Solar-Powered Additive Manufacturing on the Moon

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Motivation

As we prepare further human and robotic exploits into deep space, a specialized set of space infrastructure in strategic locations will be necessary to support long duration missions. We will need to robotic and human habitations, radiation shelters, road networks, launch infrastructure, landing pads, and a multitude of other infrastructures to be successful (Figure 1). In an effort to circumvent the high launch costs of exporting materials and assemblies, many are now investigating additive manufacturing techniques to build these critical infrastructures using in-situ resources.

Figure 1: Artist's concept of lunar construction and habitation.

Objectives

Develop an additive manufacturing method tailored to extraterrestrial environments like the moon that can play a role in constructing necessary infrastructure for space exploration. To be effective, it must:

1. Be low-cost and low-energy.
2. Be adaptable to a variety of extraterrestrial environments.
3. Adhere to the concept of In-Situ Resource Utilization (ISRU)
4. Be suitable for an autonomous printing operation.

As showcased by the NASA Habitat Challenge, the majority of additive manufacturing (AM) techniques that have been explored for use in lunar construction have centered on Fused Deposition Modeling (FDM). Markus Kayser explored the use of focused sunlight to sinter sand and provided inspiration for a low-cost, low-energy alternate method (Figure 2).

Figure 2: Markus Kayser's solar sintering project that put the intense heat of the Moroccan desert sun to useful work.

Design Method

Through the adaptation of the Selective Laser Sinter (SLS) AM technique to utilize focused sunlight, there is potential to reach all of our design objectives. Typical SLS technique passes a CO2 laser over a powder substrate, heating it to its sinter temperature and creating a sintered layer of material. We can adapt this technique to utilize a free source of energy by replacing this laser with a beam of sunlight focused through a planar Fresnel lens (Figure 3).

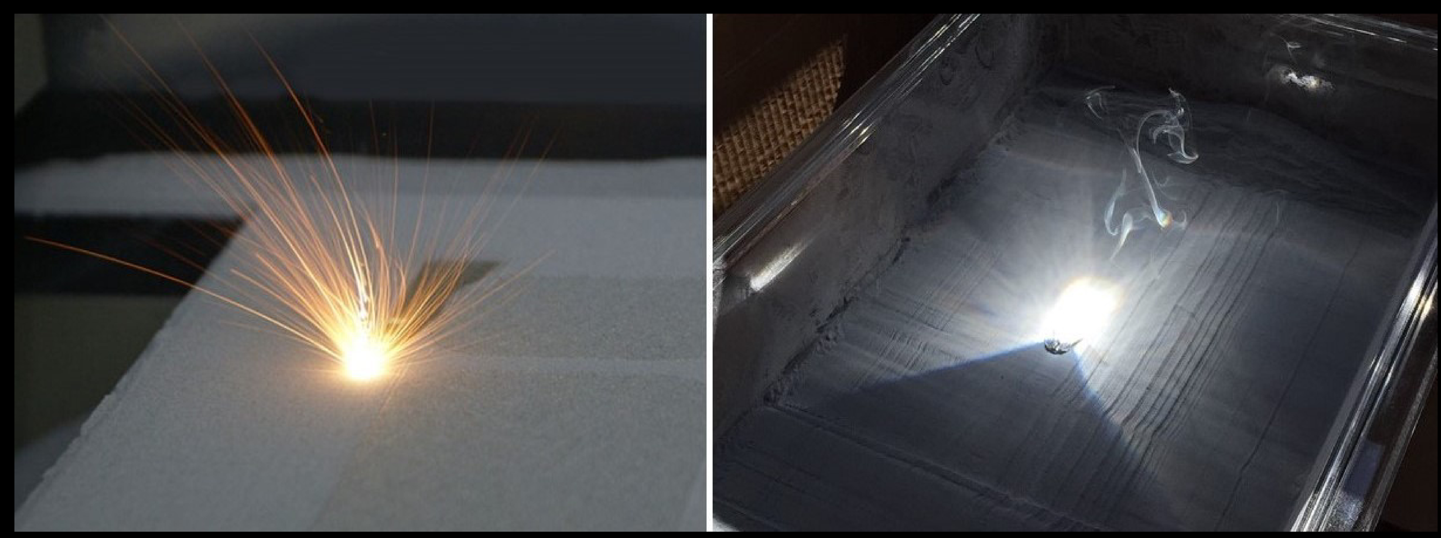

Figure 3: Typical SLS printer using a CO2 laser (left), and experimental trial using focused sunlight to sinter (right).

Another favorable characteristic of this technology is that it can be utilized to print directly onto the surface of the body where it is located. In an environment like the lunar surface, the small particle size of the regolith makes the only pre-processing task leveling of the material. Whereas, in an FDM process, the material would need to be collected, heated, and extruded. This makes the Solar Sinter an ideal candidate for ISRU.

Feasibility and Calculations

To determine the feasibility of the solar sinter on the lunar surface, we must calculate and compare the amount of available power from sunlight, the achievable lens power (Table 1), and the sinter power requirements (Table 2). Given that there is 1365 W/m^2 of solar irradiance available on the surface of the moon, we can estimate the achieveable power of a 1m^2 Fresnel lens on the Moon, with 50% efficiency:

Location	Achievable Lens Power (W)
Earth Surface	393
Moon	548
Mars	235

Table 1: Achievable lens power (W) at 3 locations.

The lunar surface proves to be an ideal candidate for the technology given its proximity to the Sun and the lack of an atmosphere to absorb solar energy.
Knowing the lens power we can achieve, we can calculate the necessary power to sinter the In-Situ materials found in these locations based on their material properties (Table 2). We determine that we can produce approximately 100 more watts than required to sinter lunar regolith.

Location	Material	Required Sinter Power (W)
Earth Surface	Sand	351
Moon	Regolith	450
Mars	Basalt	236
Deimos	Carbonaceous Chondrite	97

Table 2: Required sinter power of various in-situ materials.

Experimental Design

The development of an experimental setup is already underway (Figure 4). This experimental design will allow us to refine power calculations, improve design parameters, test with simulated regolith, and conduct environmental testing of the concept through the use of multi-axis controllable test bin that can print in similar fashion to an SLS printer.

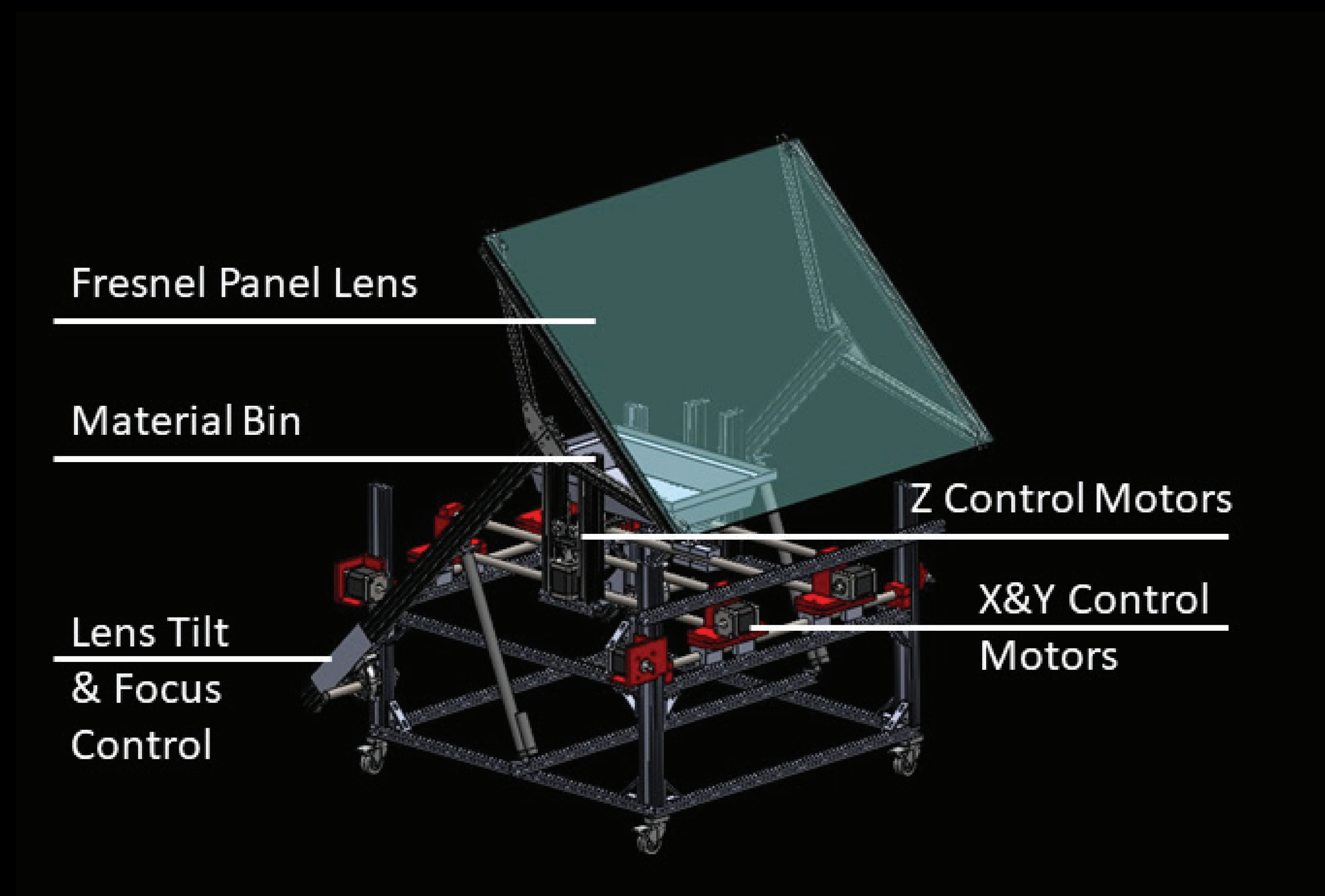

Figure 4: Experimental design will allow us to complete sinter testing on a variety of regolith materials.

Future Study

Through experimental testing and research, future studies will explore a number of areas, including:

1. What structures and designs can be achieved through solar sintering.
2. Employment of solar sintering as part of a mobile fleet of rovers to build large structures directly onto the surface of the moon (Figure 5).
3. Environmental and vacuum testing of the sinter process.
4. Improving solar collection and lens design to amplify achievable lens powers.

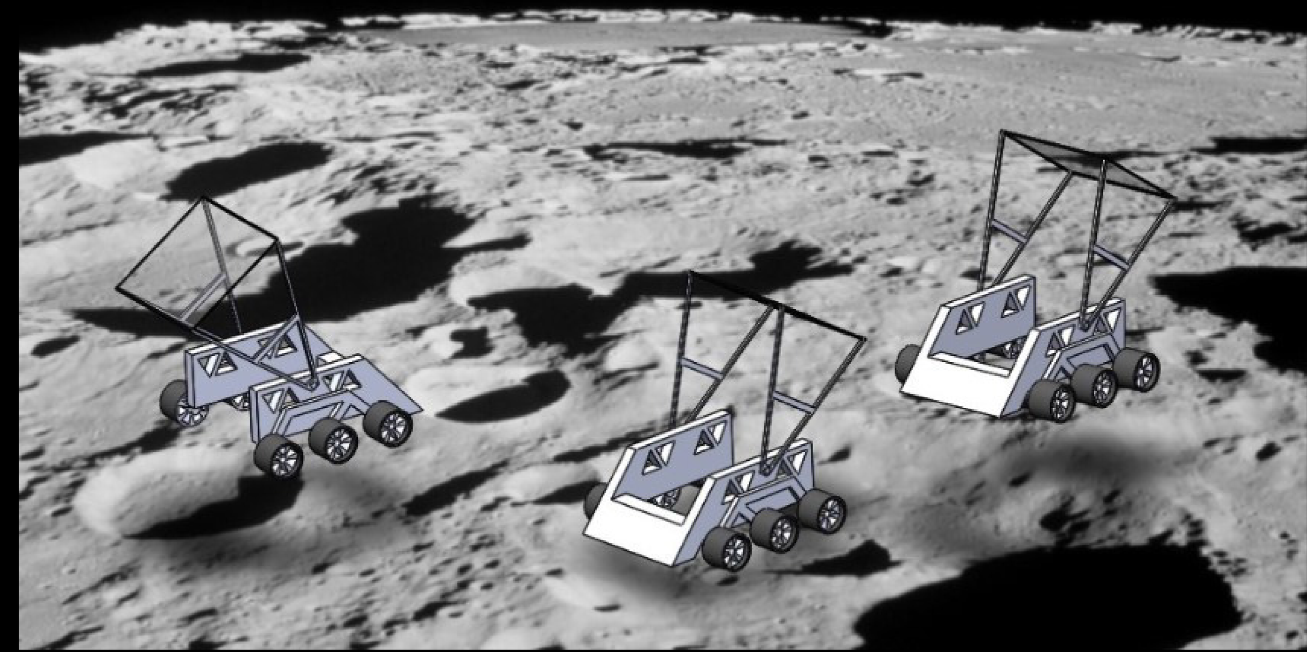

Figure 5: Future study will explore the employment of the solar sinter as part of a fleet of sintering rovers.

Acknowledgements

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