and material customization. Based on this evaluation, the voxel design concept we are pursuing for lunar regolith additive construction is shown below.

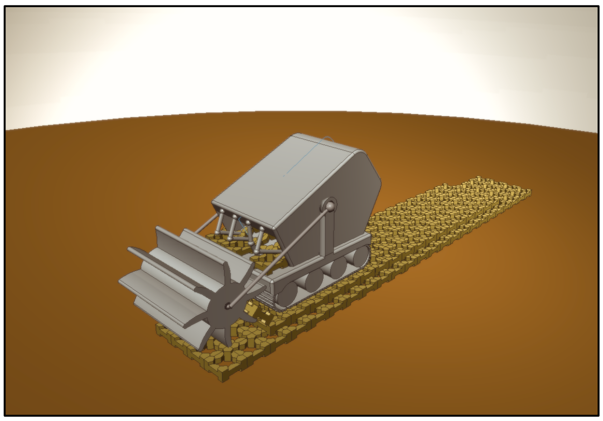


This 2.5D design is non-space filling, invariant to rotation and flip, and is able to rigidly connect to maintain a strong material. The design only interlocks to layers above and below which may limit the structural complexity; however, under a rubric that favors manufacturability and ease of assembly, this design is most highly rated [5].

Considering the desired voxel size, laser sintering may be a possible fabrication technique, although it would be challenging for large scale production. Other voxel feedstock fabrication processes that do not involve additives are greatly limited by environmental constraints. For example, traditional glass making techniques require oxygen burning furnaces. Therefore, given the availability of solar energy, we cast the lunar regolith simulant using thermal resistor heating elements. The fabricated parts will be presented, demonstrating the manufacturability of the voxel design.

Assembly Process: The voxel design presented here self-aligns upon assembly; thus the assembler only needs to place the voxel within a certain distance of its final position. The precision of the final part depends solely upon the tolerances of the voxels. In contrast, an analog fabrication system cannot make a part more accurate than its own positioning system, and performance degradation is inevitable in every subsequent replication. Work by Hiller, et al. compared the parallel layer printhead implementation with a serial implementation, using pick-and-place assembly as a baseline [6]. They found serial placement to be a viable option for rapid assembly. The serial printing method behaves much like an inkjet printer depositing droplets of ink. The self-aligning voxels greatly simplify the assembly process.

The figure below shows a prelimary model of the robot concept we propose for rapid serial assembly of this voxel design. We have a benchtop proof-of-concept that has demonstrated the assembly mechanisms and functionality.



Digital Material Properties: Habitat construction in space needs to be resilient to the unique combination of conditions it will be exposed to in addition to meeting the functional requirements. These expected challenges in space include but are not limited to - forming an environmental seal, responding to drastic changes in temperature, resisting or easily repairing damage from micro-meteoroids and debris in space, and ability to retain or expel heat.

In the realm of digital additive manucturing, our lab has demonstrated the ability to tune properties of digitally manufactured structures by simulating voxel assemblies and varying composition, micro-structure placement, and fabrication precision [7]. The digital materials were compared with respect to stiffness, density, thermal expansion and failure modes. This has demonstrated the ability to fine-tune physical properties of digital assemblies for desired applications by controlling voxel design, placement, and base material.

Upon fabrication of the regolith voxel, we have begun to study preliminary material science properties by performing stress and strain analyses, hardness tests, and thermal cycling. We will be presenting our findings on the physical, mechanical properties of the structures. Based on these studies, we plan to optimize the voxel design and fabrication techniques for the purpose of extraterrestrial construction using in-situ resources. Ideally, the fabrication process of regolith voxels should not require imported or manufactured additives or complicated chemical processing. However, we will be evaluating the trade-offs of melting and sintering at high temperatures with the use of additives and preprocessing, with particular emphasis on the cost and feasibility of transporting the required tools and materials in each case.

Conclusion: Digital materials have unique characteristics that address several drawbacks of traditional 3D printing. One area that would benefit from advancements in digital printing is the construction of in situ resourced habitats and infrastructure in space, a crucial step for human space travel. We have presented an early prototype for a digital manufacturing framework that has significant potential to further ISRU for habitat and infrastructure construction.

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