

Generative Design and Digital Manufacturing Using AI and Robots to Build Lightweight Instruments



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"Research is what I'm doing when I don't know what I'm doing."

-Wernher von Braun

Agenda

- Generative Design at NASA Goddard
- Application example: EXCITE Tip/Tilt Bracket
- More application examples
- How Generative Design works
- Prompt engineering mindset
 - Bolted interfaces
 - Obstacles: Avoiding other assembly components
 - Loads: Remote mass with accelerations
 - Design Objectives
 - Manufacturing: CNC vs. Additive Manufacturing (AM)
 - Handling complex structures
 - Resolution: Managing your voxels
 - Tolerances and Inspection
- Managing uncertainty: where are my requirements?
- Summary

Context

- Developed on NASA Goddard Internal Research funding (IRAD)
 - **Goal:** create and **infuse** a broadly applicable **process** to rapidly develop lightweight spaceflight structures
 - **Method:** build and test parts for **diverse NASA applications**
 - **Status:** development of typical metallic structures now **automated**
 - Requirements → parts for fab in **1-2 days(!)**
 - Demonstrated by **test**
- Goals of this presentation
 - Share lessons learned about **practical implementation** of Generative Design and Digital Manufacturing
 - Enable projects to improve the **mass/stiffness/strength** of structures by **2x-4x** while **reducing development time/cost** by **~10x**
 - Engage the **Generative Design** community

"Not every change is an improvement, but every improvement is a change"

Inspiration

*"AI is one of the most important things humanity is working on. It is more profound than, I dunno, **electricity or fire**,"*
-Sundar Pichai (Google CEO)



Image source: <https://www.artstation.com/artwork/Z5IYJm>



Image source: https://en.wikipedia.org/wiki/Millennium_Falcon

Image source: https://expanse.fandom.com/wiki/Tycho_Station?file=Tycho-stn-3.png

- We aren't going to get there with current development methods
 - ~\$250K per kg
- How can AI be applied to spaceflight structure development?



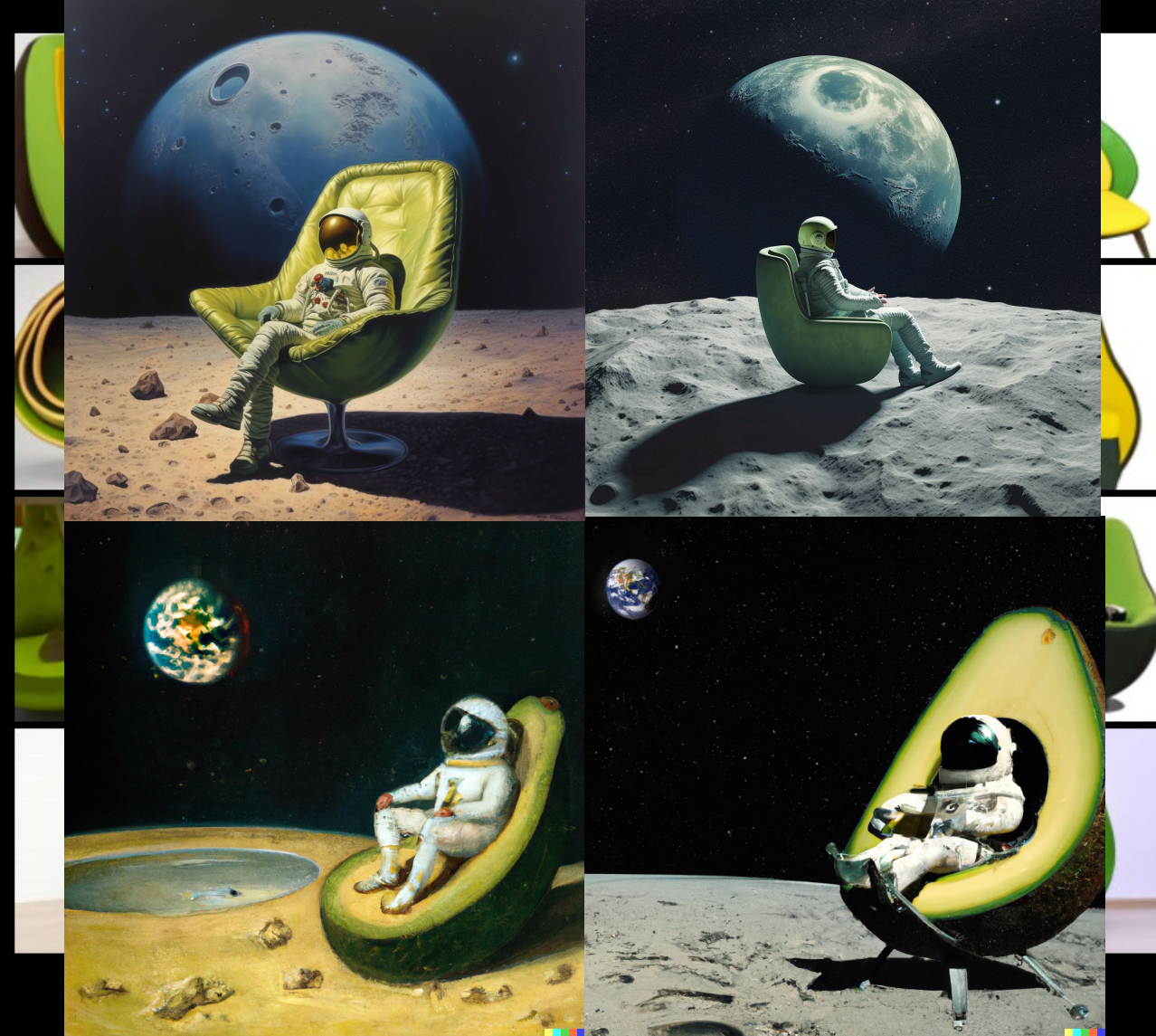
Generative Design

- AI that generates multiple design outputs based on constraints
 - Human designer collaborates to get ideal design
- Applications
 - Visual art
 - Text
 - Music
 - Architecture
 - Structural design

TEXT PROMPT

An armchair in the shape of an avocado, on a armchair imitating an avocado.

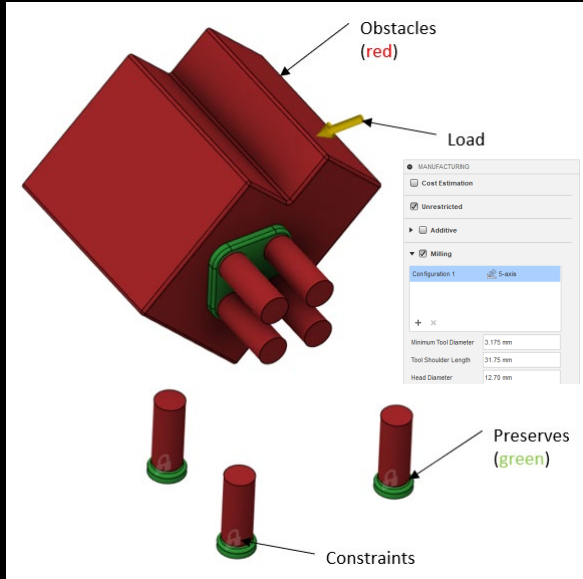
AI-GENERATED
IMAGES



"astronaut seated in an armchair in the shape of an avocado, on the surface of the moon during the Apollo moon landings, by Salvador Dali, blue earthrise in the background"

Evolved Structures: Prompt Engineering for Structures

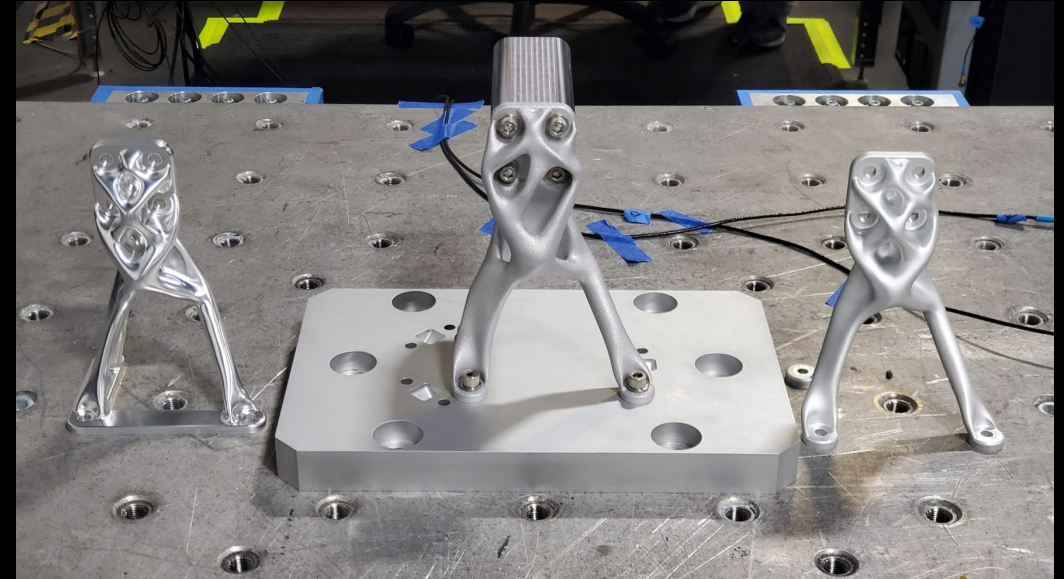
- (1) **Create input** to digitally encode structure requirements into software
 - Follow written *Evolved Structures Guide for NASA applications*
- (2) Use Generative Design AI to **evolve optimal designs** meeting requirements
 - Using COTS software adapted for GSFC needs
- (3) Fabricate parts directly from Generative Design output using **Digital Manufacturing** (software + robots)
 - Using industrial processes such as **automated CNC** and **Additive Manufacturing (AM)**



Encode Requirements
~1 hr



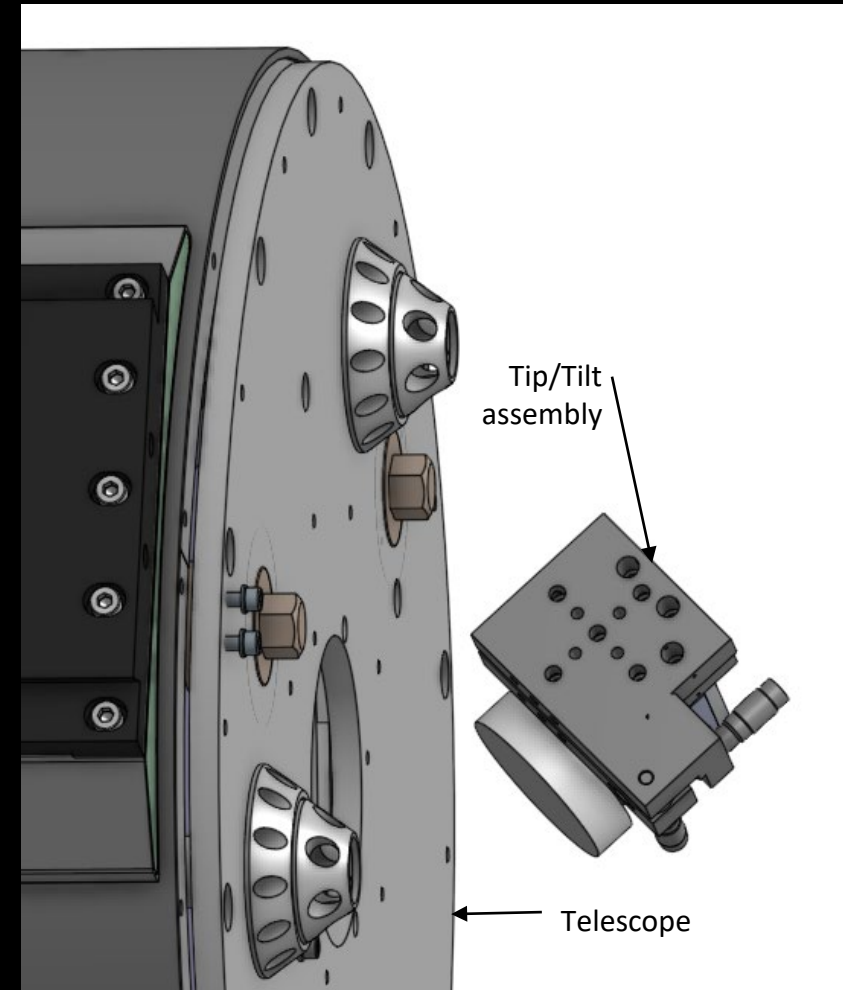
Evolve Designs
~1 hr



Fabricate Parts
1 day – 3 weeks

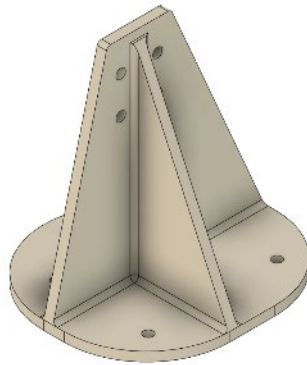
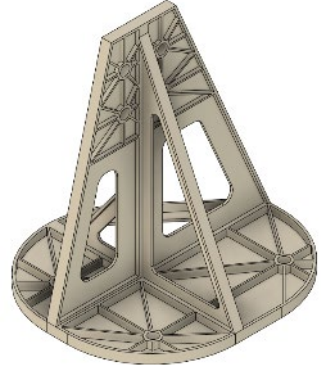
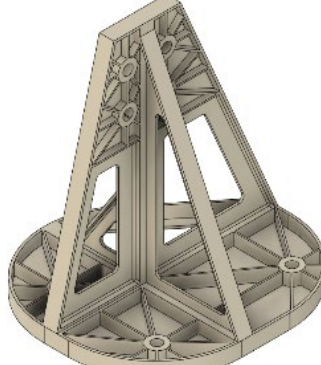
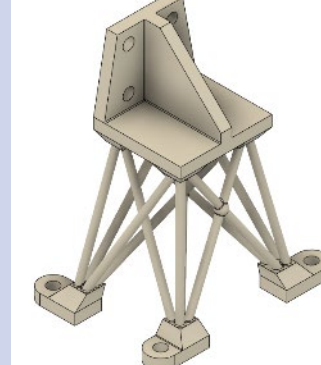
Application Example: EXCITE Tip/Tilt Bracket

- **Mission:** Analyze atmospheres of exoplanets
- **Goal:** Mount Tip/Tilt mirror assembly to the back of the Telescope (PI: Peter Nagler)
- **Interfaces:** Bolt pattern on Tip/Tilt stage and bolt pattern on Telescope. Avoid Tip/Tilt assembly volume and optical path.
- **Loads:** 10g vertical (x) 3g lateral(y and z) applied to Tip/tilt stage center of gravity (1.35 kg mass)
- **Modes:** >100 Hz per standard practices and to avoid cryo-cooler excitation
- **Bracket mass target:** 0.2 kg

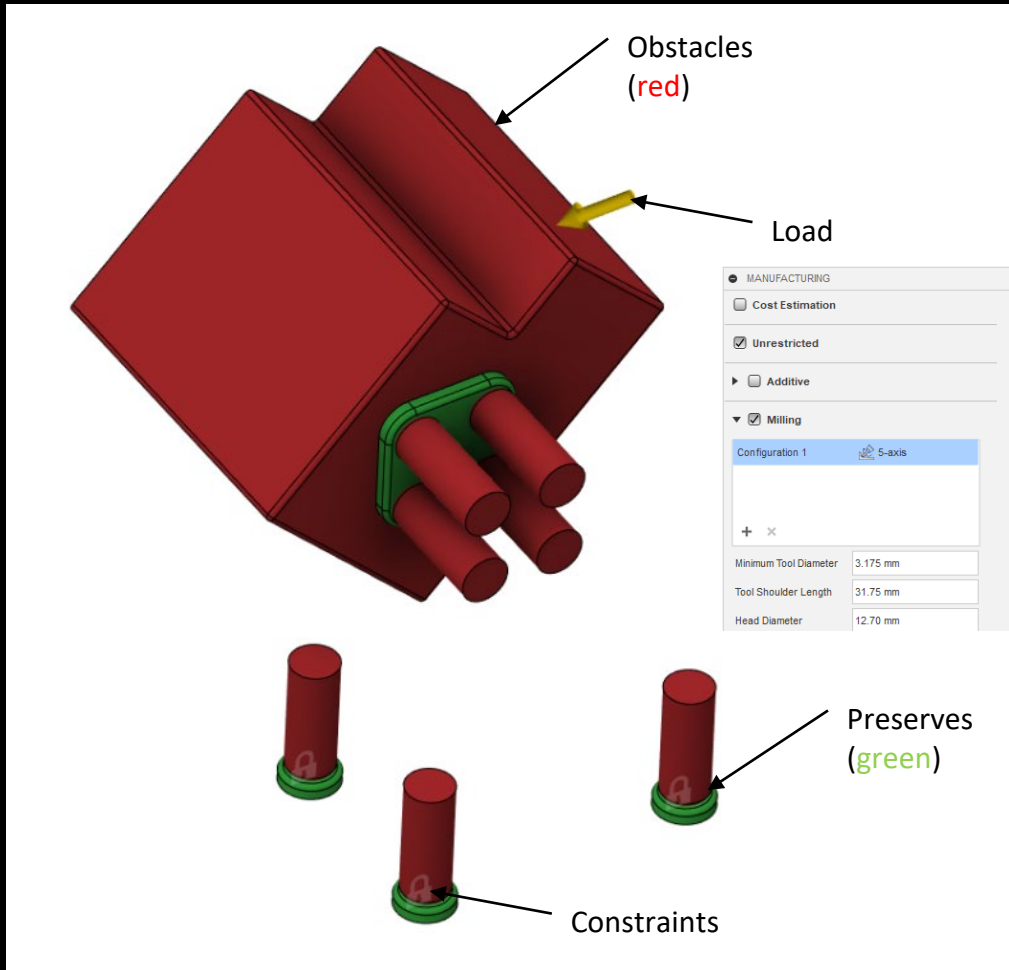


Application Example: Human Design

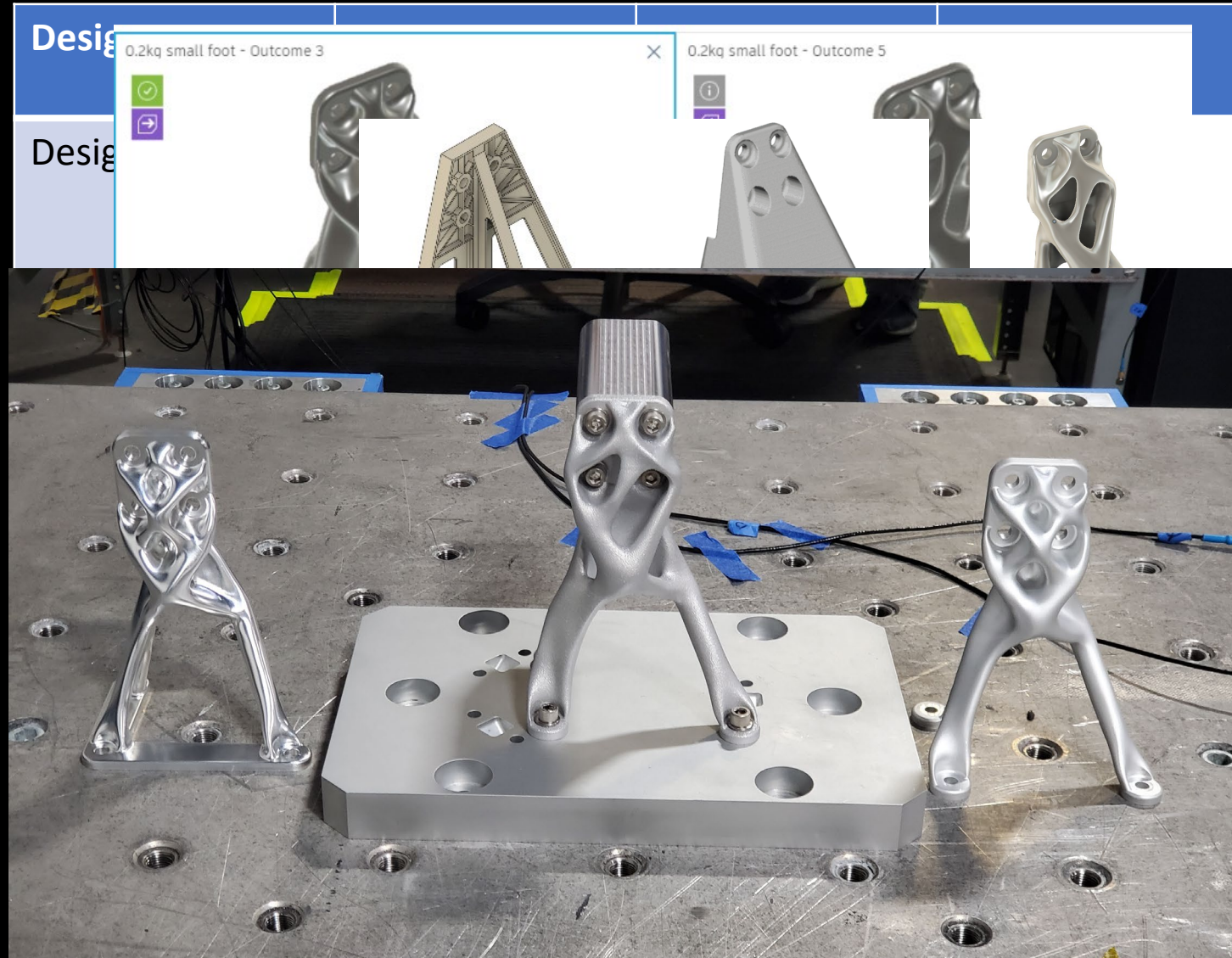
- Design problem given to senior design engineer
- Finite Element Analysis (FEA) done by me
 - Design improved with iteration
- **No manufacturable design meets the mass target**
- Elapsed time: 2 days

Designer / Iteration	Drew 1	Drew 2	Drew 3	Drew 4
Design (Aluminum)				
Mass (kg)	0.59	0.18	0.27	0.18
1 st Mode (Hz)	137	37	65	108
Stiffness/mass (Hz/kg)	232	205	240	600
Max Stress (MPa)	26.3	189	103	60.7
Manufacturing	CNC	CNC Difficult to machine hog-outs – no quote	CNC Difficult to machine hog-outs – no quote	Not machinable/printable – no quote

Application Example: Evolved Structures



Inputs



Outputs

Application examples

"The trick to having good ideas is not to sit around in glorious isolation and try to think big thoughts. The trick is to get more parts on the table."

- Steven Johnson



EXCITE: Tip/Tilt mount



EXCITE: Radiator mount



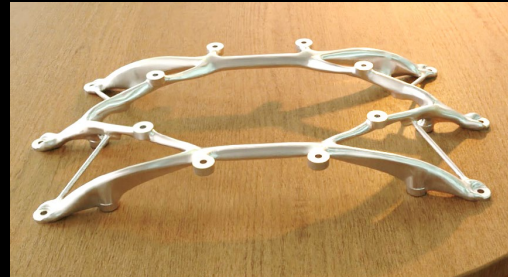
EXCITE: Detector mount



NGXO: Mirror mount



MSR-CCRS: Diode Mount



STAR-X Detector bench



HERMES: MAG Stanchion



Optical Bench



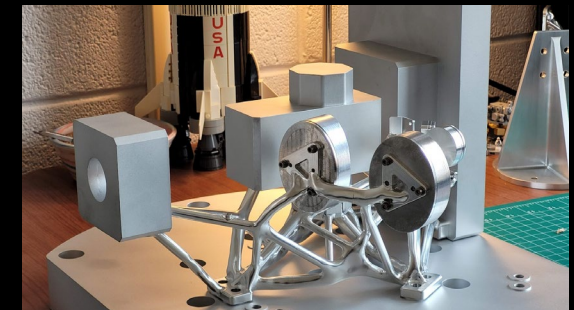
CCRS: LTM Paddle



EXCITE: Optical Bench

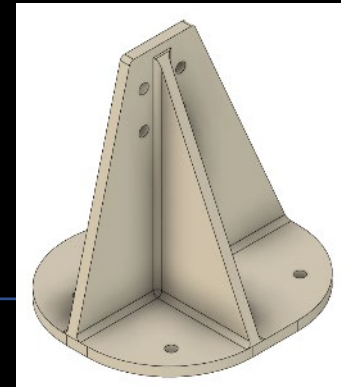


Venus lander

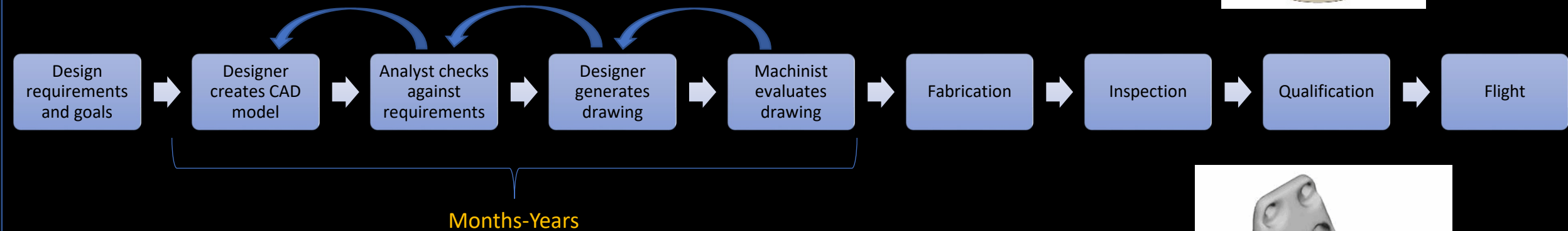


Optical Bench

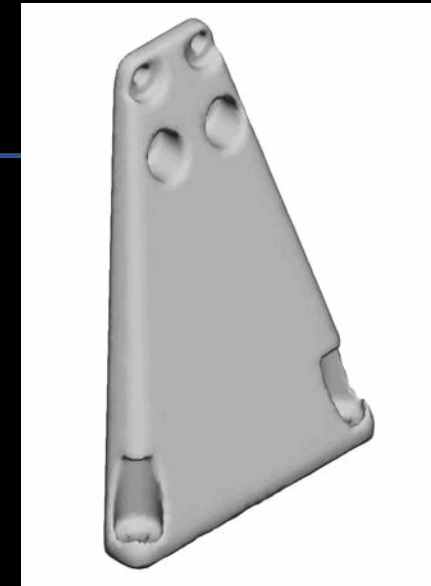
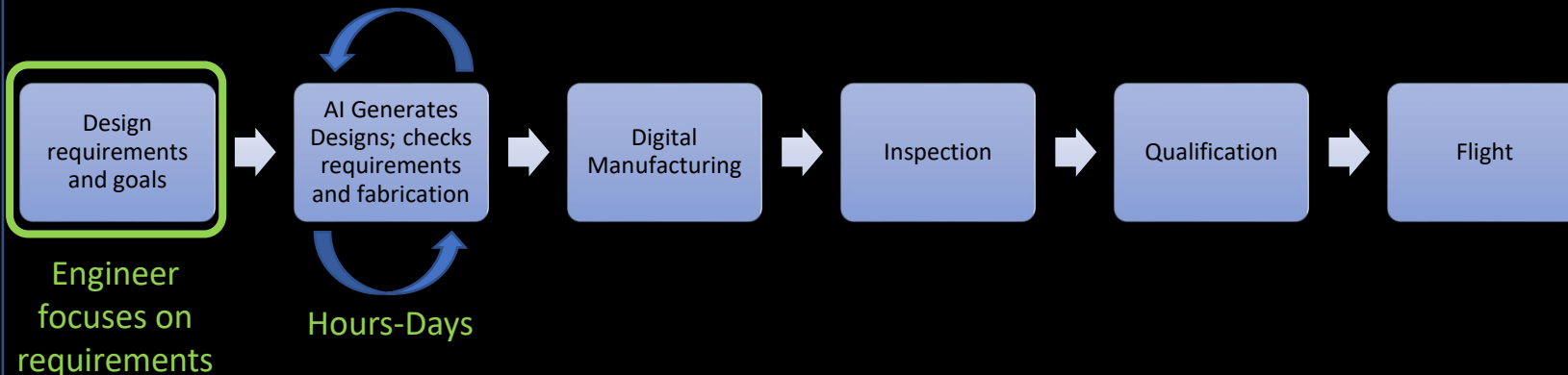
Generative Design: Paradigm Shift



Current GSFC Process



Evolved Structures Process



Demonstrated: Requirements known to parts in-hand in <2 weeks. 2x-4x lighter.

How it works

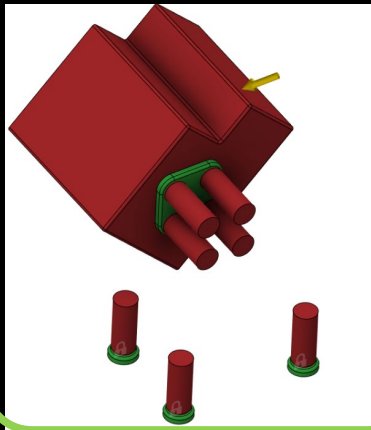
AI: Computer systems able to perform tasks that normally require human intelligence

AI Generates Designs; checks requirements and fabrication

Hours-Days

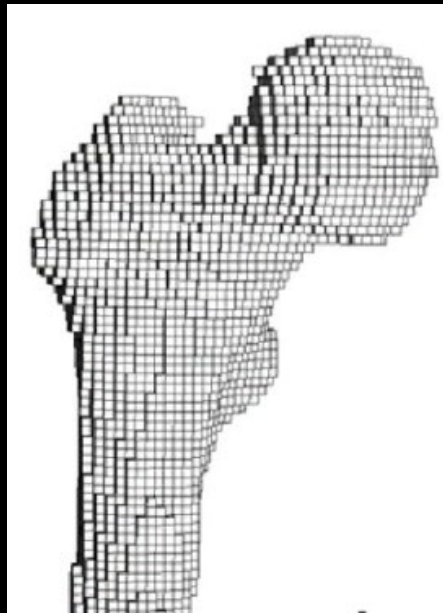
User inputs

- Digitally encoded design requirements:
- Interfaces
- Loads and modes
- Factor of Safety
- Mass target
- Materials
- Fabrication methods



Create voxel mesh of design space

- 3D version of a pixel
- Can represent any geometry at any level of detail
- Limited total number of voxels



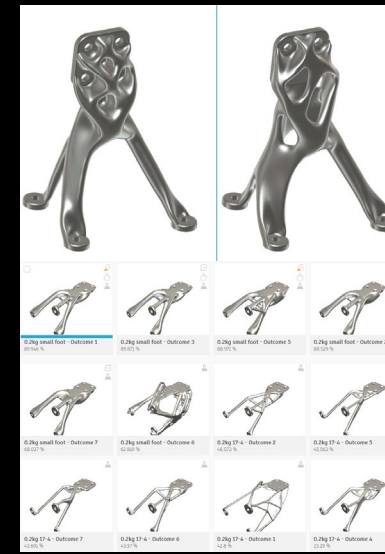
Run Topology Optimization

- Eliminate voxels with low stress (that can be removed with fabrication method)
- Check against requirements
- Iterate until optimized
- SIMP method (older)
- Level set method (newer)



Output results for user review

- Organize for simple user interaction
- Recommendation engine (mass, stress, cost)
- Reconstructed design preview



Reconstruct CAD model of selected outputs

- Turn voxel mesh into T-spline surfaces
- Merge preserves and cut obstacles
- User can manually tune design
- CAD ready for fabrication

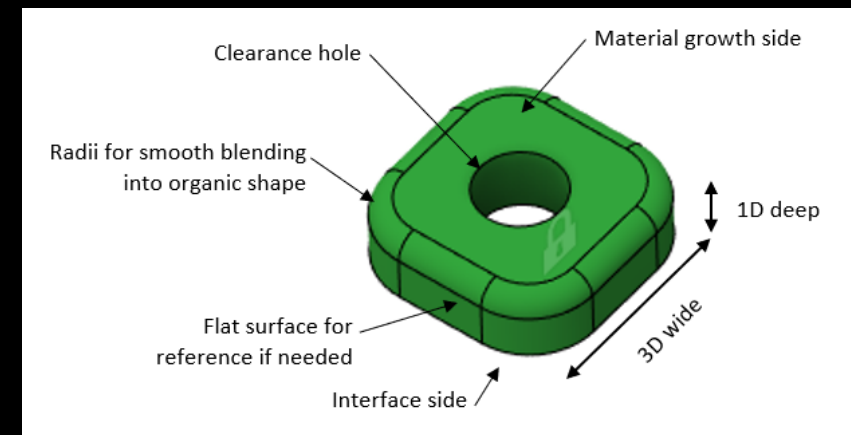
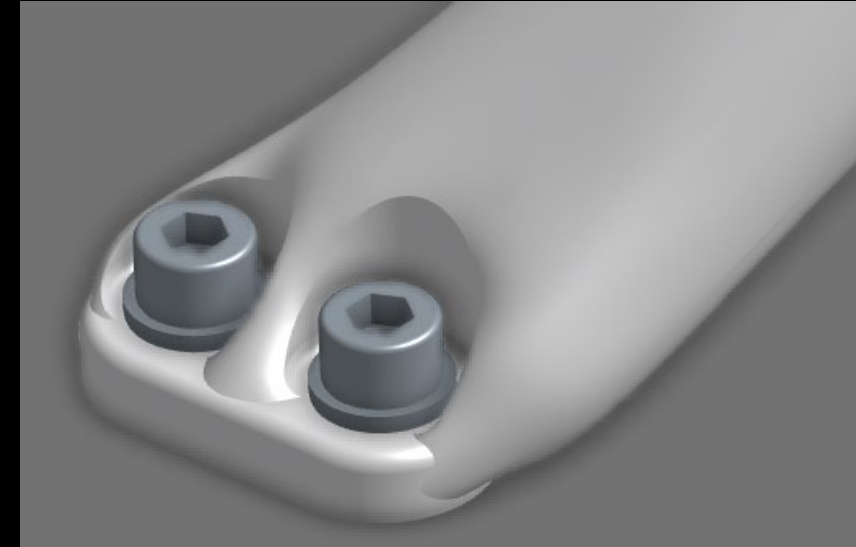


Prompt engineering mindset: Goals

- Requirements → Manufacturable CAD
- Get the inputs right the first time every time (aspirational)
- Every dimension has a REASON → Computational Design thinking
- Comply with internal standards
- Compatible with manufacturing processes
- Inspectable
- Assemble-able
- **Recommendation: Create a Generative Design “Prompt Guide” for your organization**
 - Helps get Generative input “prompts” right the first time
 - Helps scale adoption across your organization

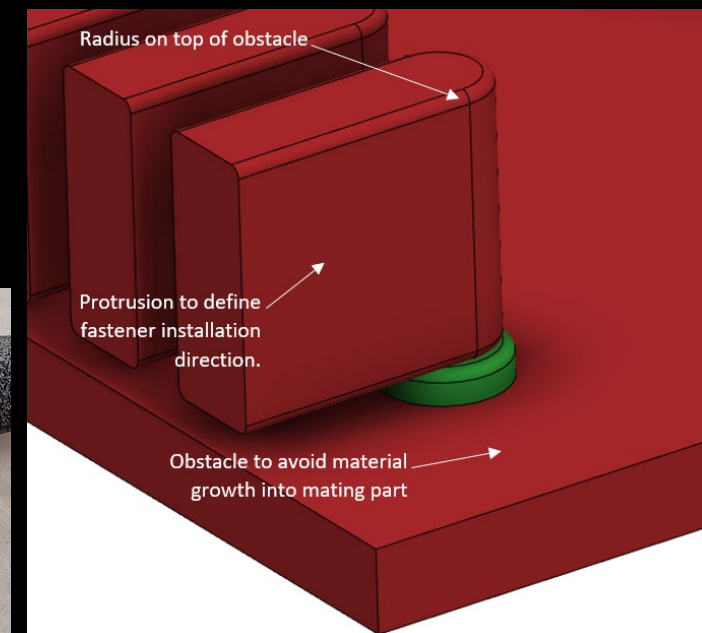
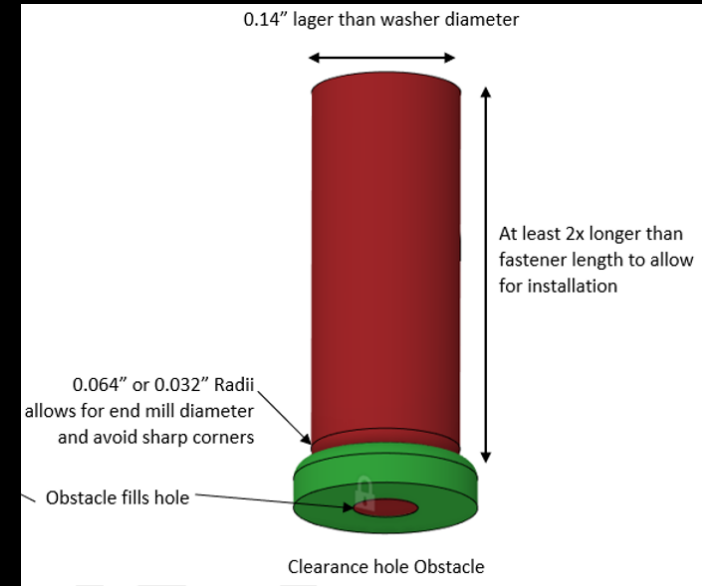
Bolted Interfaces: Preserve considerations

- Fastener edge distance → preserve width
- Grip length → preserve thickness
 - Strongly affects part strength
- Round or rectangular bolt pattern → round or square preserves
- Hole diameter → use standards such as ASME B18.2.8-1999
- Radii → avoid sharp edges where material grows



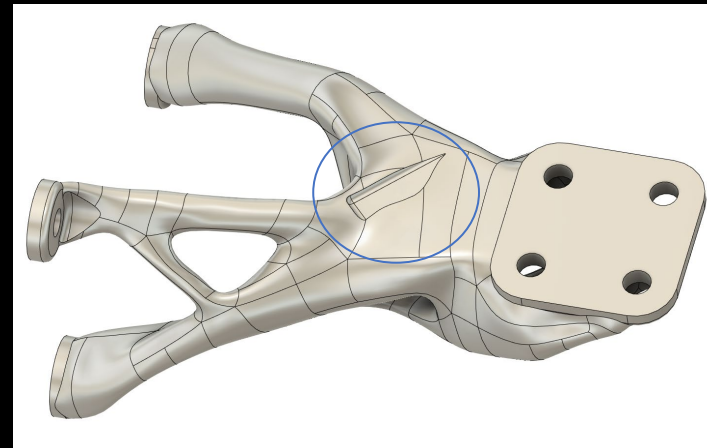
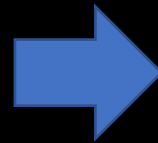
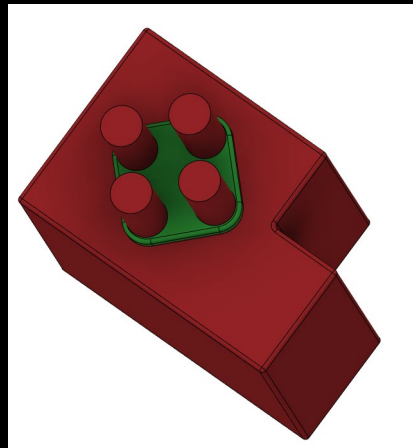
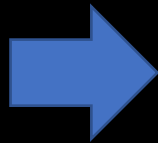
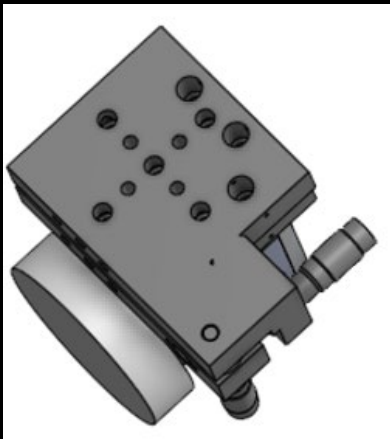
Bolted Interfaces: Obstacle considerations

- Washer/fastener maximum diameter → obstacle diameter
- Hole tolerances → obstacle diameter
- Radii for manufacturing → obstacle radius and diameter
- Obstacle diameter = washer/fastener maximum diameter + hole tolerance + radius*2
- Fastener length and tool clearance → obstacle length
- Fastener installation → advanced obstacle
- **Recommendation: Use Configurations for standard bolted interface preserves and obstacles**
 - Configurations for clearance and tapped holes
 - Can also used Connector Obstacle tool 



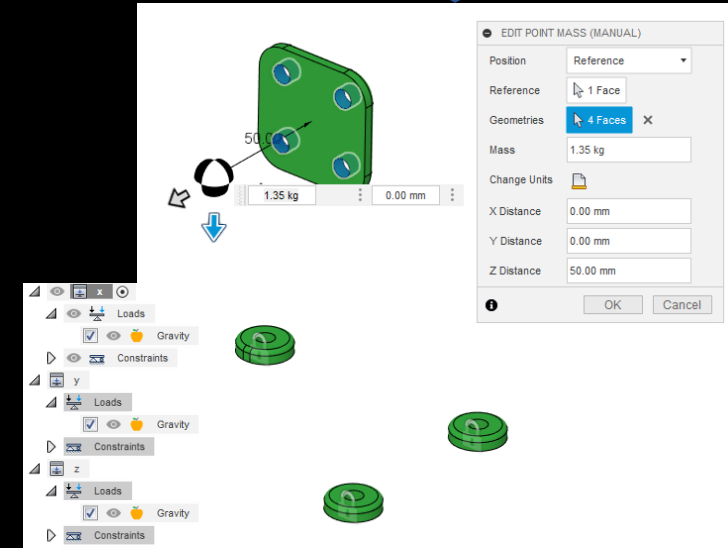
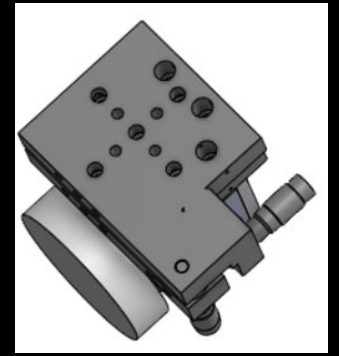
Obstacles : Avoiding other assembly components

- Simplify assemblies → faster modeling
 - **Recommendation: Only have what is needed for the Generative part**
- Close holes → prevent unneeded voxels
- Add radii → prevent sharp corners in part
 - Reduces stress
 - Improves manufacturability
- Add Obstacle Offsets
 - Obstacles are CUT, Offsets discourage material growth (not cut)
- **Recommendation: Create Preserves and Obstacles in your native CAD software → keep parametric**

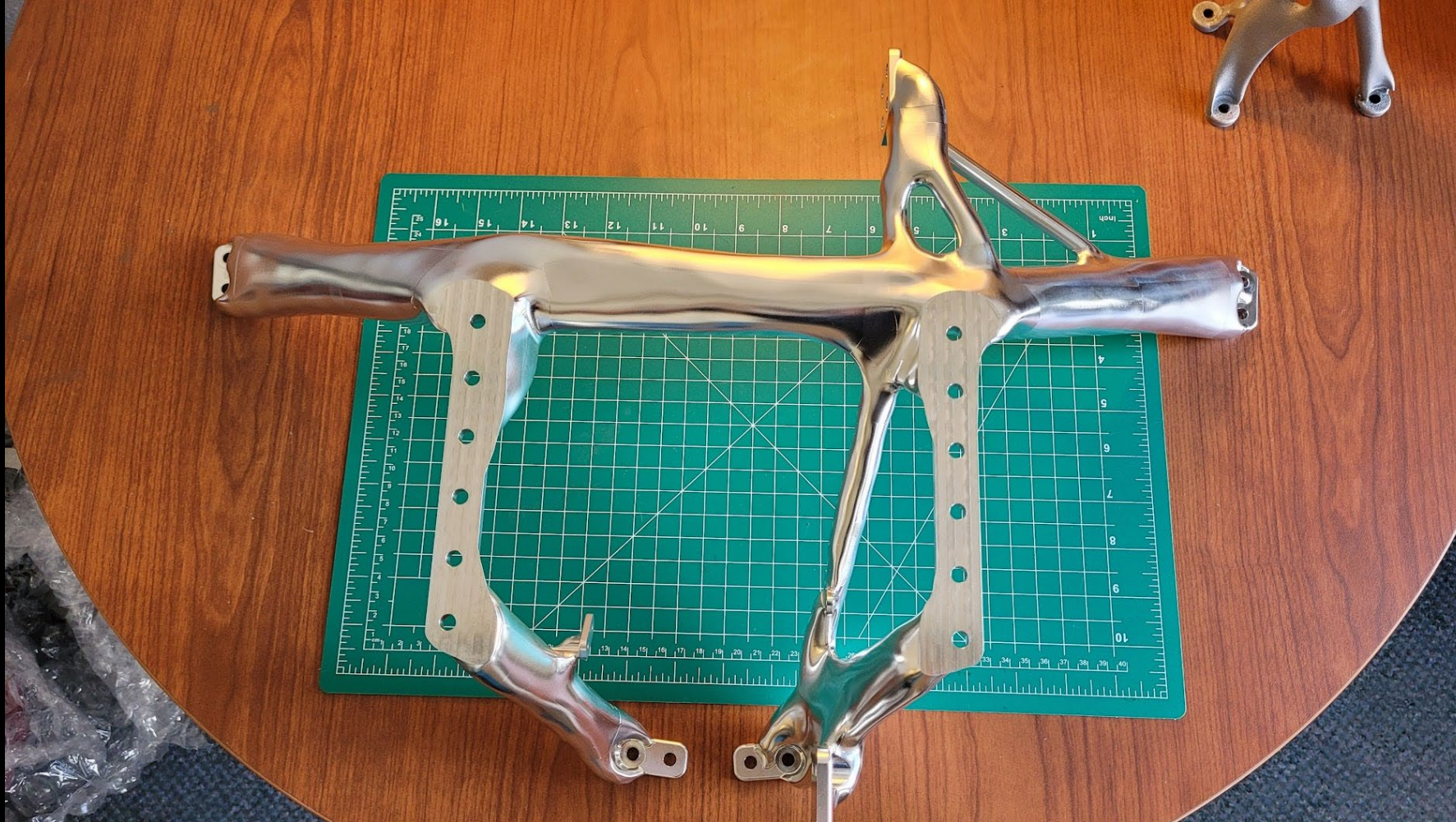


Loads: Remote mass with accelerations

- For space applications, structures are mostly supporting mounted components, e.g. optical assemblies, detectors, electronics, tanks, comm equipment, etc.
- **Recommendation: represent mounted components with Remote Masses**
 - Simple/fast 2 element representation Masses (COM2 +RBE3 in NASTRAN terms)
 - Makes no assumption about component stiffness → conservative
- Apply acceleration loading in three separate load cases
 - Not one!
- Preliminary design used Mass Acceleration Curve (MAC)
 - Lighter components see more acceleration

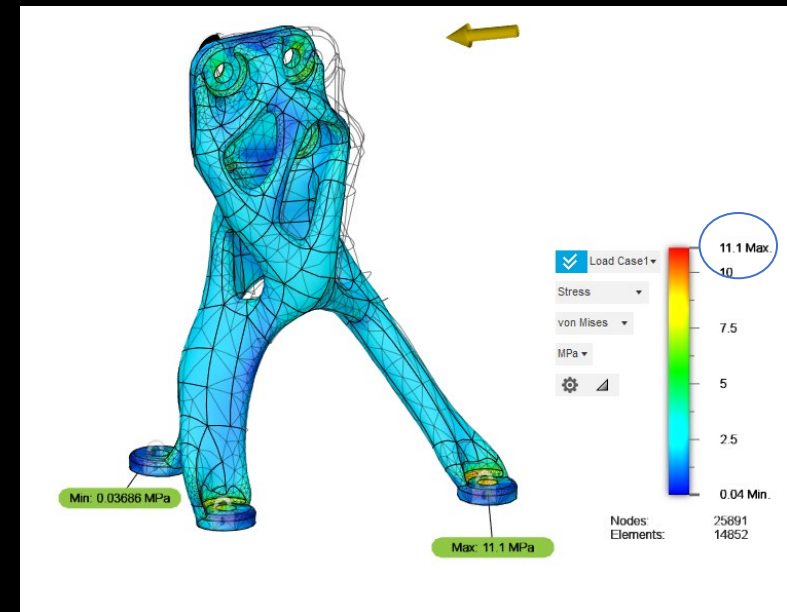
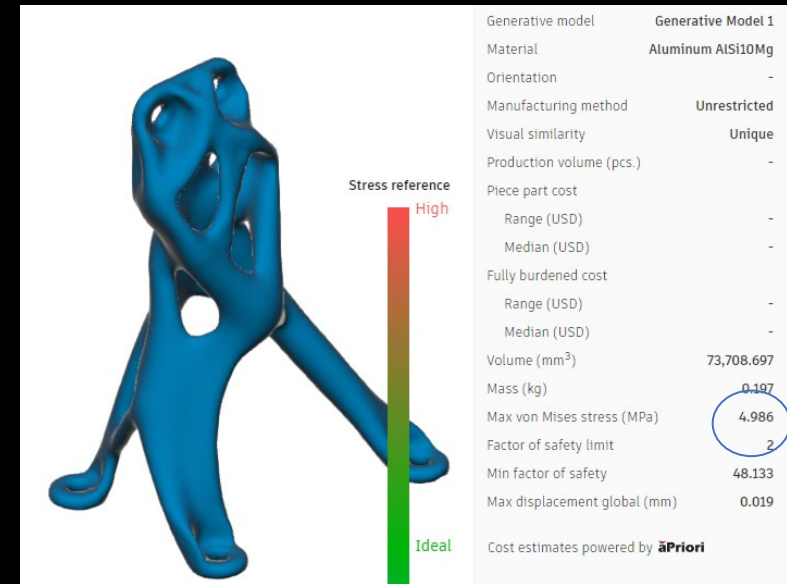
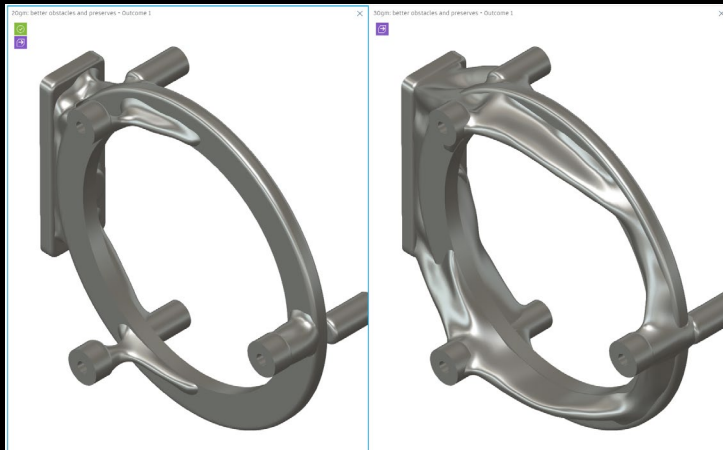


Demo: EXCITE Evolved Optical Bench



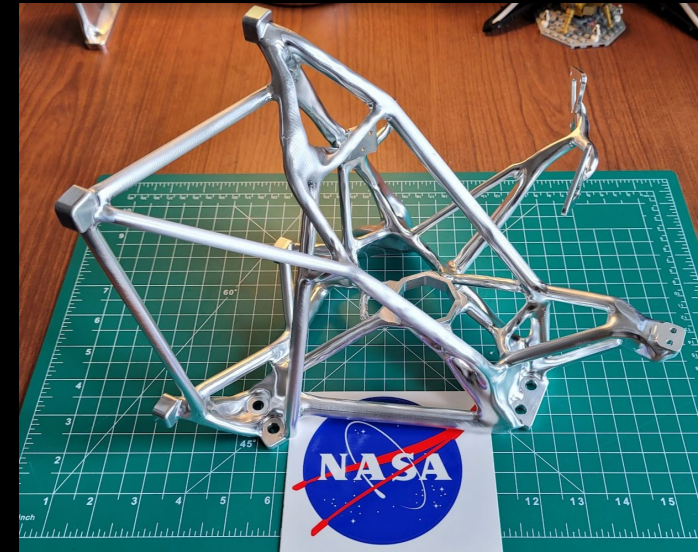
Design Objectives

- Prefer Maximize Stiffness with a fixed mass target
 - NASA designs are usually stiffness driven
 - Not pushing the envelope on failure
 - Maximum stress is at the interfaces
 - Not captured well by voxel mesh
 - Can cause issues with Minimize Mass
 - Use Modal/Buckling/Displacement constraints as needed
- Recommendation: Use Maximize Stiffness, starting with a mass target 1/3 of human design
 - Vary until design “looks good”



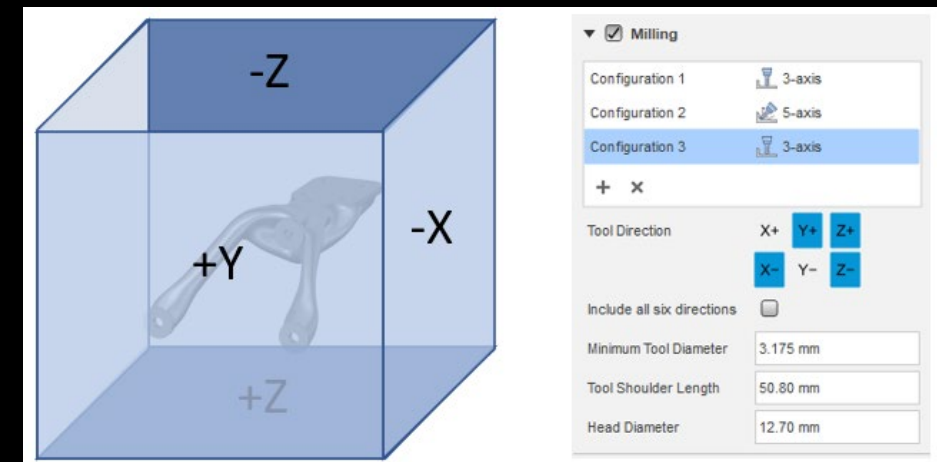
Manufacturing: CNC vs. AM

- Organic structures can generally be **CNC machined**
 - State-of-the-art CNC **far beyond engineers' expectations**
 - **Inherent stiffness** of Evolved Structures improves machinability
- AM advantages
 - Improvement in stiffness due to **design freedom**
 - Large monolithic **Titanium parts may be cheaper**
- AM generally has **cost and schedule disadvantages** for aerospace
 - Limited choice of AM vendors, especially for parts >250mm
 - Material properties process dependent, varies by vendor
 - Tolerances are poor compared to CNC – post machining
 - Surface finish is rougher than CNC machining.
 - Removal of supports requires manual finishing, leading to variable surface quality
 - Heat treatment usually required
 - Additional testing and inspection required NASA-STD-6030
 - Build failures expected



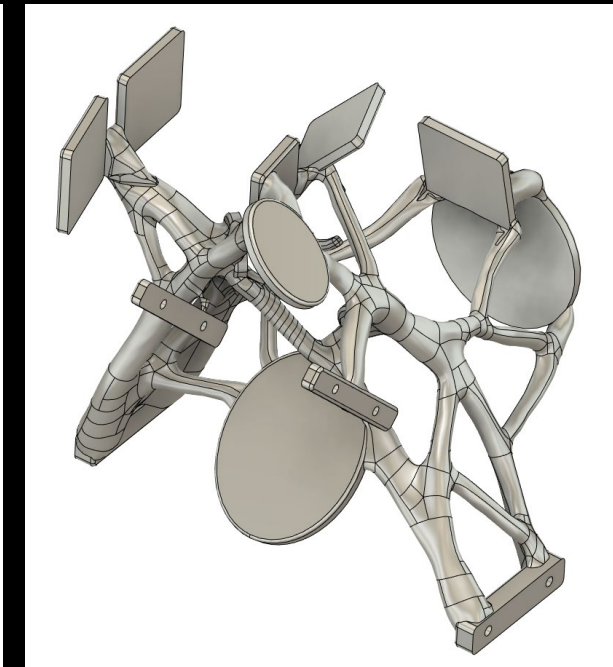
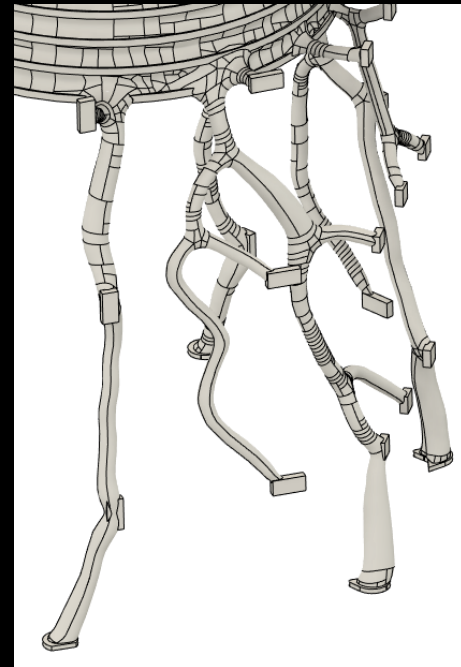
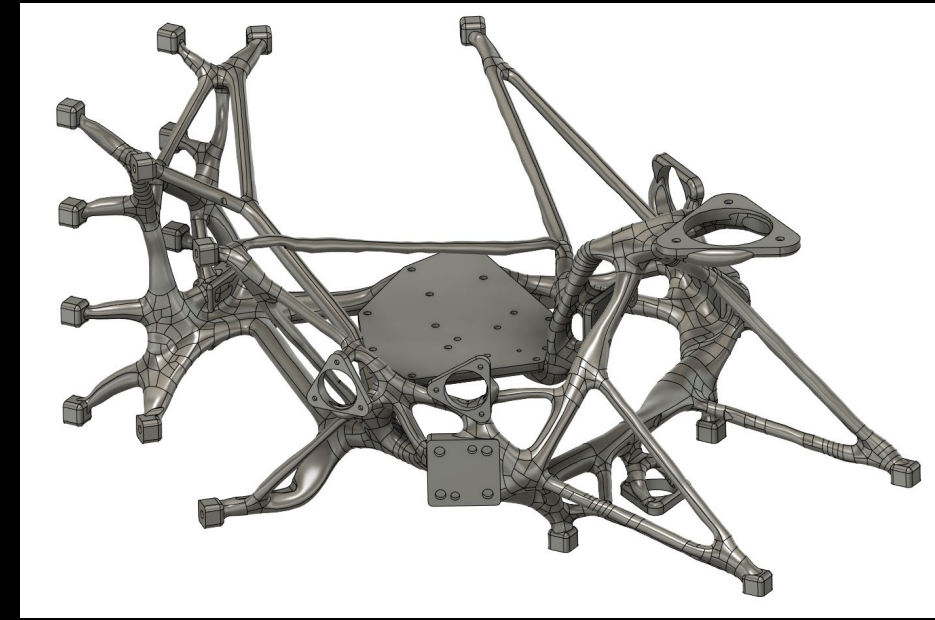
CNC Manufacturing

- **Recommendation: talk to the people likely to fabricate your part after the first iteration**
 - Ideally the CNC programmer or the AM slicer/operator
- **Recommendation: Always run an Unrestricted to see the ideal design**
 - Could inform what directions are best to machine from
- **Milling** → Fusion checks voxels can be removed by selected tools from selected axes
 - Has been very accurate so far!
- **Tool direction** → fewer directions = easier to machine
 - Reduced number of setups
- **Minimum Tool Diameter** → larger easier to machine, smaller enables more design details
 - **Recommend 1/8"** for moderate size parts
- **Tool Shoulder Length** → longer reaches into part better
 - **Recommend 10x Tool Diameter for Aluminum**
- **Head Diameter** → smaller reaches into part better
 - **Recommend 1/2"** for 1/8" cutter → check with your shop

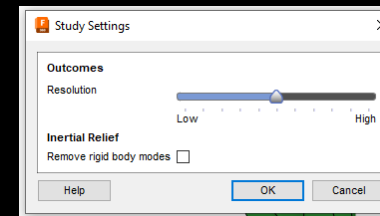


Handling complex structures

- Complexity is driven by the number of interfaces
 - 2-3 interfaces → 1 day to design, analyze, and prepare for fabrication
 - Development time increase with additional interfaces
- Very complex structures possible
 - Great for part consolidation
 - Great for mounting parts at weird orientations
- Beware lightly loaded components!
 - E.g. structure supports a 5 kg component and a 0.5 kg component → failure to process/converge or weird results
 - Stress near light load is low compared to overall stress → optimization wants to delete those elements
 - Solution 1: Increase the smaller load to $\sim 1/5$ largest load
 - Solution 2: Put the smaller load in a separate load case
- Consider how the assembly components will be installed
- May need additional obstacles
- Insufficient voxels to represent preserves or structural members
 - Need a few voxels though the thickness of any structure



Resolution: Managing your voxels

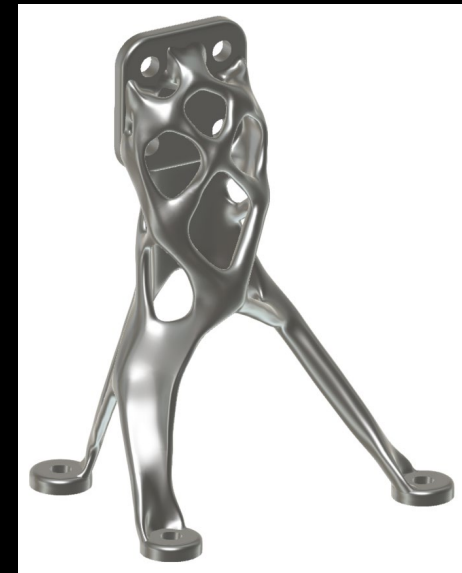


- The Study Resolution setting determines the total number of voxels available to represent your design at iteration 1
 - More voxels → slower run time but more detailed parts
- **Recommendation: Use the lowest resolution that gives to a good result (and successfully reconstructs)**
 - Faster run/iteration time
 - Part performance difference is usually marginal (with <20%)
 - Coarse → less complex → easier to fabricate
 - Fine → more complex → better performance
 - Aesthetic differences
- **Recommendation: Before fabrication, try highest Resolution to check for improvement and aesthetics**

Coarse



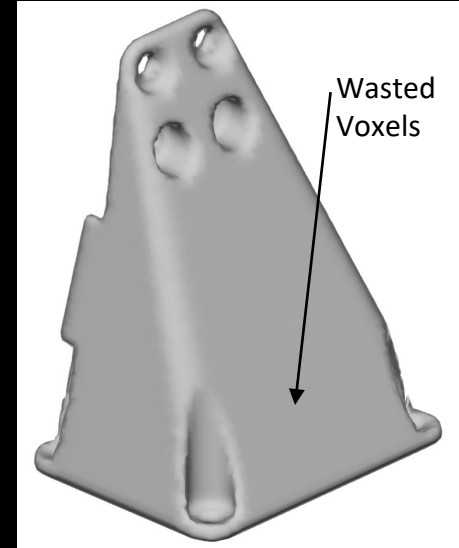
Fine



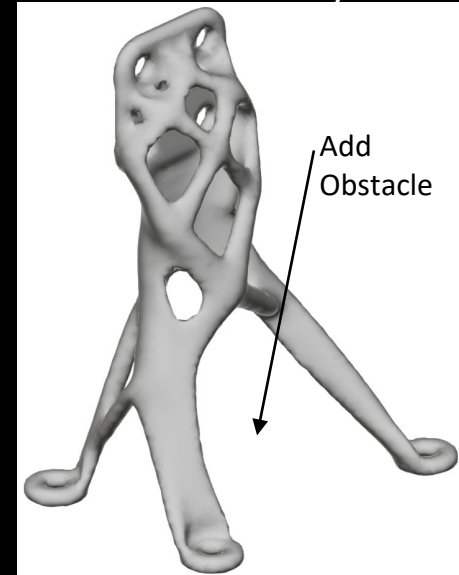
Resolution: Adding Obstacles to get more voxels

- The Study Resolution setting determines the total number of voxels available to represent your design at iteration 1
 - More voxels → slower run time but more detailed parts
- Very complex models can become voxel-limited
 - Small preserved or structures can't be represented
- **Recommendation: Add Obstacles in empty spaces**
 - Run a study to see where the spaces will be
 - Faster run/iteration time
 - More voxels where you need them

Iteration 1/34



Iteration 15/34

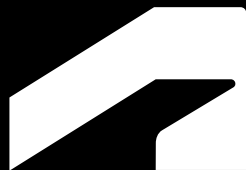


Managing uncertainty

- The single longest step in Generative Design (in calendar time) is **getting the requirements from stakeholders!**
 - Stakeholders often want to get the requirements PERFECT before starting because design and analysis is SLOW
 - Chicken-and-egg issue:
 - Design Engineer “how light does it need to be?”
 - Systems Engineer “how light can you make it?”
- **Recommendation: The best way to get requirements is to make a design**
 - Make assumptions about interfaces, loads, mass target, etc
 - Show stakeholders how fast Generative Design is to iterate
 - Find missing requirements AFTER you have a design, because design and analysis is now FAST
 - Finding missing requirements is INEVITABLE for complex designs anyway

Summary

- Generative Design can lead to revolutionary improvements in both part performance AND cost/schedule
 - ~3x improved strength/stiffness/weight in 10x less time
 - New paradigm for engineering design
- Prompt engineering mentality fully realizes these benefits
 - Requirements → Manufacturable CAD
 - Get the inputs right to get the right output
 - Write a Guide for your organization's applications
 - Iterate on your process → feedback for continuous improvement
 - No more making things up



AU 2023

THE DESIGN & MAKE CONFERENCE

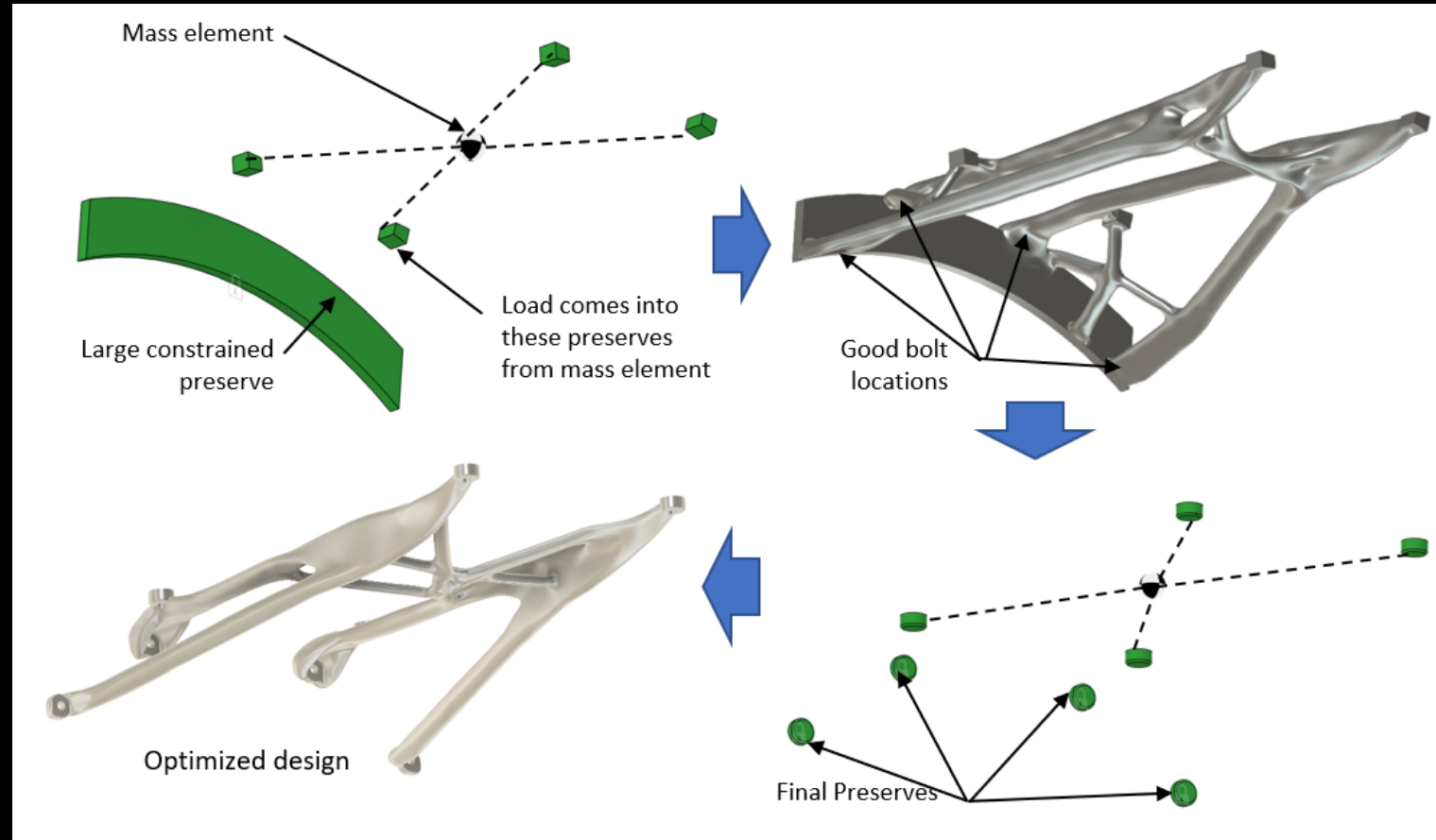
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Backup

Bolted Interfaces: Finding the best bolt locations

- If you have freedom of where to locate bolts, let Generative guide you!
- Step 1: Constrain a preserve representing possible bolt locations
- Step 2: Using a minimize mass study, see where the structures want to join
- Step 3: Create new preserves at those locations
- Step 4: Generate a new design



Tolerances and Inspection

- Generative Design makes inspection EASIER not HARDER
- Interfaces can be checked with **traditional tools** (e.g., Coordinate Measuring Machine, CMM)
 - No different than a traditional part
 - All tight tolerances should be at the interfaces
- Organic shapes can be spot checked with a CMM or fully checked with **3D scanning**
 - Organic shapes generally **insensitive** to tolerances
 - **Recommendation: for CNC use ~0.020" profile tolerance**
- Additively Manufacturer parts may require internal **Non-Destructive Evaluation (NDE)**
 - CT scan – returns voxel density
 - Eddy current testing

