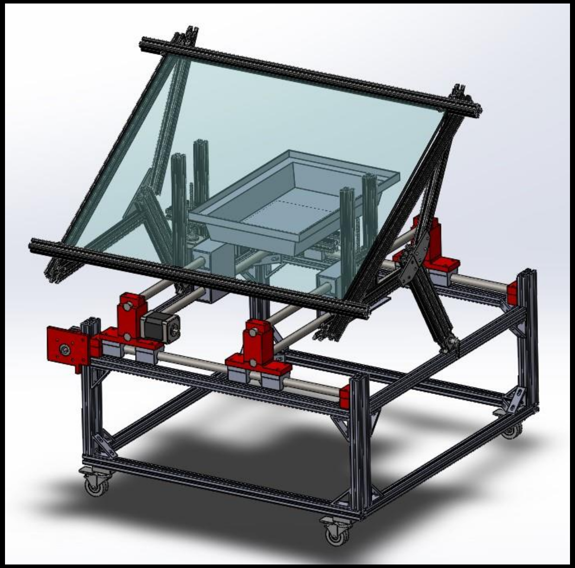
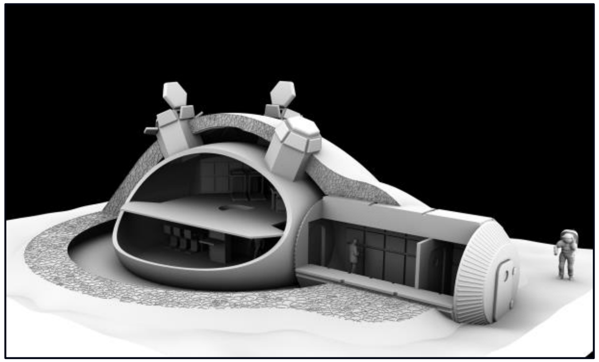


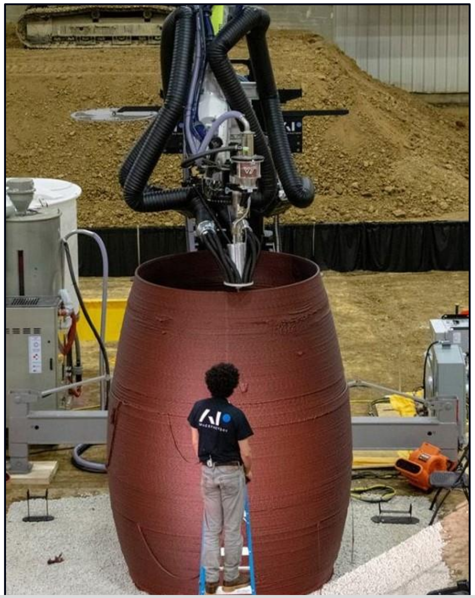
Solar 3D Printing of Structures for Off-World Bases

Steven Anderson, Abraham Marquez, Jekan Thanga
Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory
Aerospace and Mechanical Engineering Department
University of Arizona

Background

As we continue to expand our presence in space and on extraterrestrial worlds, the demand for low-cost, high-performance structures is growing.





Need for new ways of assembling and constructing simple and complex structures off-world.

Objective

Develop a method of 3D printing structures for off-world environments.

- Low-cost, low-energy
- Adaptable to a variety of extraterrestrial environments
- Adhere to the concept of In-Situ Resource Utilization (ISRU)
- Suitable for an autonomous printing operation

Challenges

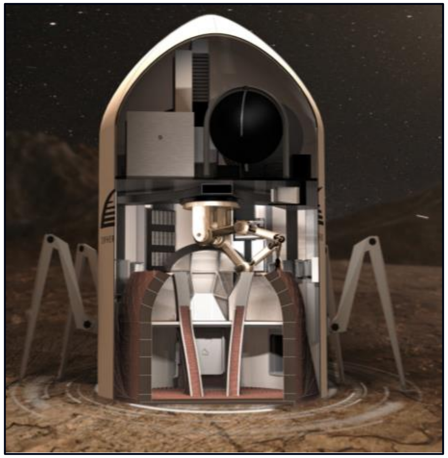
- Adaptability to variety of materials
- Availability of materials
  - High cost of import
  - Refinement of print material
- Power availability
  - Fuel sources for printing operations

Challenges to 3D printing in off-world habitats include power, material availability, and material refinement.

Off-World 3D Printing Concepts

Winner of NASA Mars Habitat Challenge, **AI SpaceFactory**, combines ISRU with FDM process to create **basalt fiber layered structures**.

Team Zopherus, NASA Mars Habitat phase winner, designed a **movable FDM printer** that uses a team of rovers to retrieve local materials.



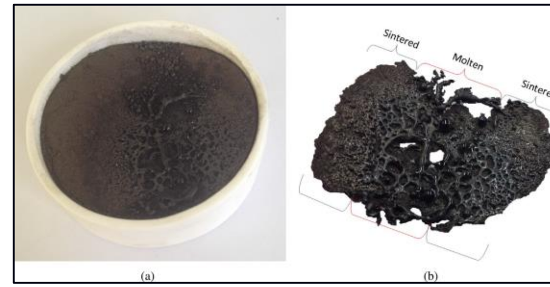
Off-World 3D Printing Concepts

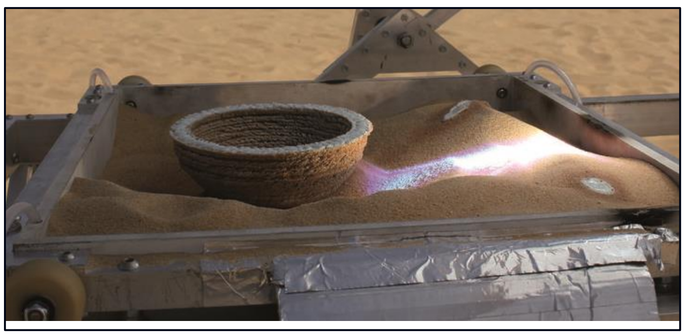
Apis Cor uses a **radial FDM print arm** to **build commercial and residential structures**. They were finalists in the NASA Mars Habitat competition.

Made In Space developed a 3D FDM printer that was designed specifically forr **use aboard the ISS**. Study concluded that FDM **printing in microgravity is similar to on Earth**.

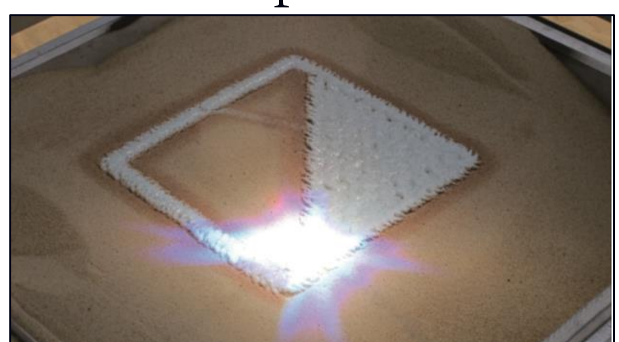
Off-World 3D Printing Concepts

Alexandre Meurisse, 2018 used focused simulated sunlight to **sinter artificial lunar regolith.**





Markus Kayser, 2011 used **focused sunlight** to **sinter sand** in the Moroccan desert to make intricate shapes.



Shortcomings from Current Works

- Mainly centered on single method:
  - Fused Deposition Modeling (FDM)
- Resource gathering
- Material refinement
- Power source

Many of these issues can be addressed with a new approach.

Many gaps stem from current off-world 3D printing concepts.

A New Approach

Selective Laser Sintering (SLS) fits our design criteria:

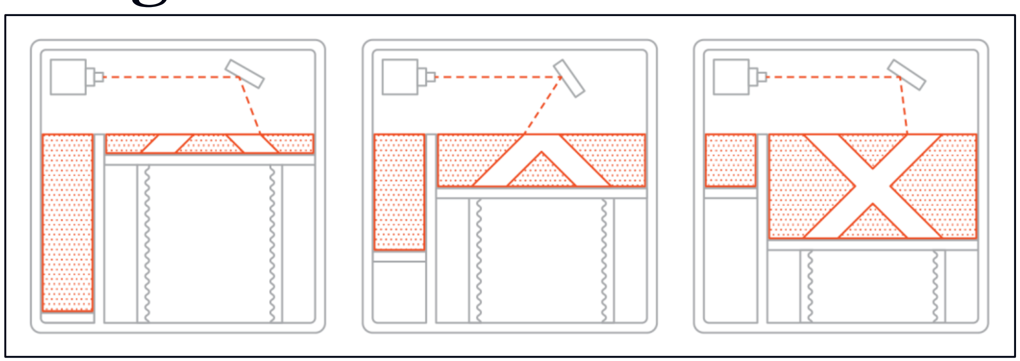
- Adaptable technique
  - Print directly onto the surface of the body where it is stationed
- Minimal pre-processing and handling of material compared to FDM
- Adaptable to variety of materials
  - Variable input power from lens
- Low-energy usage if adapted to use solar power

The SLS 3D printing technique is modifiable to fit our off-world 3D printing needs.

Concept Overview

SLS 3D printing method:

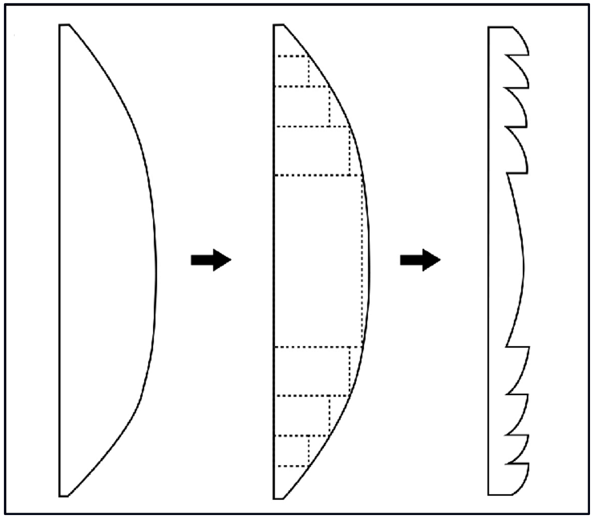
- Laser is guided via a mirror to sinter a powdered material and create a structure layer-by-layer
- Print bed provides its own support structure
- Material is joined through sintering
  - Inhomogeneous materials

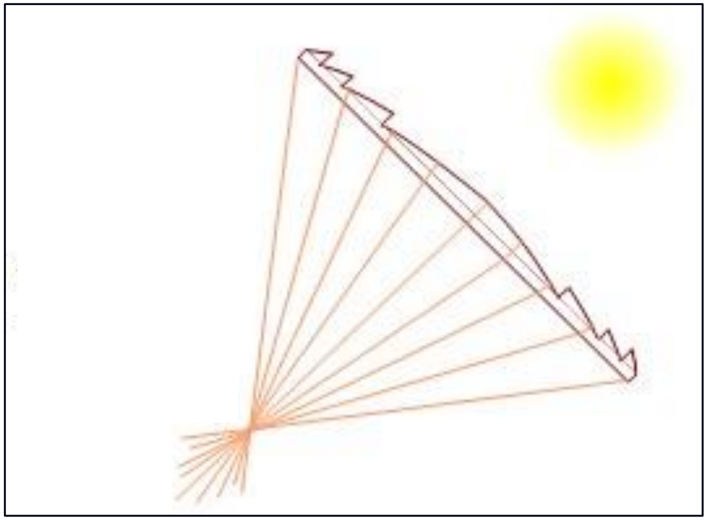


SLS technique uses a guided laser to sinter inhomogeneous materials.

Concept Overview

- Replace laser with the sun
  - Renewable energy source
- Focus sunlight using a Fresnel lens
- No need for high energy laser for sintering

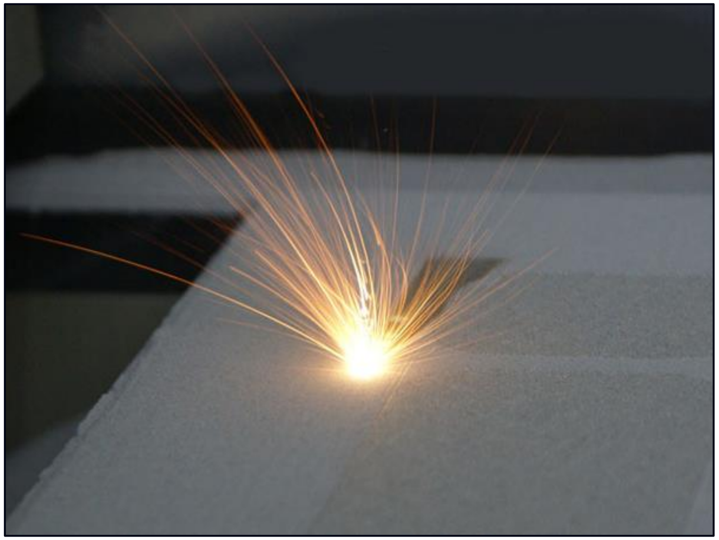




Use focused sunlight in place of high energy laser.

Considerations of Sunlight vs Laser

- Focused sunlight
  - Inconsistent solar spectrum available in atmospheres
  - Dependent on location and orientation of body
- Laser
  - CO_2 laser used in SLS is in infrared wavelength
  - Laser has consistent beam width
  - Controllable parameters



Solar Irradiance Available

	Sun Approach Distance (AU)			Solar Irradiance (W/m^2)		
Object	Closest	Farthest	Mean	Max	Min	Mean
Mercury	0.307	0.466	0.387	14656	6361	9247
Venus	0.718	0.728	0.723	2679	2606	2643
Earth/Moon	0.980	1.010	0.995	1438	1354	1395
Mars	1.380	1.660	1.520	725.3	501.3	597.9
Asteroid Belt	2.200	3.200	2.700	285.4	134.9	189.5
Jupiter	4.950	5.460	5.205	56.38	46.34	50.99
Saturn	9.050	10.120	9.585	16.87	13.49	15.04
Uranus	18.400	20.100	19.250	4.080	3.419	3.728
Neptune	29.800	30.400	30.100	1.555	1.495	1.525
Pluto	29.700	49.300	39.500	1.566	0.568	0.885

Calculating Lens Power

Using:

- Thin Lens Equation
- Magnification Equation
- Ratio of apparent sun height to its distance

Calculate:

$$\frac{h_o}{d_o} = \frac{1}{110} \ (on\ Earth)$$

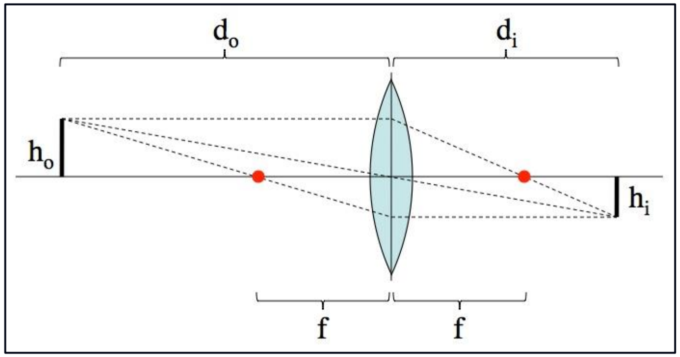
$$\frac{h_i}{h_o} = \frac{d_i}{d_o} = \frac{1}{110}$$

$$d_i = f \ (assuming\ Sun\ is\ at\ infinate\ distance)$$

$$h_i = f \cdot \frac{1}{110} \ (height\ of\ focal\ point\ on\ Earth)$$

$$A_f = \pi \cdot (\frac{h_i}{2})^2 \ (area\ of\ focal\ point)$$

$$P_{lens} = Irradiance\ [W/m^2] \cdot Lens\ Efficiency \cdot Lens\ Collection\ Area$$



Calculate lens power and focal area.

Power Requirements

Given 1 m^2 Fresnel lens with 50% lens efficiency:

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

Estimated Sinter power requirements:

Location	Material	Required Sinter Power (W)	Feed Rate (mm/s)
Earth Surface	Sand	351	2.50
Moon	Regolith	450	1.00
Mars	Basalt	236	4.50
Deimos	Carbonaceous Chondrite	97	5.00

Power variable: location, lens size, rotational sun exposure, feed rates, etc.

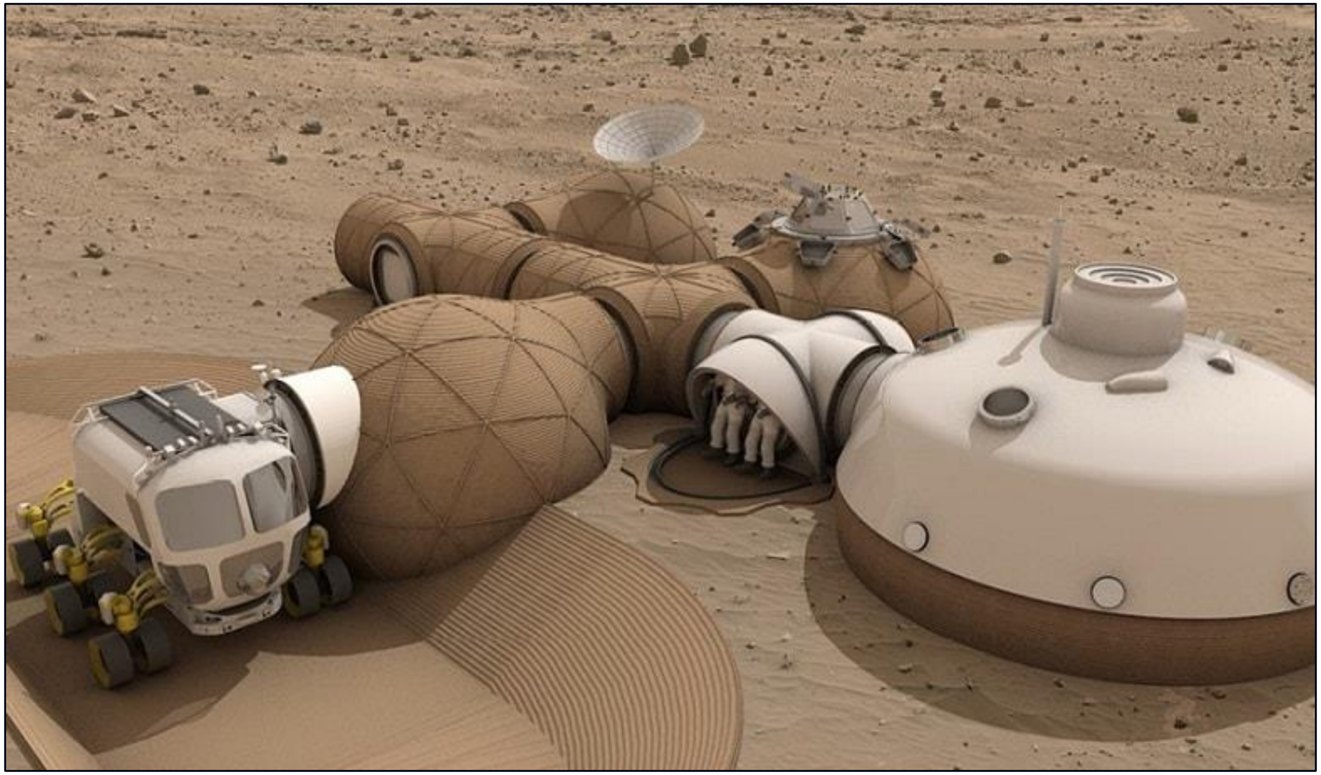
Solar 3D Printing Considerations & Techniques

- Deployed on a robotic fleet for autonomous construction
  - In advance of human habitation
  - Work alongside human habitants
- Most well-suited for low-standing structures:
  - Foundations
  - Road surfaces
  - Structural pieces/beams for later assembly in inflatable habitats

Solar 3D printing is best deployed as an autonomous fleet before human habitation.

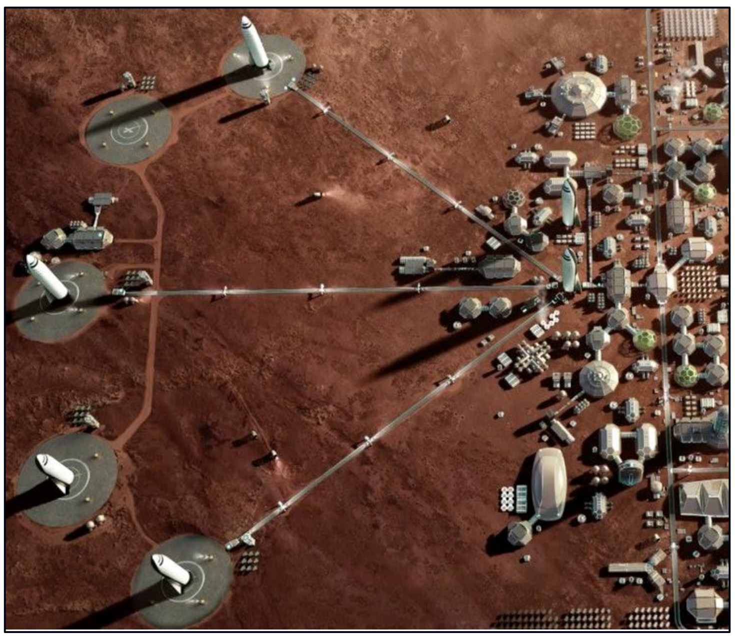
Solar 3D Print Considerations & Techniques

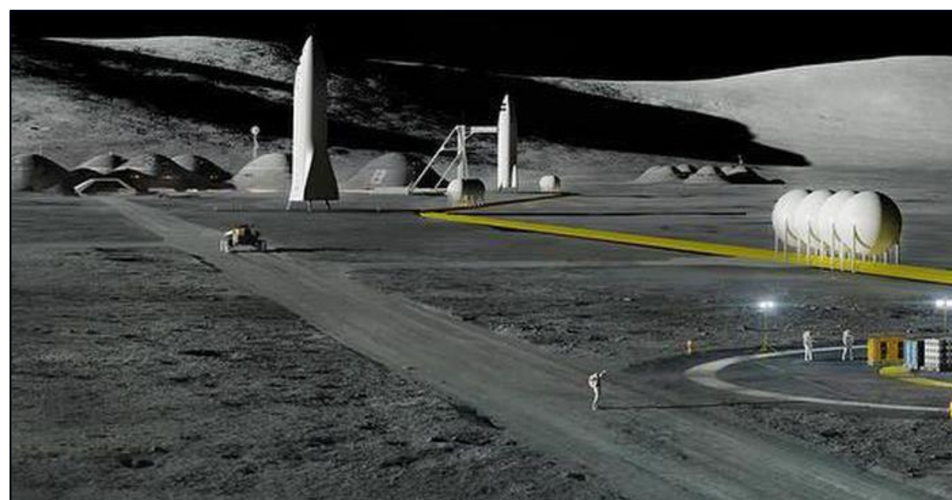
Foundations



Solar 3D Print Considerations & Techniques

Road Networks



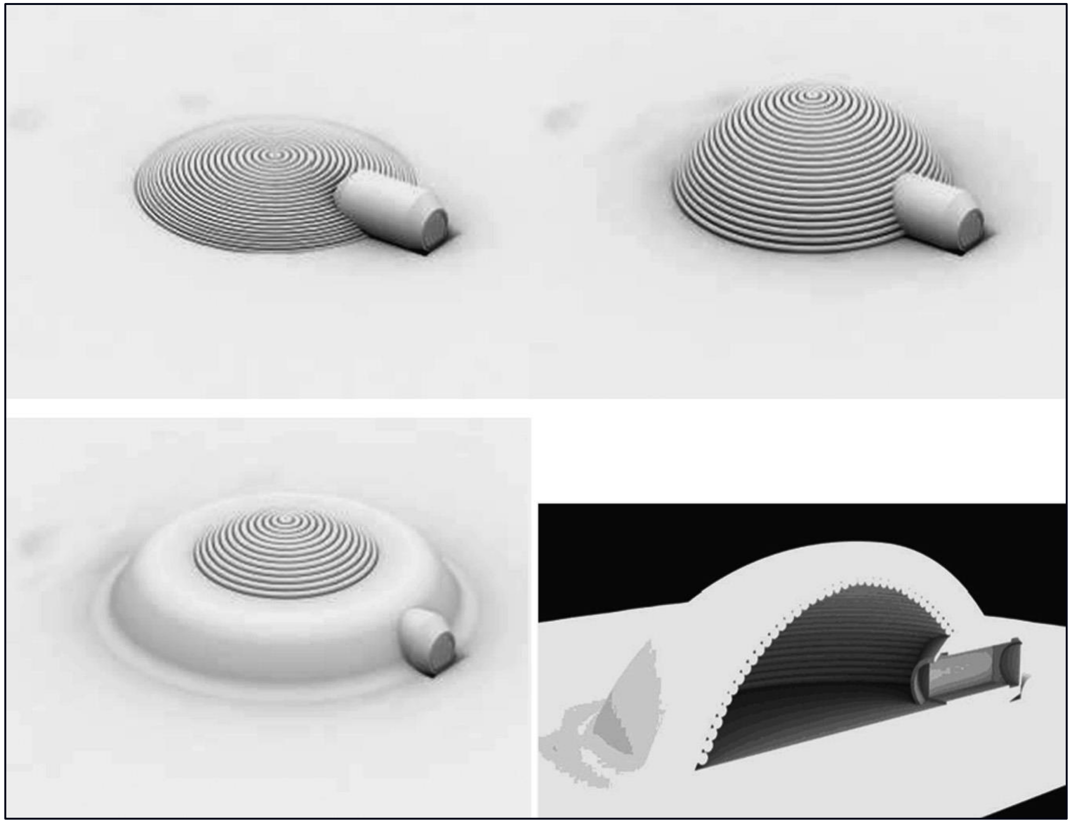


Solar 3D Print Considerations & Techniques

Structural Components

Solar 3D Print Considerations & Techniques

Concept for 3D printing a structural shell around a pressurized, inflatable dome (Cesaretti, 2012)



Solar Printing Challenges

- Print bed and ambient temperatures
- Reflectivity and thermal properties of materials
- Variable density & porosity of print material
- Layering & bed leveling

While a promising concept, there are still challenges associated.

Prove the Concept Through Experimentation

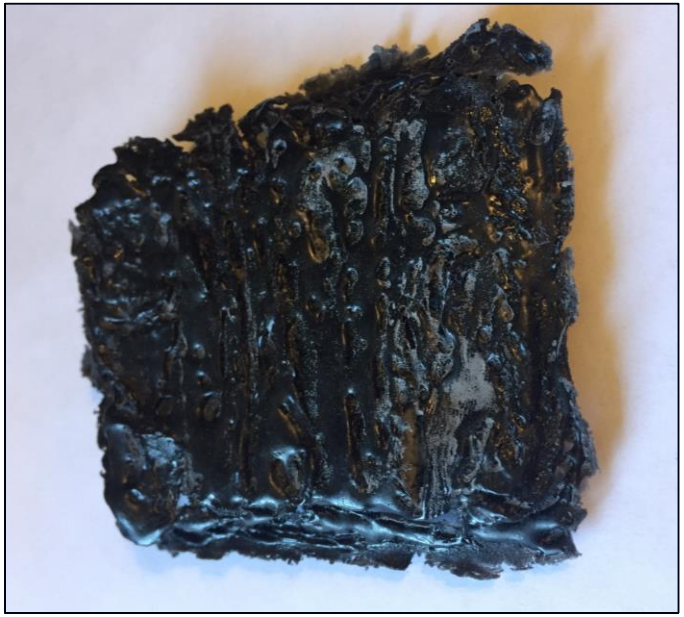
Develop a 3D printer capable of sintering sand by focusing sunlight with a Fresnel lens.

- Reach ~1723°C in order to sinter sand and build glassified structures
- Test sintering process on a variety of materials in various conditions
    - Confirm sinter temperatures achievable
- Subject process to various light and ambient conditions

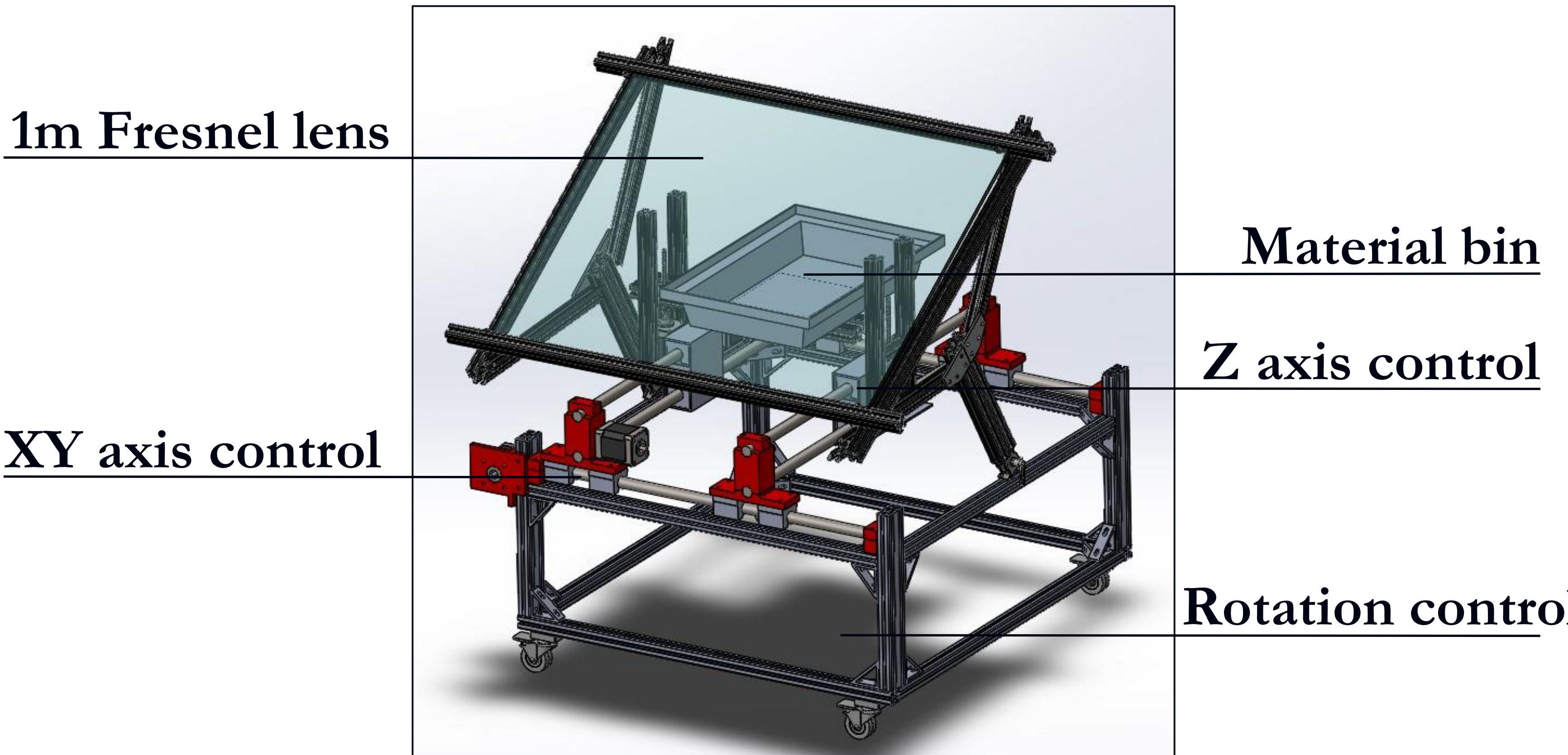
Early Feasibility Testing

- Small Fresnel lens (8.5" x 11") and sinter powder allowed us to create rough layered structure



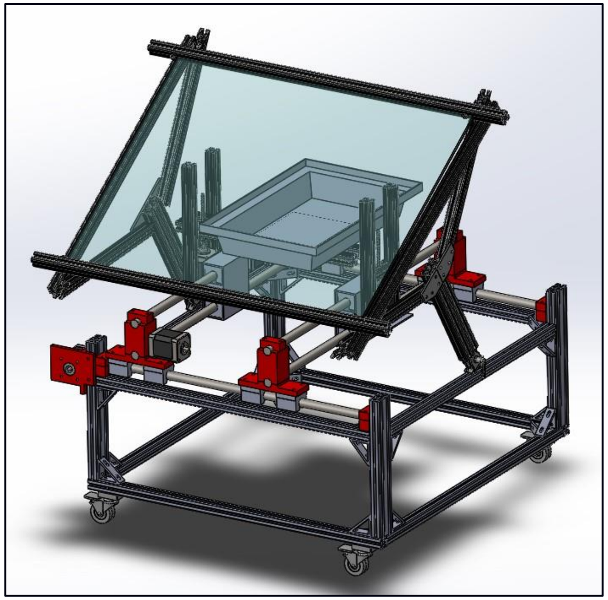


Experimental Design Overview



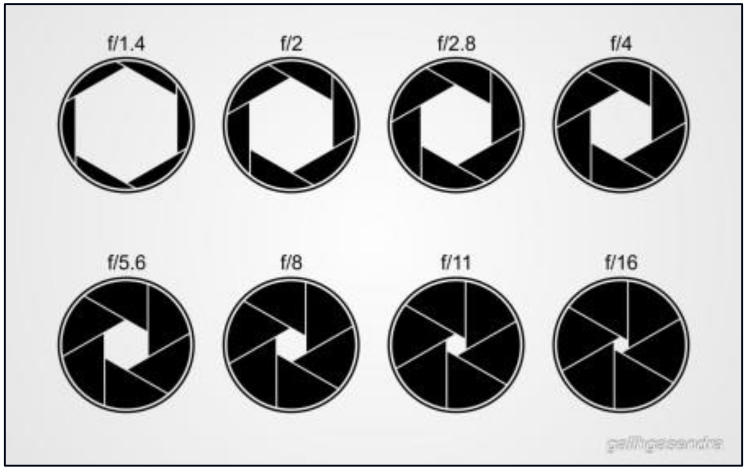
Experimental Design Overview

- Sunlight focused through Fresnel sheet lens
  - Variable arm length to focus beam
- Control lens tilt and machine's rotation to track sun
  - Beam consistency
- Print bed with test material translates in x-y-z
  - Powder leveling manual
- Programmable movements using Arduino controller with Gcode commands



Next Steps

- Using additives to enhance structure
- Building air-tight structures
- Adjusting aperture of lens to vary power
- Coordination of printing with autonomous fleet



Research Context

- Major industry focus on developing 3D printing technologies
- Aim to fit solar sinter technology into the framework of off-world habitat construction
  - Fill gaps in FDM capabilities
- Low-energy alternative to other 3D printing technologies

Experimental Challenges

- Environmental testing
  - Vacuum testing
  - Temperature testing
- Scaling the design while maintaining power output
- Refining sinter calculations to environments and foreign materials
  - Experimentally prove the power estimations

Summary

- Determined feasibility of adapting SLS printing to be powered by sunlight in a variety of off-world environments.
- Solar-powered 3D printing can reduce the energy demand for robotic printing operation.
- Applications of the technology in building off-world structures.
- Objectives of experimental testing.

References

https://kayserworks.com/#/798817030644/
https://www.nasa.gov/directorates/spacetech/centennial_challenges/3DPHab/index.html

Effects of Microgravity on Extrusion based Additive Manufacturing, Made In Space Solar 3D printing of lunar regolith, A. Meurisse, 2013, Acta Astronautica.

Building components for an outpost on the Lunar soil by means of a novel 3D printing technology, Giovanni Cesaretti, 2012.

https://reprap.org/forum/read.php?153,231867, Laser Power Calculator for SLS, Igor Lobanov

Image Credits:

https://www.3dhubs.com/knowledge-base/introduction-sls-3d-printing/#pros-cons

https://www.researchgate.net/figure/The-shape-of-Fresnel-lens-Fresnel-lens-is-made-by-removing-the-non-refractive-part-of-a_fig2_288700936

https://www.nasa.gov/directorates/spacetech/centennial_challenges/images.html

https://www.esa.int/Applications/Telecommunications_Integrated_Applications/Technology_Transfer/3D_Printing_our_future_in_space_and_on_Earth

SpaceTREx

LABORATORY

Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory

ASTEROID
CENTER

Asteroid Science, Technology and Exploration Research Organized by Inclusive eDucation (ASTEROID) Center


SpaceTREx
Adventure Awaits