Transforming Lunar Regolith into a Digital Printing Material

Voxel Advanced Digital-manufacturing for Earth and Regolith in Space (VADERS)

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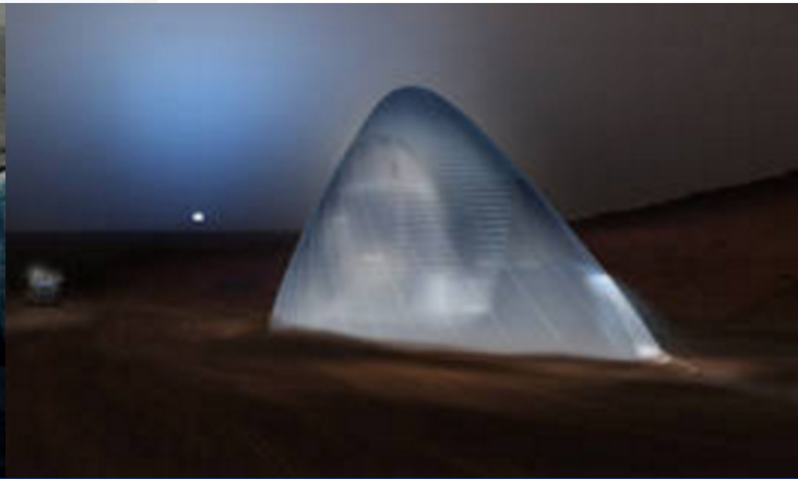
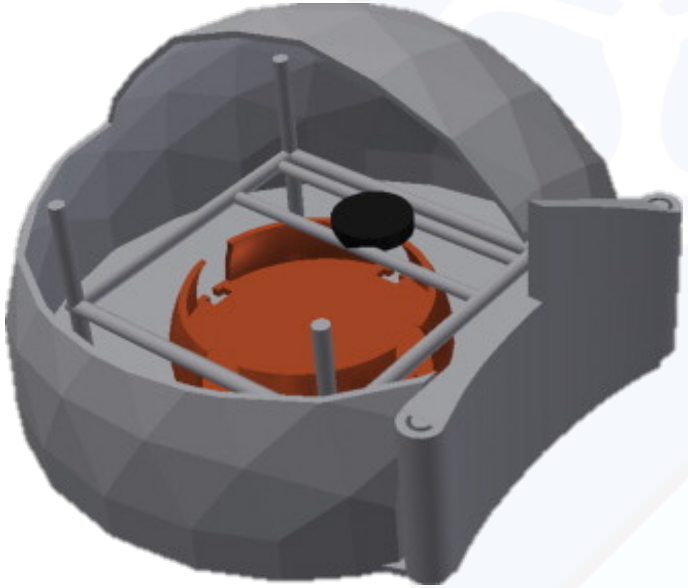
NASA's Journey to Mars: Pioneering Principles

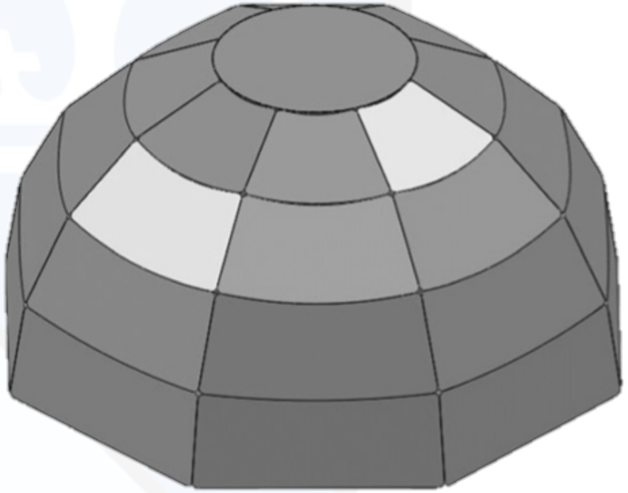
"Resilient architecture featuring multi-use, evolvable space infrastructure, minimizing unique major developments, with each mission leaving something behind to support subsequent missions"



ISRU for Habitat Construction



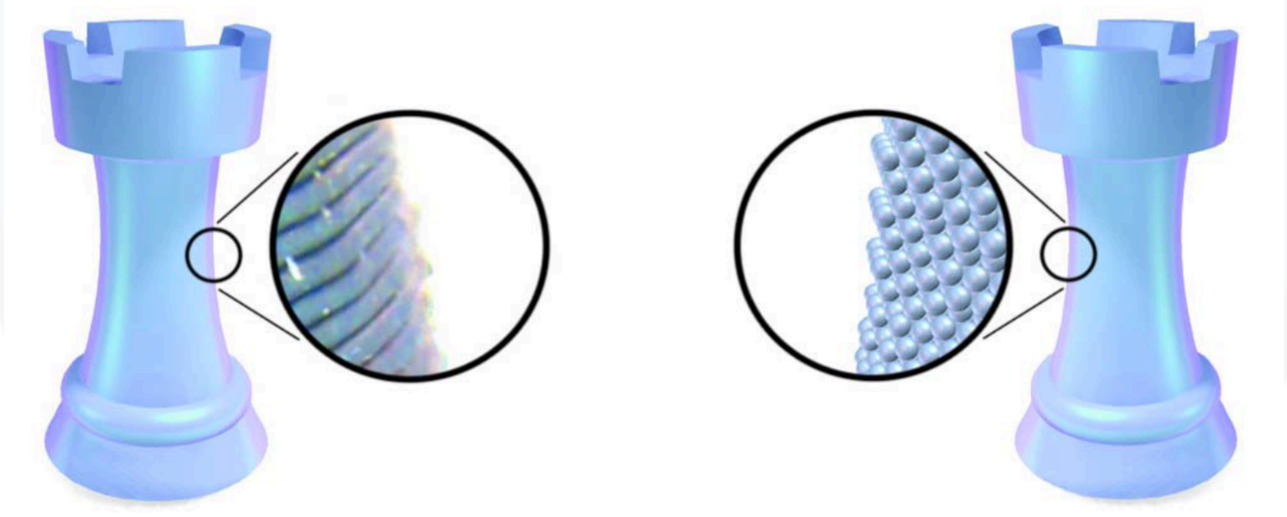
Dome structures consisting of basalt structural triangles assembled onto temporary scaffolding. The tiles may be sealed or pressurized (Kading, et al)



Voissoir structure in which parts are produced by geothermite reaction in unique silica slip crucibles (Faierson, et al)

Digital 3D Printing

Digital materials are comprised of physical, self-aligning, fundamental units known as “voxels”. Digital printing forms structures by placement of discrete voxels instead of continuous material deposition of analog, traditional 3D printing.

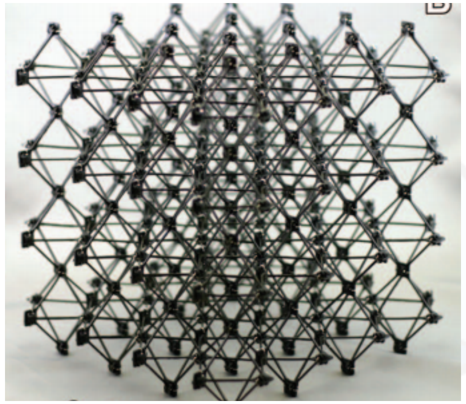


Analog 3D Printing   Digital 3D Printing

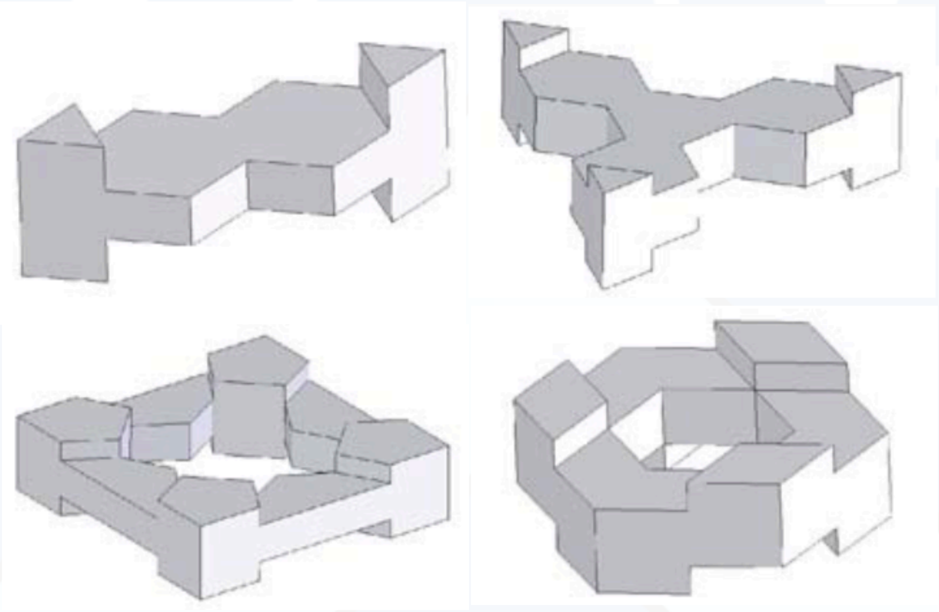
- Allow for zero noise despite using a noisy and inaccurate substrate
- Repeatable and scalable with no loss in 3D information
- Inherent capability of co-fabrication using a diverse set of materials

Voxel Design

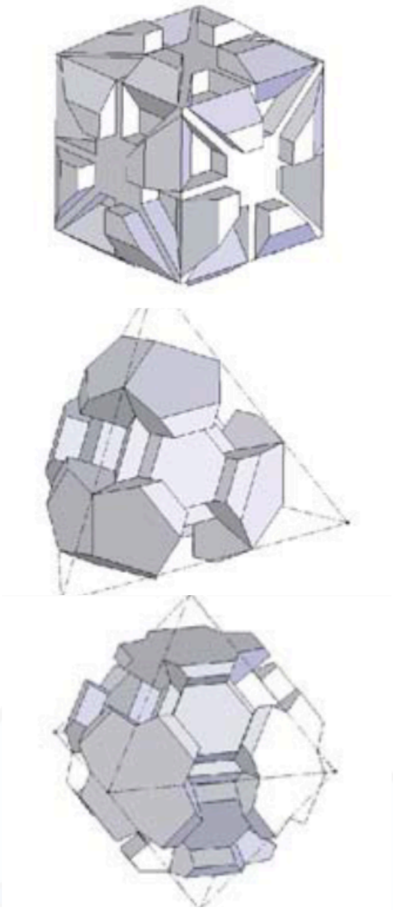
Gershenfeld's GIKS concept



Gershenfeld's lattice (cuboct) concept



2.5D Interlocking Design



3D Interlocking Design

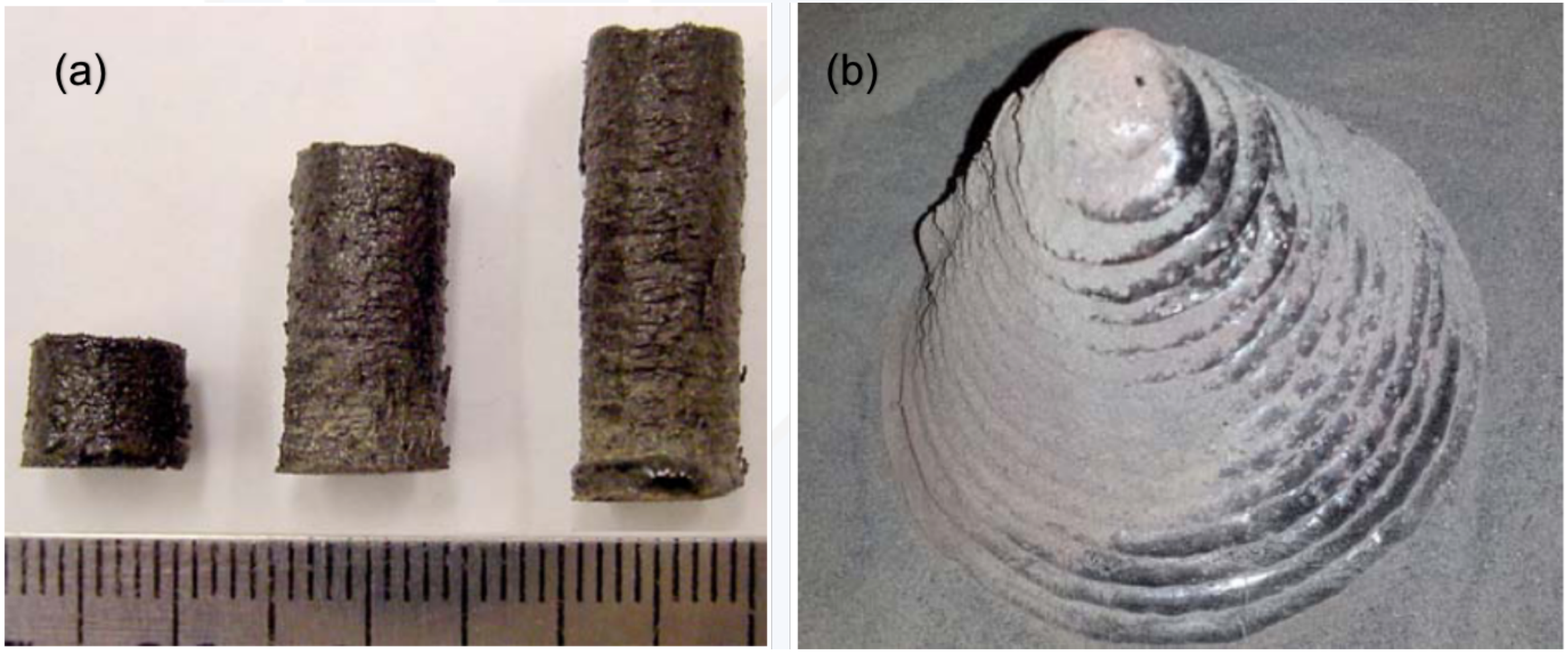
Proposed Design for Regolith Fabrication

- 2.5D square design has interlocking capability which obviates the need of post-processing
- To mitigate need for mining of scarce in situ materials or transported binders from Earth, geometric interlocking capability becomes a particularly important consideration

- Space-filling
- Rotation and flip invariance
- Manufacturability
- Assembly complexity
- *Poor self-alignment*
- *Tessellation in R^2*

Fabricating Voxels from Lunar Regolith

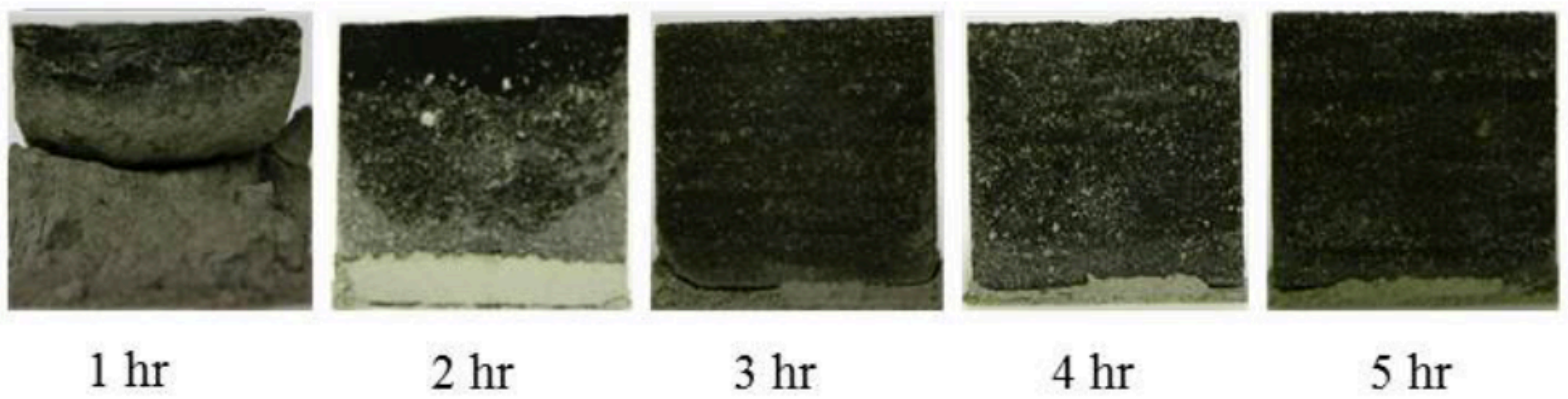
- Thermal Processing



Solid lunar regolith simulant parts laser fabricated using (a) a 50W Nd-YAG laser forming layers of 0.25mm thickness (Balla, et al) and (b) a 500W diode laser forming 8.9mm thick layers (Mueller, et al)

Fabricating Voxels from Lunar Regolith

- Thermal Processing
- Additives and Binders



Solidification of lunar concrete using the artificial lunar soil and thermoplastic polymeric material as binder (Lee, et al)

Fabricating Voxels from Lunar Regolith

- Thermal Processing
- Additives and Binders
- Chemical Reactions

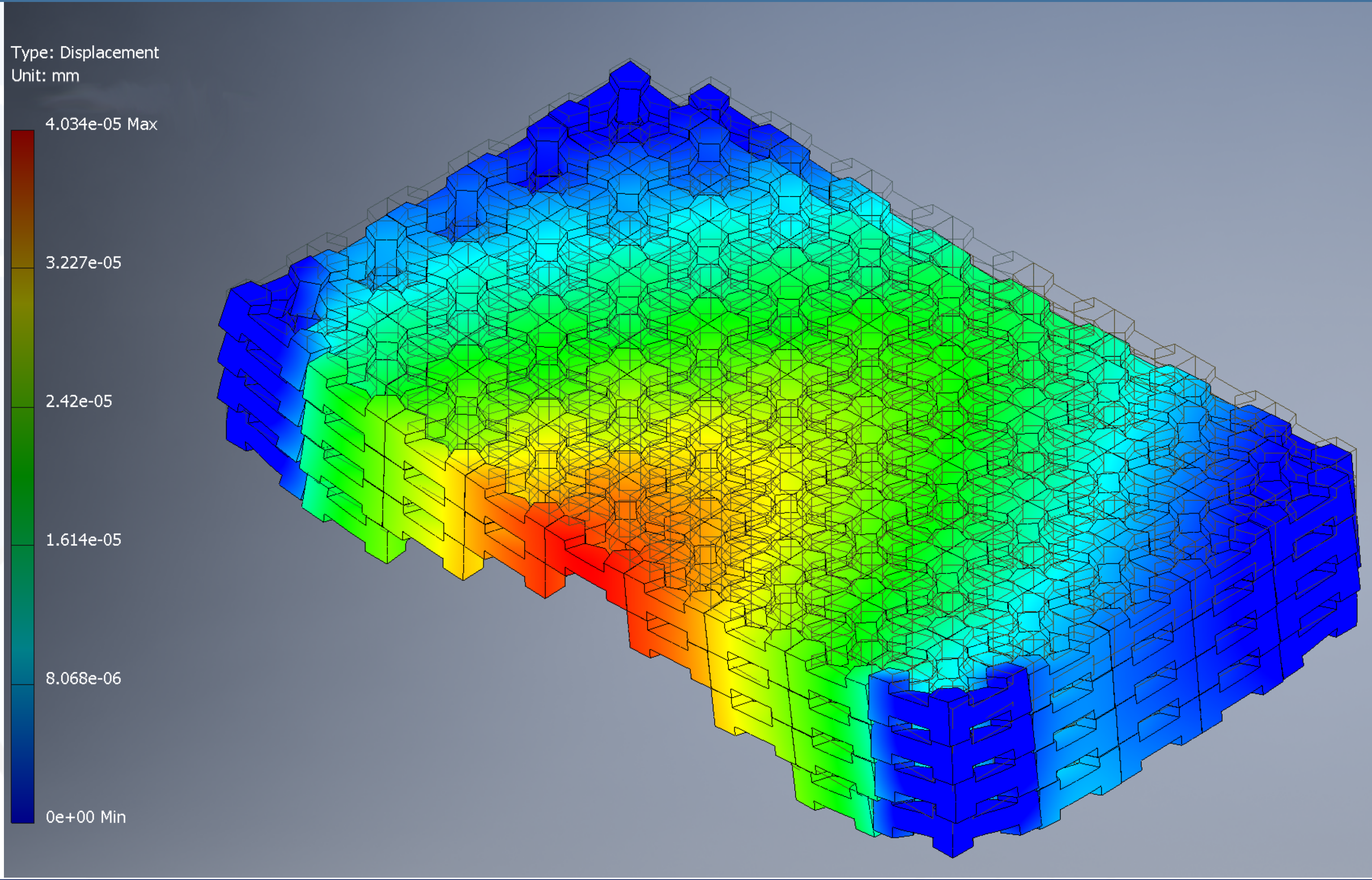
Fabricating Voxels from Lunar Regolith

- Thermal Processing
- ~~Additives and Binders~~
- ~~Chemical Reactions~~

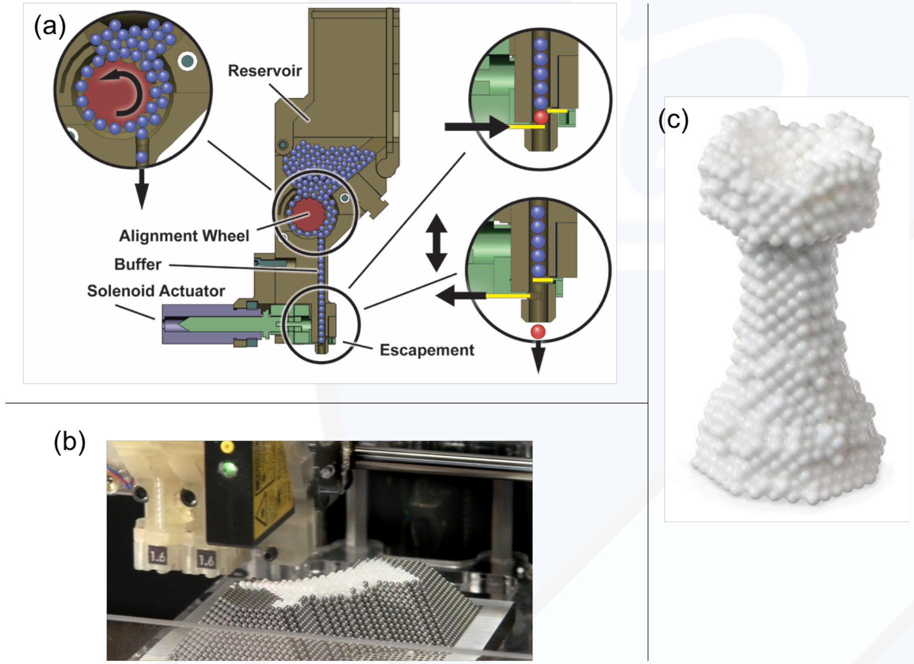
Regolith voxel shown is approximately 25mm by 25mm by 10 mm

Stress/Strain Analysis of a Digital Structure

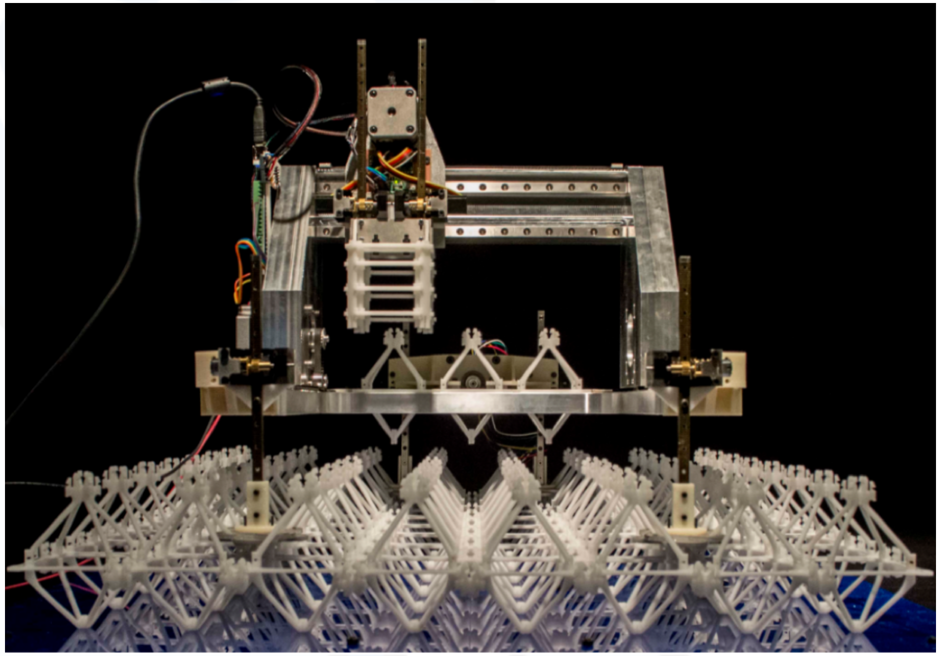
Assumed that the fabricated regolith has the same properties of non-reinforced glass and subjected the structure to 10 times lunar gravity



Digital Assembly



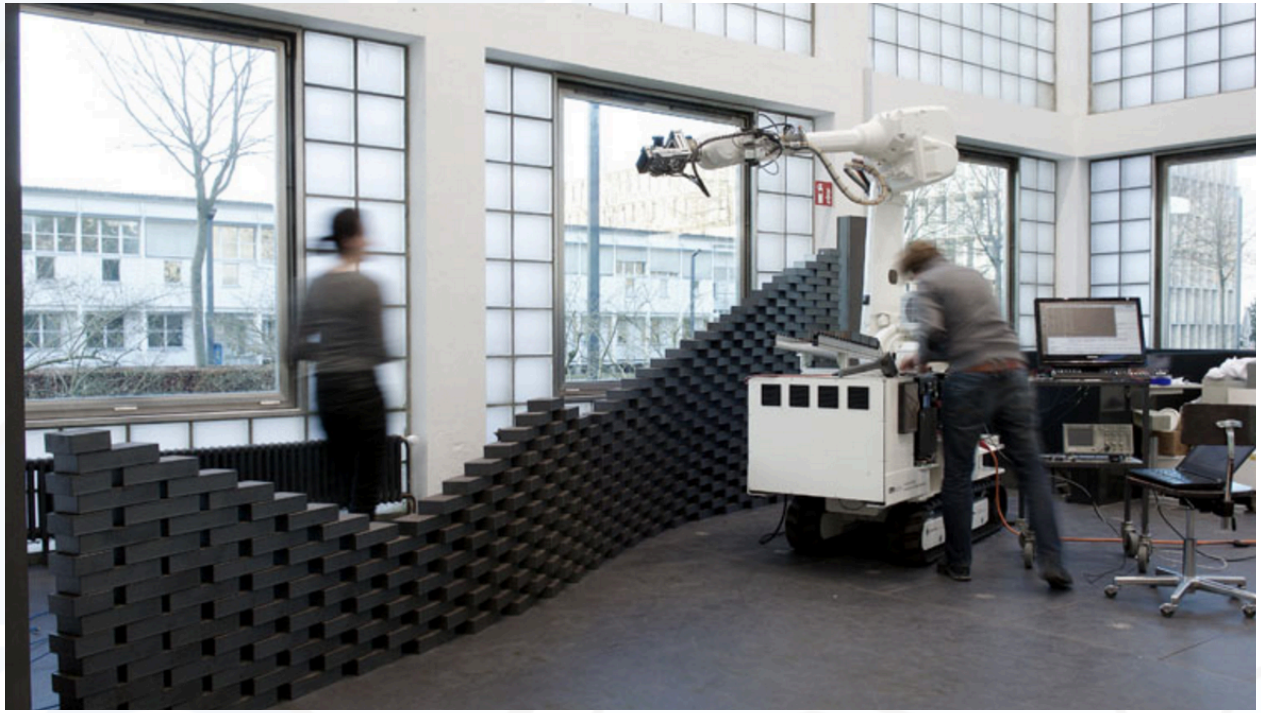
Rapid serial assembly using spherical elements: (a) the mechanism of jetting discrete elements, (b) implementation of rapid assembly shown partway through a 10,000 element build, and (c) assembled digital object consisting of selectively bonded elements to enable freeform shape (Hiller)



Discrete cellular lattice assembler that is bounded to the structure being constructed, as opposed to the traditional gantry-type motion systems (Gershenfeld)

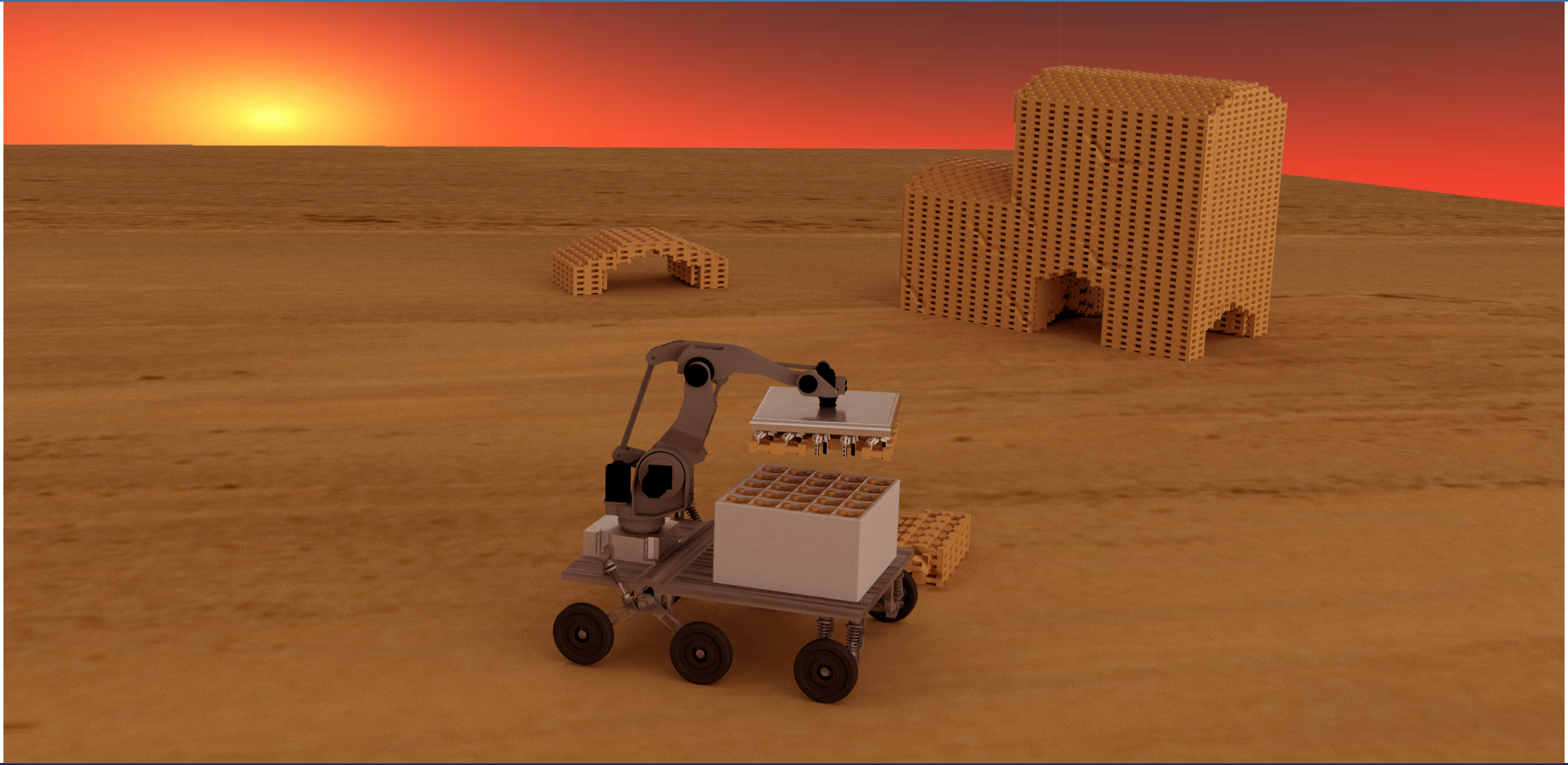
Digital Construction Technology

MX3D Bridge – 3D printing a steel bridge in Amsterdam



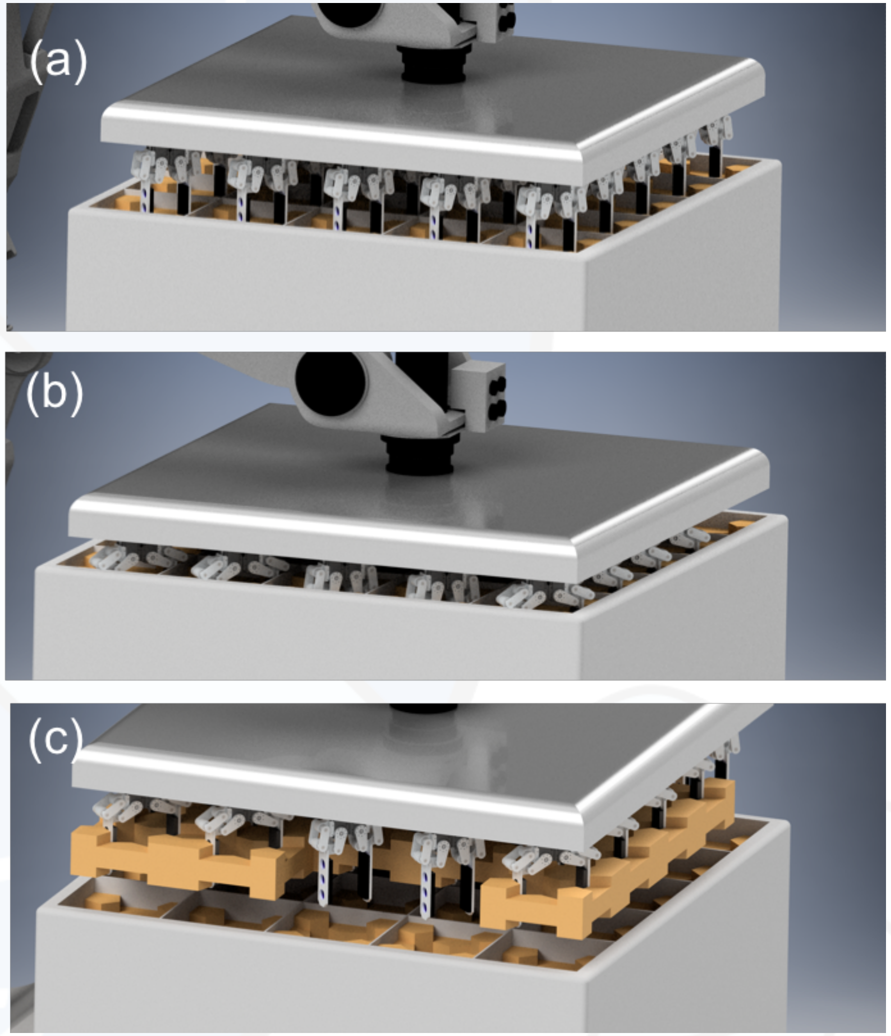
In situ fabricator designed by Kathrin Dorfler under the Chair of Architecture and Digital Fabrication, ETH Zurich

Proposed Assembler

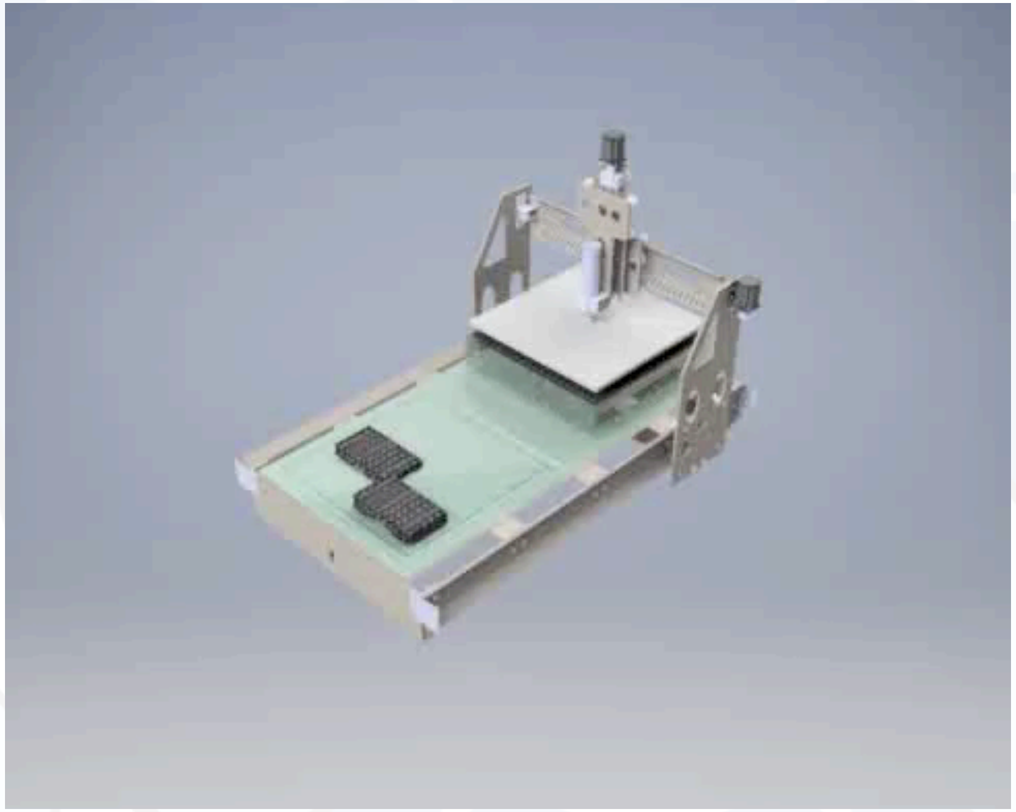


Printhead Design Concept

- Parallel selective placement
- Mounted on a mobile platform
- Mechanism at the base of feedstock supply to keep the top layer populated



Printhead Design Concept



Thank you!

Acknowledgments

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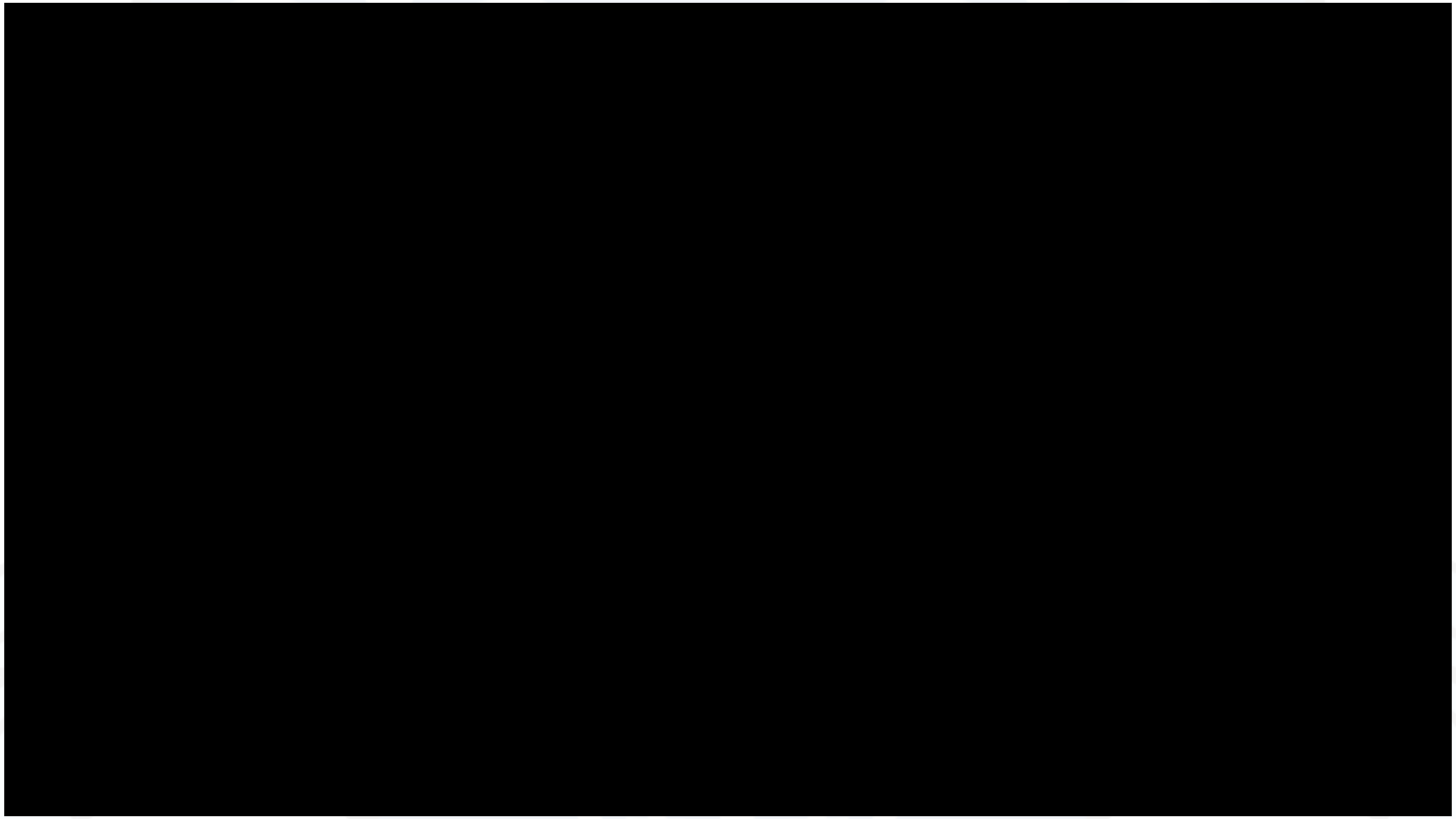
Printhead Design Concept



<table>
<tr><th>Property</th><th>Minimum</th><th>Maximum</th></tr>
<tr><td>Volume</td><td colspan="2">5.625×10^{3} mm^3</td></tr>
<tr><td>Mass</td><td colspan="2">1.22625×10^{-2} kg</td></tr>
<tr><td>Von Mises Stress</td><td>6.52105×10^{-6} MPa</td><td>2.73331×10^{-1} MPa</td></tr>
<tr><td>1st Principal Stress</td><td>-7.60642×10^{-2} MPa</td><td>1.62595×10^{-1} MPa</td></tr>
<tr><td>3rd Principal Stress</td><td>-2.95661×10^{-1} MPa</td><td>5.23447×10^{-2} MPa</td></tr>
<tr><td>Displacement</td><td>0 mm</td><td>4.03384×10^{-2} mm</td></tr>
<tr><td>Safety Factor</td><td>1.5×10^{1}</td><td>1.5×10^{1}</td></tr>
<tr><td>Stress XX</td><td>-1.35025×10^{-1} MPa</td><td>1.23309×10^{-1} MPa</td></tr>
<tr><td>Stress XY</td><td>-5.30395×10^{-2} MPa</td><td>4.944549×10^{-2} MPa</td></tr>
<tr><td>Stress XZ</td><td>-6.20798×10^{-2}</td><td>5.98036×10^{-2} MPa</td></tr>
<tr><td>Stress YY</td><td>-1.67326×10^{-1} MPa</td><td>9.78457×10^{-2} MPa</td></tr>
<tr><td>Stress YZ</td><td>-9.53303×10^{-2} MPa</td><td>9.17011×10^{-2} MPa</td></tr>
<tr><td>Stress ZZ</td><td>-2.56439×10^{-1} MPa</td><td>1.30839×10^{-1} MPa</td></tr>
<tr><td>X Displacement</td><td>-5.20557×10^{-6} mm</td><td>3.48644×10^{-6} mm</td></tr>
<tr><td>Y Displacement</td><td>-3.40824×10^{-6} mm</td><td>4.00937×10^{-5} mm</td></tr>
<tr><td>Z Displacement</td><td>-9.12192×10^{-6} mm</td><td>9.12791×10^{-6} mm</td></tr>
<tr><td>Equivalent Strain</td><td>7.65714×10^{-11}</td><td>3.50444×10^{-6}</td></tr>
<tr><td>1st Principal Strain</td><td>-3.53152×10^{-7}</td><td>3.50444×10^{-6}</td></tr>
<tr><td>3rd Principal Strain</td><td>-4.2002×10^{-6}</td><td>2.09938×10^{-7}</td></tr>
<tr><td>Strain XX</td><td>-1.95993×10^{-6}</td><td>1.74816×10^{-6}</td></tr>
<tr><td>Strain XY</td><td>-9.28196×10^{-7}</td><td>8.6546×10^{-7}</td></tr>
<tr><td>Strain XZ</td><td>-1.0864×10^{-6}</td><td>1.04656×10^{-6}</td></tr>
<tr><td>Strain YY</td><td>-1.92431×10^{-6}</td><td>1.37308×10^{-6}</td></tr>
<tr><td>Strain YZ</td><td>-1.66828×10^{-6}</td><td>1.60477×10^{-6}</td></tr>
<tr><td>Strain ZZ</td><td>-3.62511×10^{-6}</td><td>1.52865×10^{-6}</td></tr>
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	Mars			Earth		Moon	
Oxide	**JSC Mars-1 Martian Simulant**	**Pathfinder**	**Viking Lander**	**Black Point, AZ (BP-1 Lunar Simulant)**	**Mauna Kea, HI Tephra (Basalt)**	**Mare**	**Highlands**
SiO_2	43.7	43.8	44.7	47.2	50.4	46.7	43.7
TiO_2	3.8	0.7	0.9	2.3	2.71	1.7	3.5
Al_2O_3	23.4	10.1	5.7	16.7	17.1	13.2	17.4
Fe_2O_3/FeO	15.3	17.5	18.2	12.1	11.3	16.3	12.2
MnO	0.3	0.6		0.21	0.21	0.21	0.16
MgO	3.4	8.6	8.3	6.5	3.93	10.9	11.1
CaO	6.2	5.3	5.6	9.2	6.91	10.4	11.3
Na_2O	2.4	3.6		3.5	4.55	0.38	0.42
K_2O	0.6	0.7	0.3	1.1	1.95	0.23	0.09
P_2O_5	0.9	1.0		0.52	0.88	0.16	0.08
SO_3		5.4	7.7				
Cl		0.6	0.7				
Total	**100.0**	**97.9**	**91.8**	**99.33**	**99.94**	**100.18**	**99.95**