Virtual Research Presentation Conference

Tunable Additively-Manufactured Impact Attenuation System for Entry, Decent, and Landing

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Program: Topic R&TD

Assigned Presentation RPC-177

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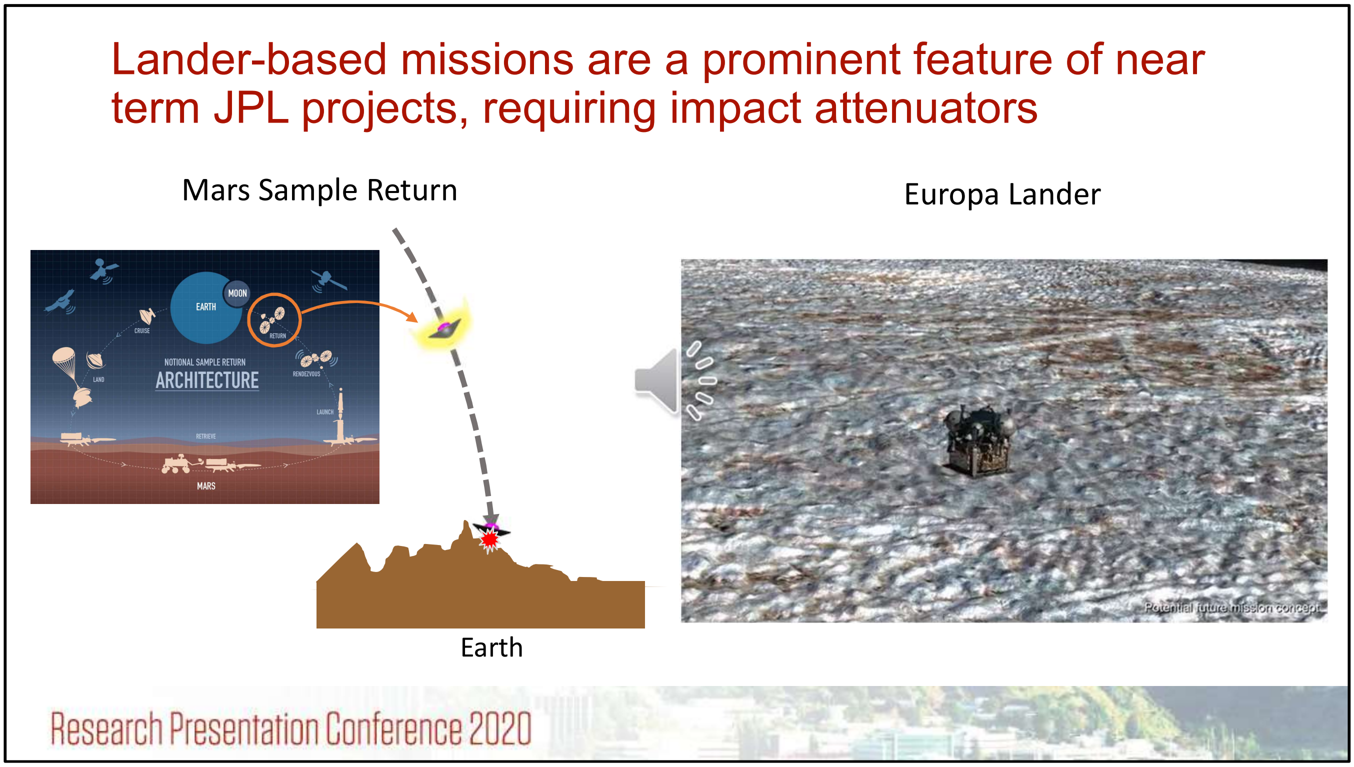

Lander-based missions are a prominent feature of near term JPL projects, requiring impact attenuators

Mars Sample Return

Europa Lander

Earth

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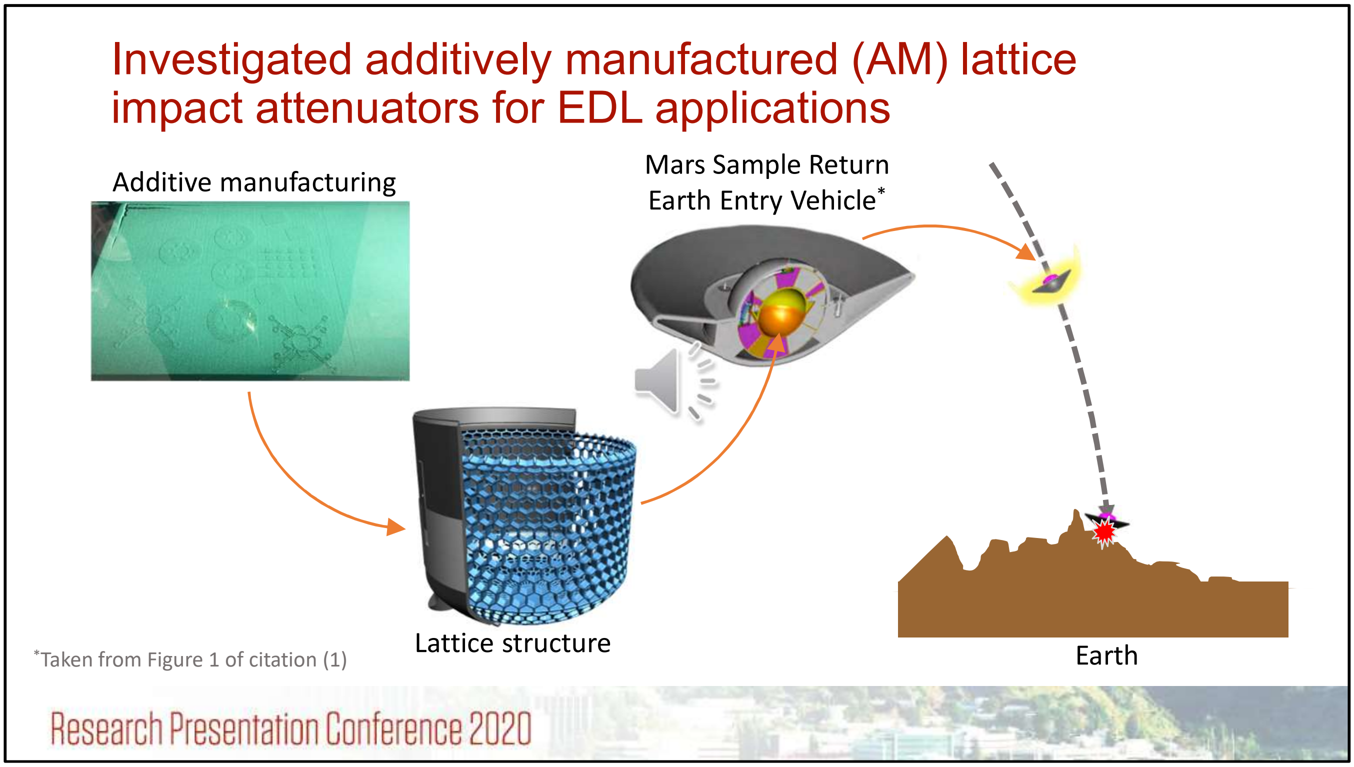
Lander based missions are a prominent feature of near term JPL projects. Programs like Mar Sample Return require passive impact attenuation for the Earth Entry vehicle, while for a program like Europa Lander, which is proposed to have an active decent system similar to the mars rover sky crane, still experiences impact loading and requires secondary attenuation systems. Efficient impact attenuators are therefore an import features of these lander-based systems.



Investigated additively manufactured (AM) lattice impact attenuators for EDL applications

Additive manufacturing

Mars Sample Return
Earth Entry Vehicle*

Lattice structure

Earth

*Taken from Figure 1 of citation (1)

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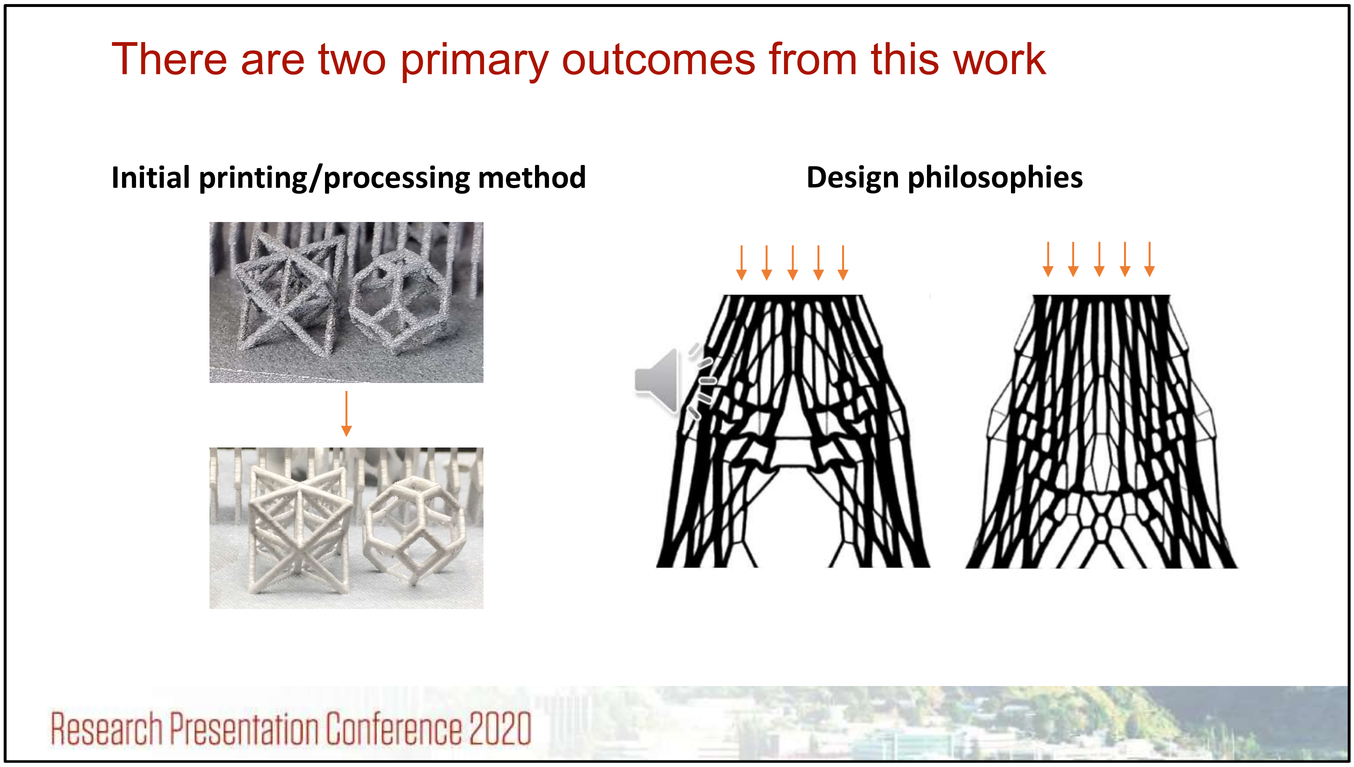
In this Topical RTD, we leverage the flexibility of metal additive manufacturing to create highly efficient lattice impact attenuators suitable for Entry, Descent, and Landing applications. In comparison to conventional honeycombs and foams, an AM lattices geometry can be spatially varied to achieve optimal efficiency while circumventing forming and bonding issues by printing fully conforming bodies. AM lattices therefore have the potential to not only decrease system mass, but to also significantly decrease the manufacturing complexity and lead time.



There are two primary outcomes from this work

Initial printing/processing method

Design philosophies

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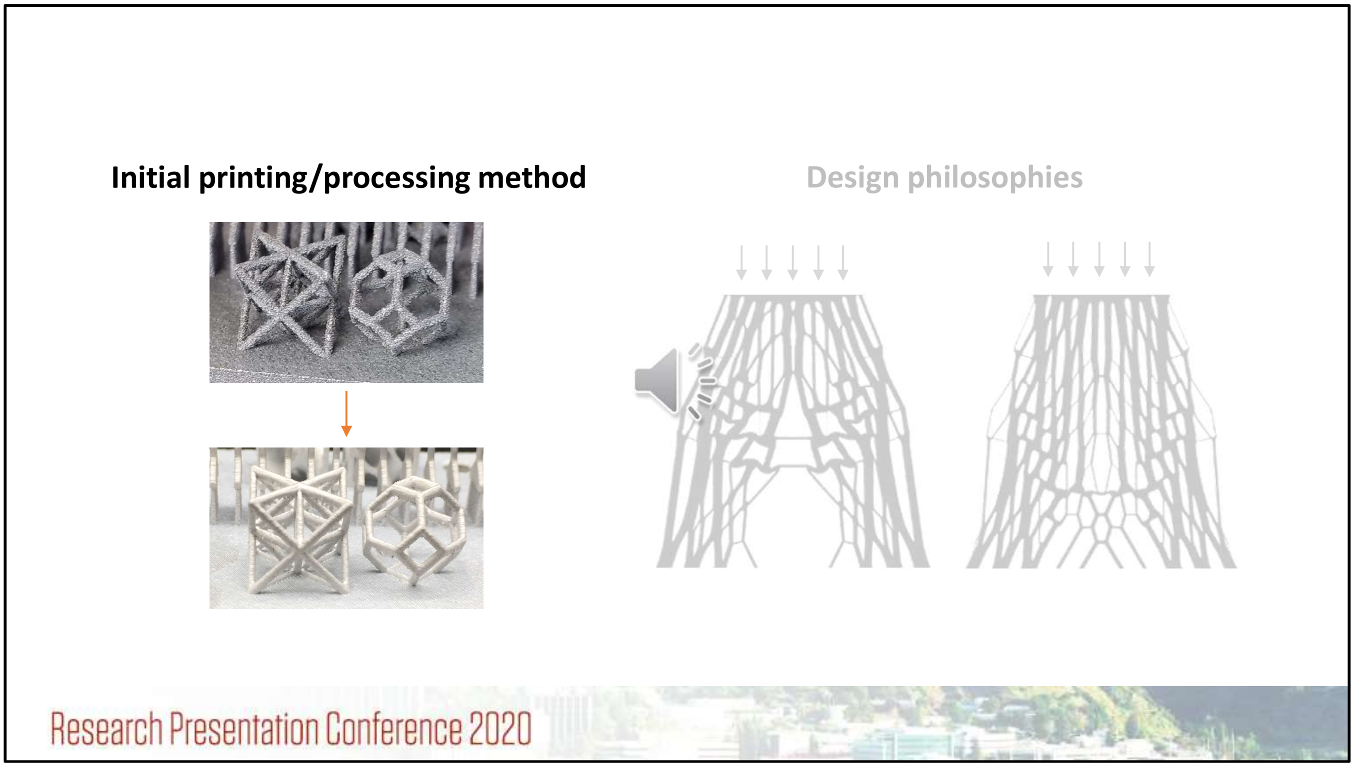
Although AM lattices pose a number of improvements over conventional materials, there are two primary issues that need to be overcome: poor mechanical properties due to small feature print defects and understanding the complex design space allotted by lattice structures. This work therefore focused on these 2 fundamental issues.



Initial printing/processing method

Design philosophies

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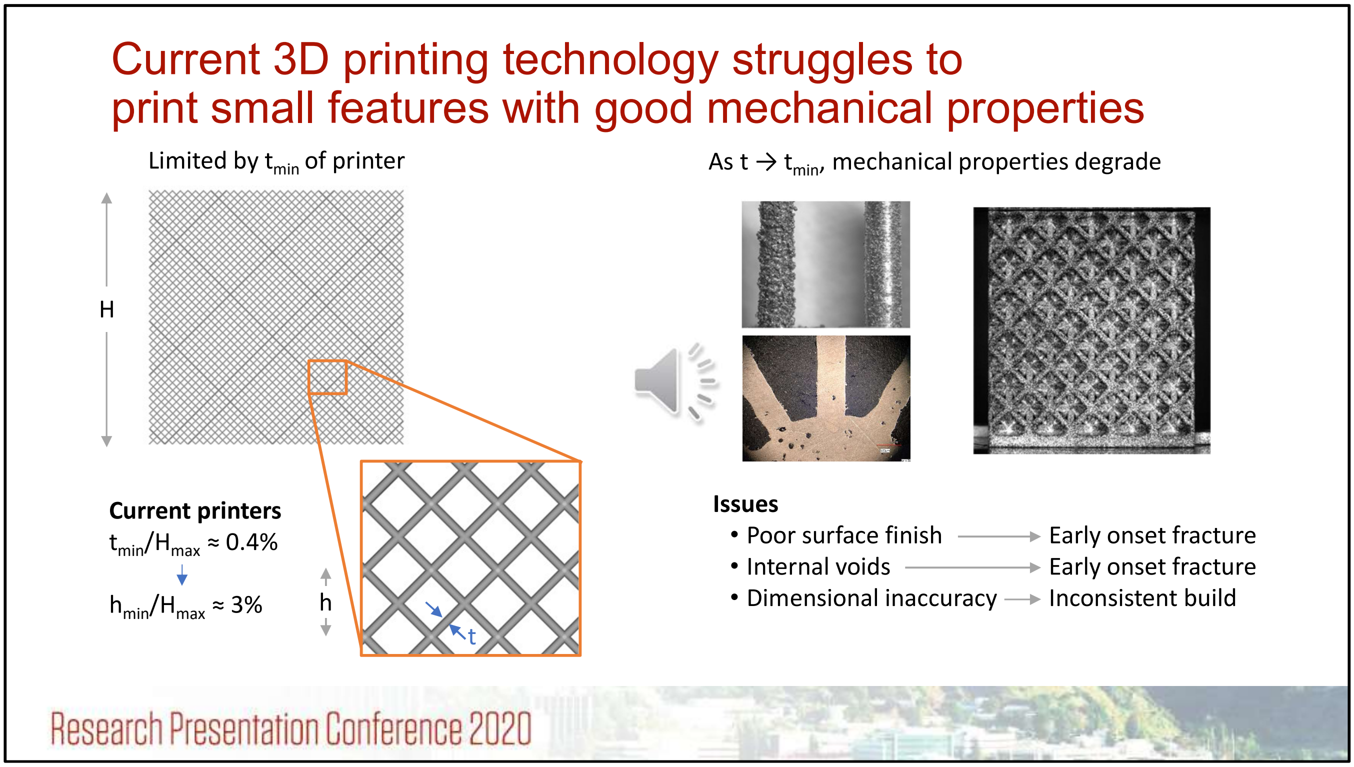
First looking at the manufacturing issues.



Current 3D printing technology struggles to print small features with good mechanical properties

Limited by t_{min} of printer

Current printers

$t_{min}/H_{max} \approx 0.4\%$

$h_{min}/H_{max} \approx 3\%$

As t → t_{min}, mechanical properties degrade

Issues

- Poor surface finish → Early onset fracture
- Internal voids → Early onset fracture
- Dimensional inaccuracy → Inconsistent build

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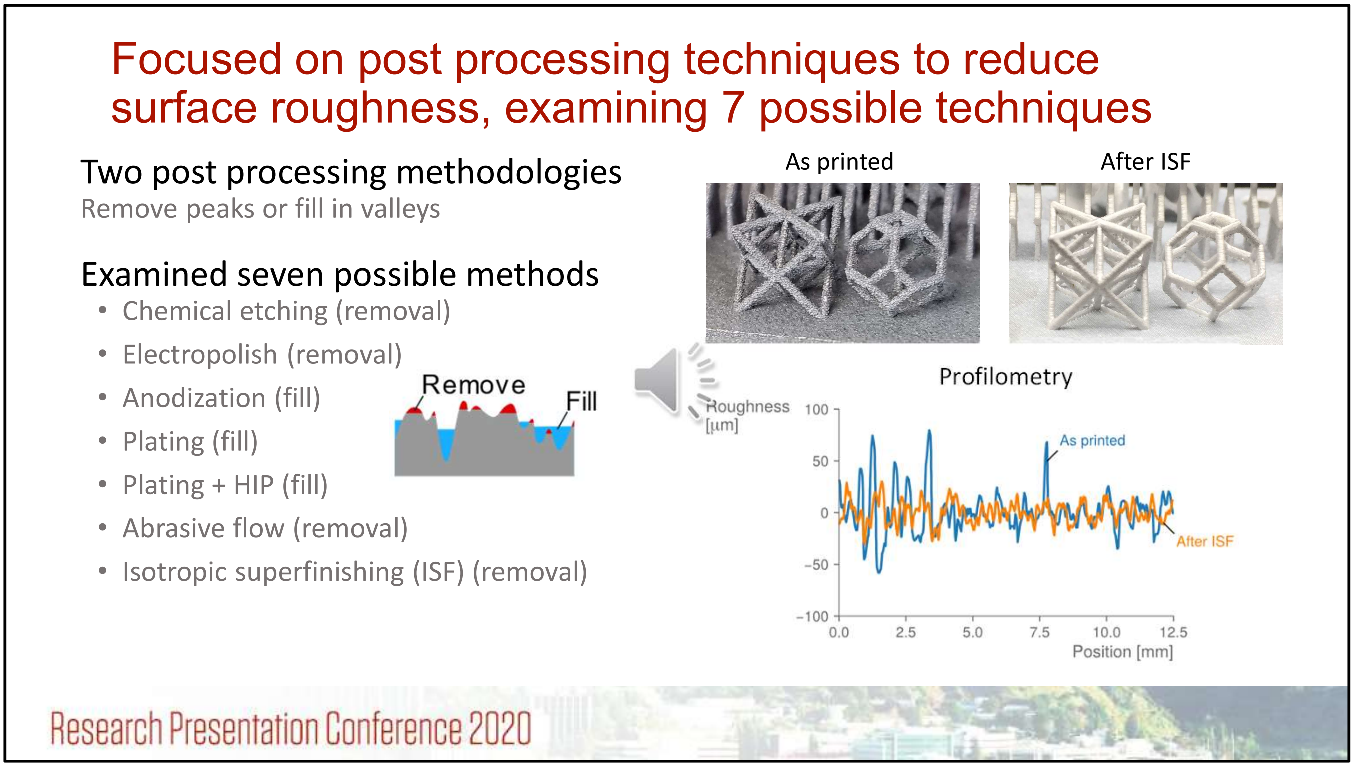
Lattice structures inherently consist of multiple length-scales: nestled within the large scale macro-structure is a much smaller sub-structure. In general, lattice structures achieve their optimal properties at low relative densities where the substructure is much smaller than the macro-structure. Unfortunately, this forces AM lattices to push up against the minimum printable feature size as noted by tmin here. Although these small feature can be printed, print defects are common, such as poor surface finish, internal voids, and dimensional inaccuracy, resulting in degraded mechanical properties. A good example of this degraded performance can be see in the compression video on the right, where the lattice ligaments fracture prematurely at the lattice nodes, rather than the desired plastic bending.



Focused on post processing techniques to reduce surface roughness, examining 7 possible techniques

Two post processing methodologies

Remove peaks or fill in valleys

Examined seven possible methods

- Chemical etching (removal)
- Electropolish (removal)
- Anodization (fill)
- Plating (fill)
- Plating + HIP (fill)
- Abrasive flow (removal)
- Isotropic superfinishing (ISF) (removal)

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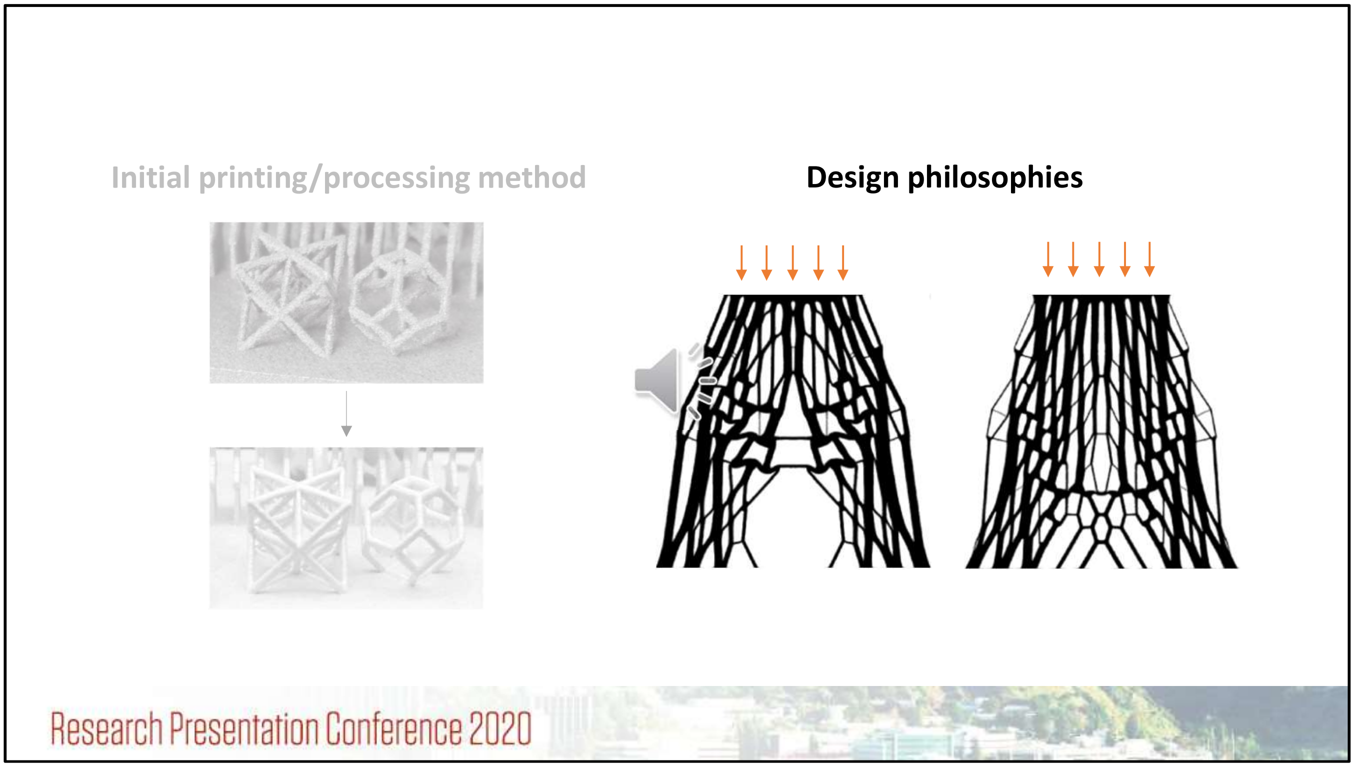
Of the aforementioned print defects, poor surface roughness is difficult to prevent during the print process. The print settings can be modified to reduce surface roughness, but this typically comes at the cost of increased internal voids and greater dimensional inaccuracy, both of which are challenging to fix after the face. We therefore focused on created prints with minimal internal voids and good dimensional accuracy, with the knowledge that we would have to fix the surface finish with post-processing. There are 2 surface roughness post processing methodologies: remove the peaks or fill in the valleys. We examined 7 different post processing techniques that applies both of these methodologies. Of these post processing techniques, the Isotropic superfinish process seems to show the greatest promise, with before and after pictures show on the right, along with the corresponding profilometry results. Of particular note is that the surface roughness was reduced by 50%. In follow on work, we plan to look into the effects of post processing on the mechanical properties of the lattices and will this information to further refine the processing.



Initial printing/processing method

Design philosophies

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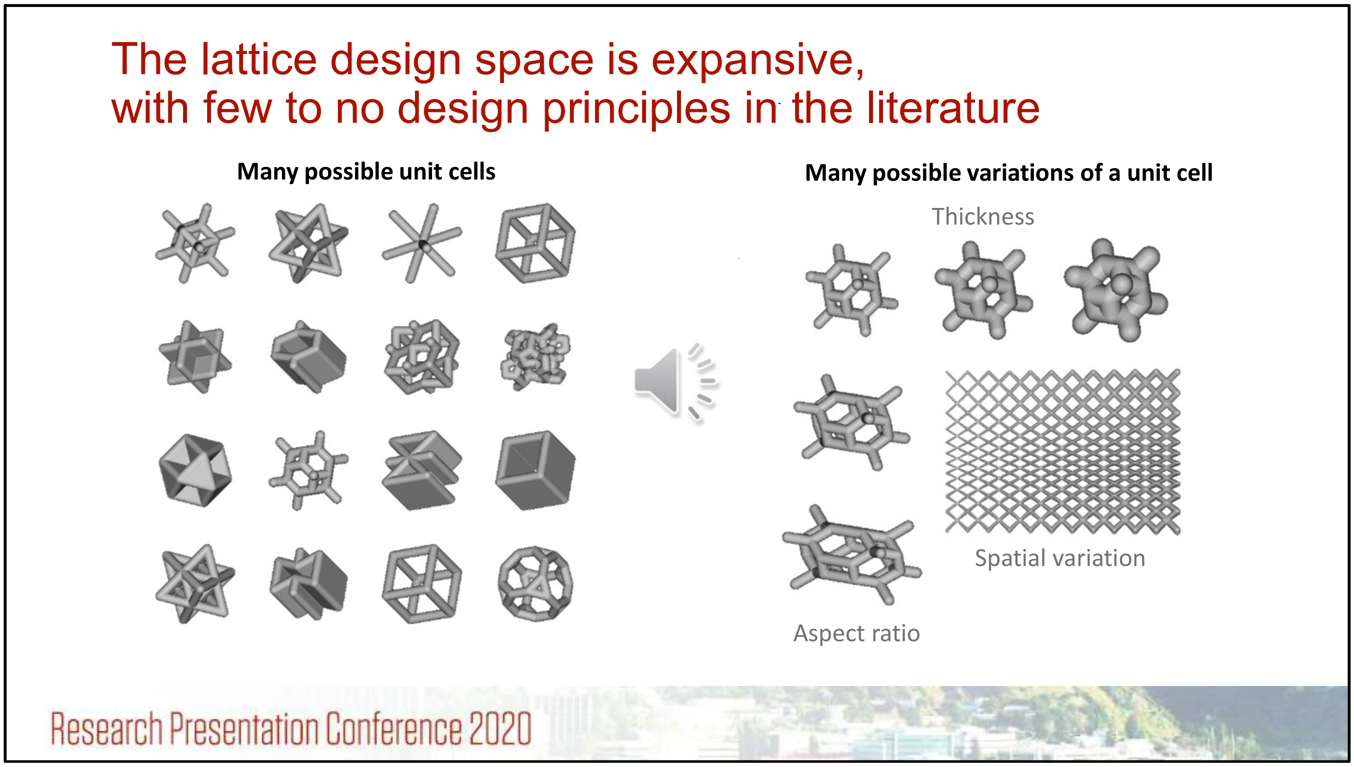
With respect to lattice design



The lattice design space is expansive, with few to no design principles in the literature

Many possible unit cells

Many possible variations of a unit cell

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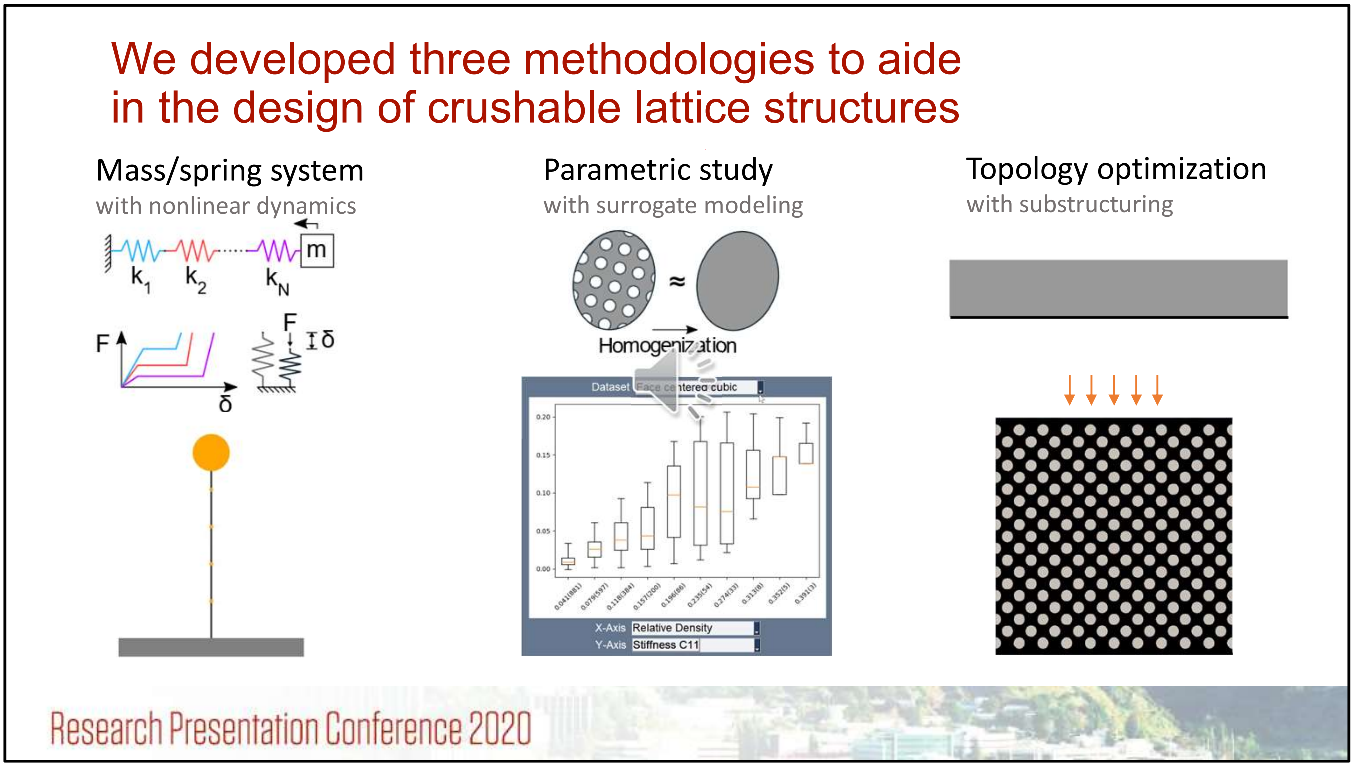
The primary challenge here is navigating the nearly infinite design space allotted by lattice structures. A sampling of unit cell geometries are shown on the left, however, there are hundreds, if not thousands, of designs that are conceivable. So, how do you go about selecting the right one? Furthermore, for each unit cell geometry, there are further variations that are achievable by varying the ligament thickness or modifying the cell aspect ratio. And, if that wasn't bad enough, you now have the flexibility to vary all of these quantities spatially throughout your structure.



We developed three methodologies to aide in the design of crushable lattice structures

Mass/spring system
with nonlinear dynamics

Parametric study
with surrogate modeling

Topology optimization
with substructuring

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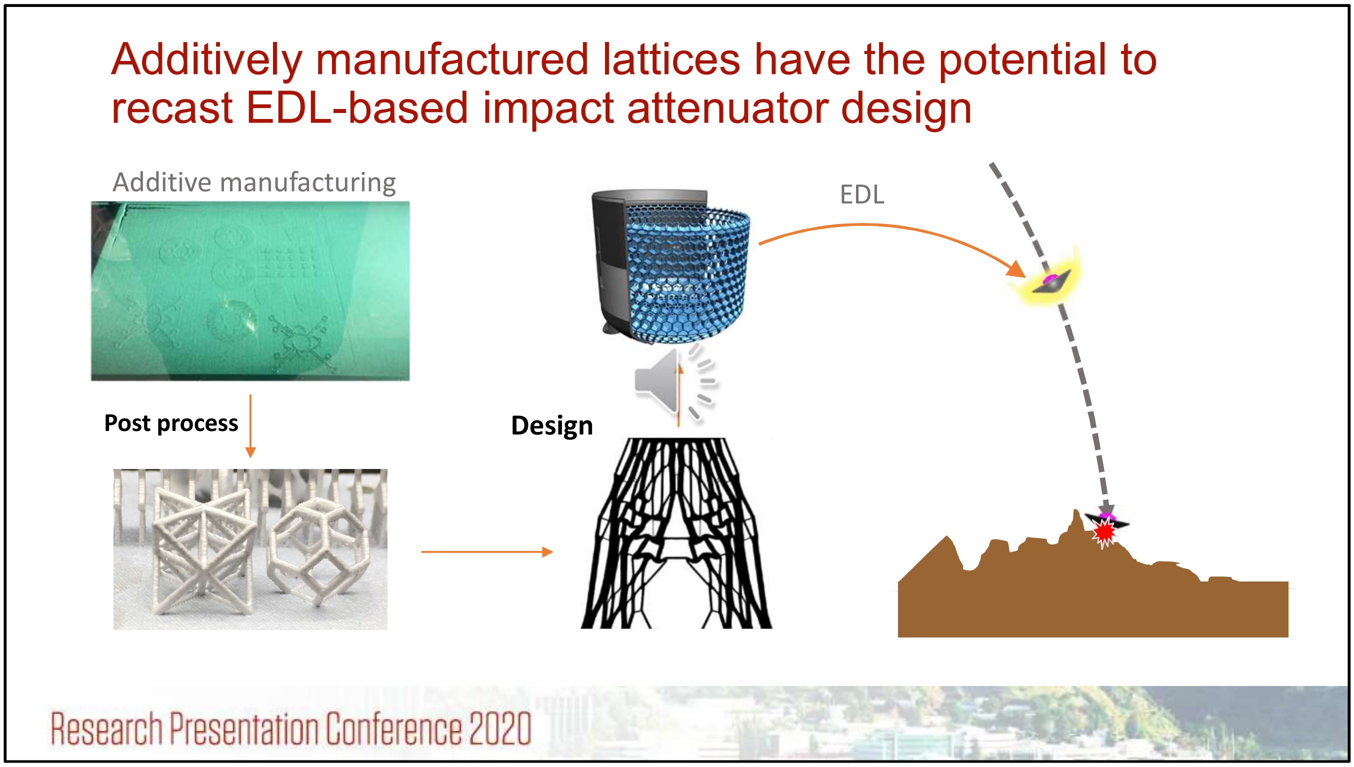
So, the help a design better understand this highly complex design space, we developed 3 complementary design tools. Each of these tools addresses a particular complexity of lattice design. The first framework leverages a nonlinear mass/spring system. The concept here is that each spring in the system represents a block of lattice that has a specific crush behavior, as indicated the force/displacement relationships on the left. The mass at the end of the system then represents the inertia of the system. The primary benefits of this modeling framework is that it captures both the nonlinear crush behavior of the lattices and the effects of system dynamics, both of which tend to be intractable from higher fidelity models. This allows the designer to iteratively vary the spatial distribution of lattice-like crush behavior to gain a better intuition on how to leverage this capability. What this design tool does not provide is what unit cells should be used to achieve a particular crush response; additional, it is a relatively low fidelity representation of the system. That is where the second design tool comes in. Here, the multiscale modeling technique of homogenization is used to create a high fidelity representation of a unit cell. We then completed an expansive parametric study, examing over 30 different unit cell geometries, and more than 10,0000 total sample points. Due to the computation cost of these simulations, a surrogate model was then developed to fill in the gaps within the design space. Ultimately, an initial graphical user interface was developed as shown in the middle video to allow a designer to compare the properties across the design space. This information could then be used to select a unit cell with the desired mechanical properties identified by the mass/spring model. Lastly, a topology optimization design framework was developed based on the level set method. The primary innovation here is the addition of substructing to the design optimization, forcing the optimizer to create lattice-like structure. Unlike the other 2 design philosophies, this methodology fully leverages spatial variation of lattice structures. Unfortunately, optimization the design based on the crush behavior of the structure was computationally intractable due to the highly nonlinear behavior of lattice crushing. We therefore focused on the linear portion of the response and formulated the optimization parameters to create a structure that will crush well in the nonlinear regime. Our initial investigations suggest that minimization of the peak strain energy within the structure results in even-load distribution throughout the structure, which should result in full utilization of the structure during crushing. Further validation of this methodology is required, but seems to show promise.



Additively manufactured lattices have the potential to recast EDL-based impact attenuator design

Additive manufacturing

Post process

Design

EDL

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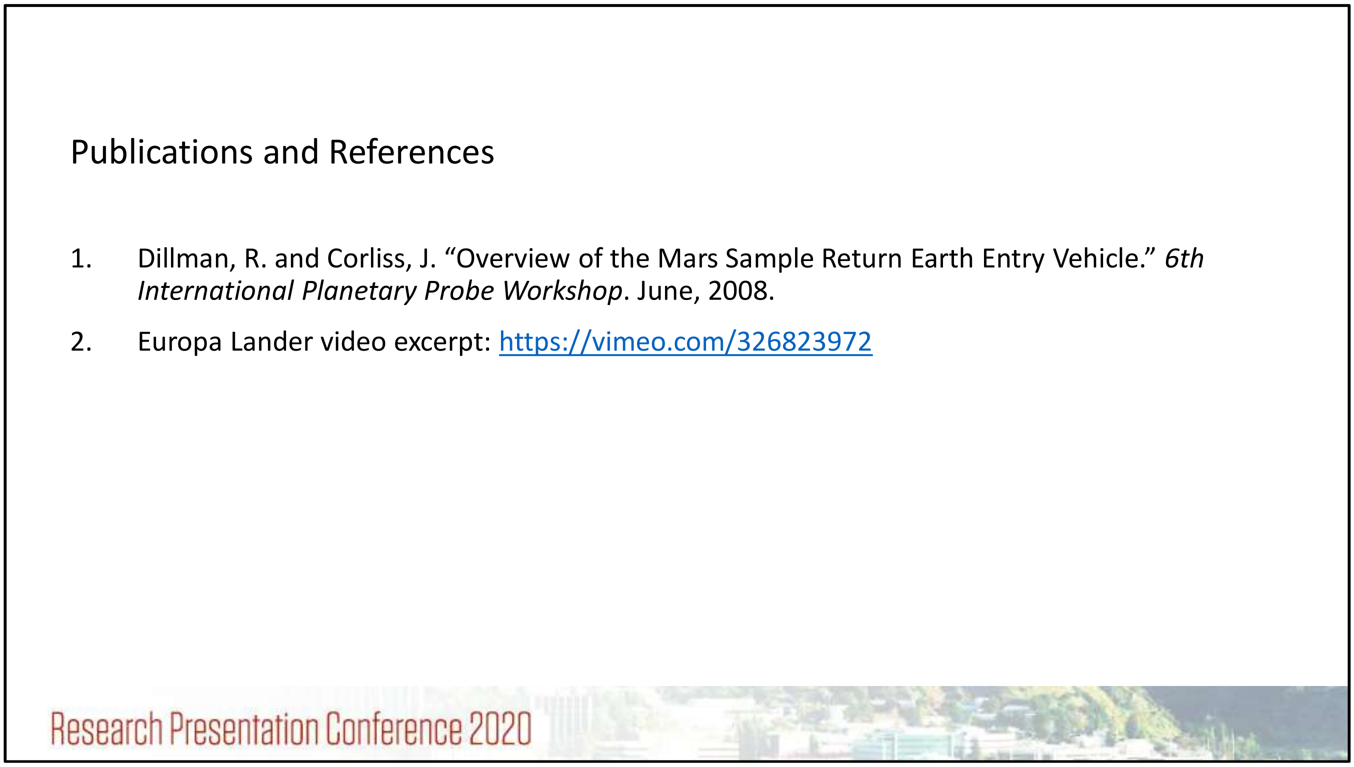
In closing, additively manufactured lattice structure have the potential to greatly improve impact attenuators used for EDL applications. Although further development is required, our work this year on improving the mechanical properties of printed lattices and the development of design philosophies show great promise and will hopefully provide engineers with the tools necessary to implement AM lattices into flight structures.



Publications and References

1. Dillman, R. and Corliss, J. "Overview of the Mars Sample Return Earth Entry Vehicle." *6th International Planetary Probe Workshop*. June, 2008.
2. Europa Lander video excerpt: https://vimeo.com/326823972

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- https://www.lpi.usra.edu/meetings/marsconcepts2012/pdf/4175.pdf