

# Generative Design and Digital Manufacturing: Using AI and Robots to build spaceflight structures



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*ch is what I'm doing when I don't know what I'm doing*  
-Wernher von Braun

# 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**
    - Being applied to **NASA missions**
- Goals of this presentation
  - Share lessons learned about **practical implementation** of Generative AI
  - Enable products to improve the **mass/stiffness/strength** of structures by **2x-4x** while **reducing development time/cost** by **~10x**
  - Engage the **Generative AI** 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/Z5YJm>



Image source: [https://expansion.fandom.com/wiki/Tycho\\_Station?file=Tycho-stn-3.png](https://expansion.fandom.com/wiki/Tycho_Station?file=Tycho-stn-3.png)



Image source: [https://en.wikipedia.org/wiki/Millennium\\_Falcon](https://en.wikipedia.org/wiki/Millennium_Falcon)

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

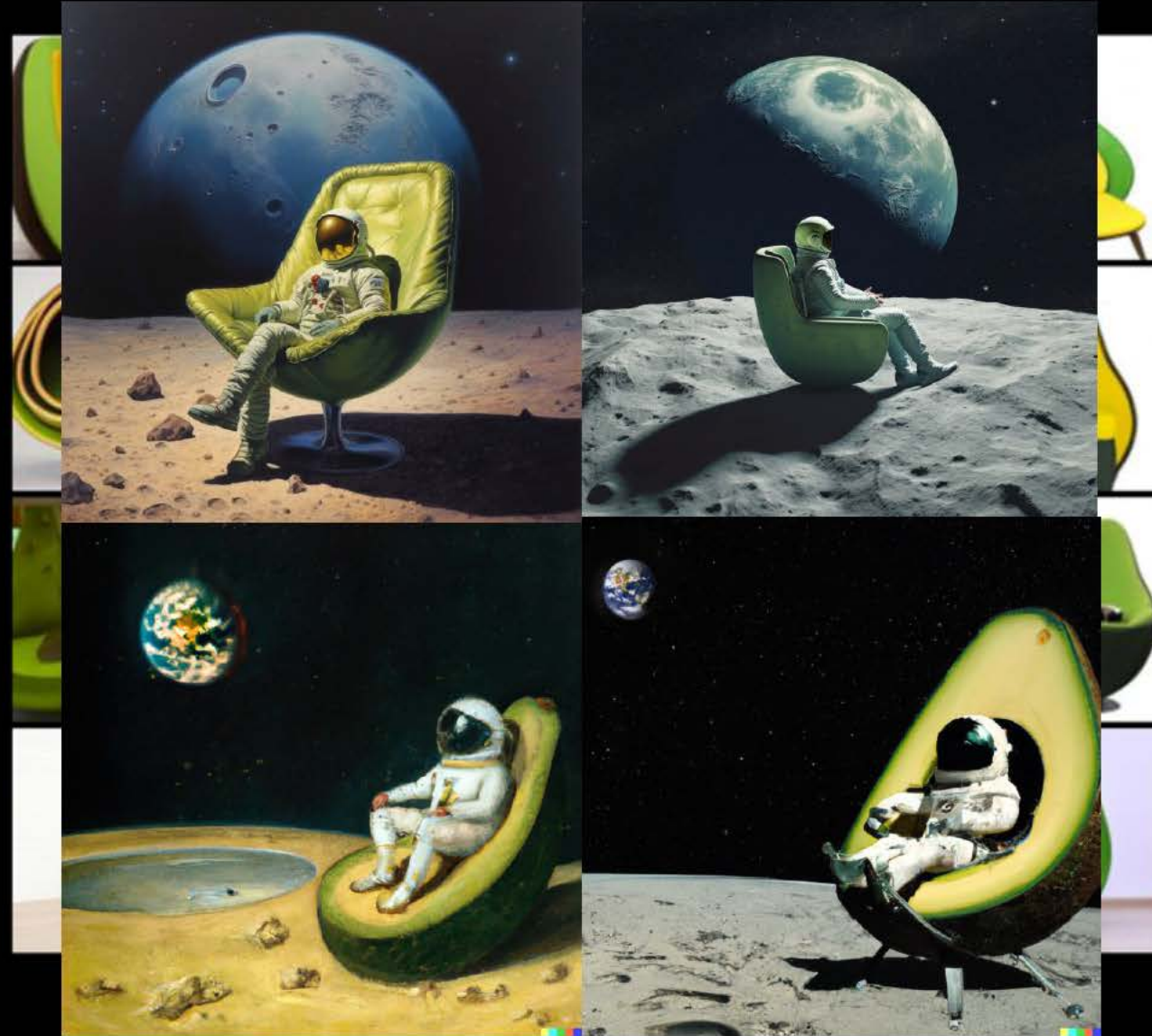
# Generative Design

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

TEXT PROMPT

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

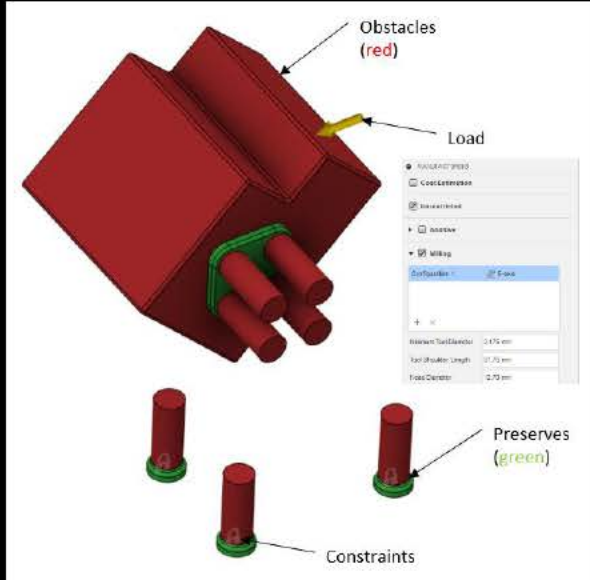
AI-GENERATED  
IMAGES



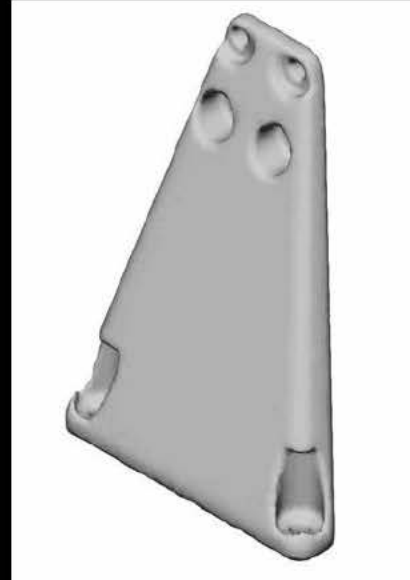
"astronaut seated in an armchair in the shape of an avocado, on the surface of the moon during the Apollo moon landings, by Salvador Dali, blue earthrise in the background"

# Evolved Structures: Prompt Engineering for Structures

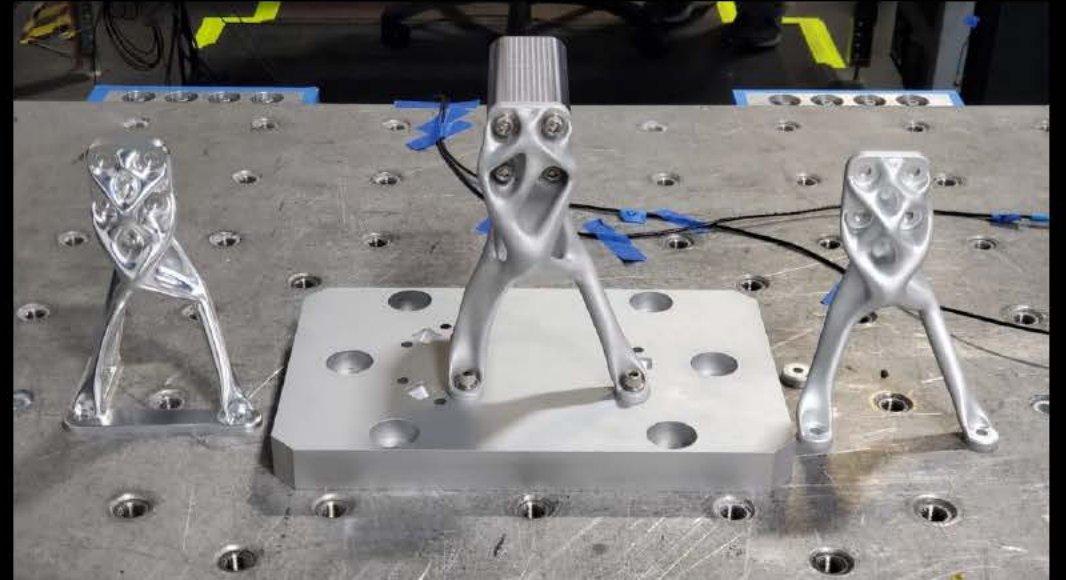
- (1) **Create a prompt** to digitally encode structure requirements into software
  - Follow written *Evolved Structures Guide for NASA applications*
- (2) Use Generative Design AI to **evolve optimal designs** meeting requirements
  - Using COTS software adapted for GSFC needs
- (3) Fabricate parts 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



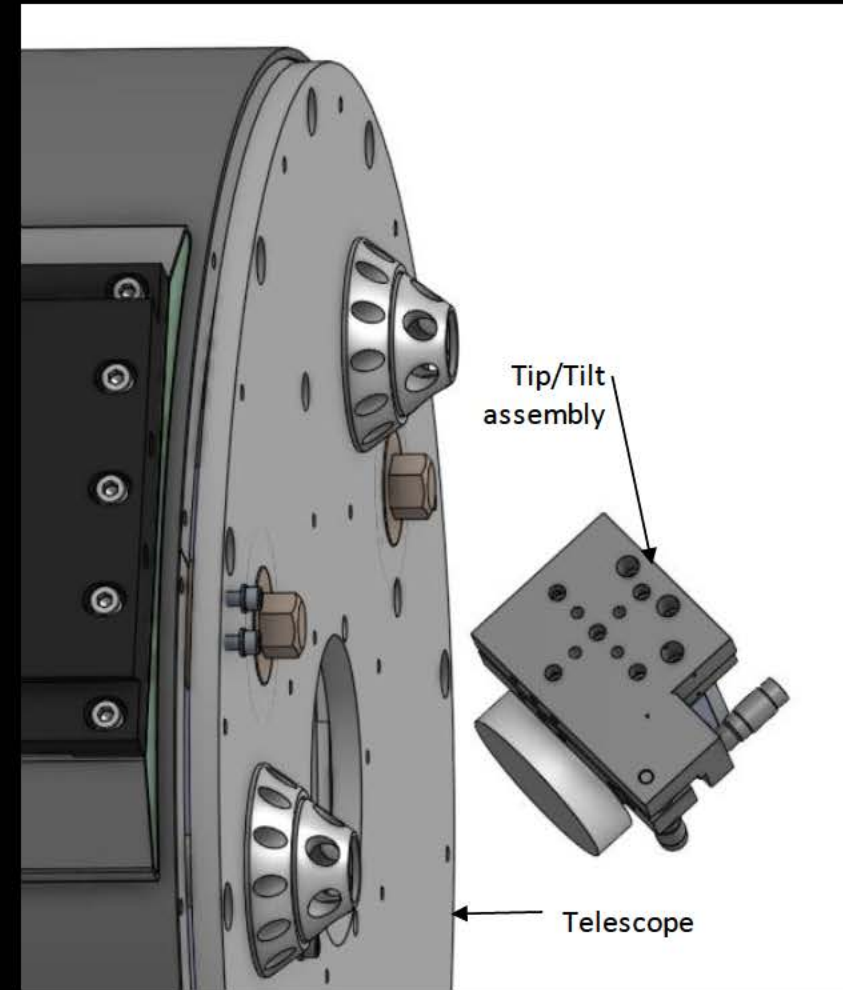
Evolve Designs  
~1 hr



Fabricate Parts  
1 day – 3 weeks

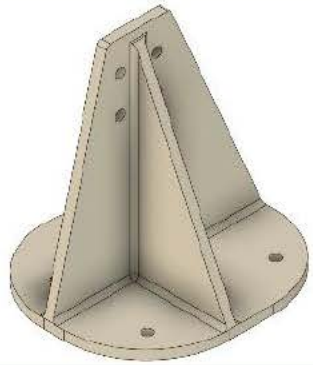
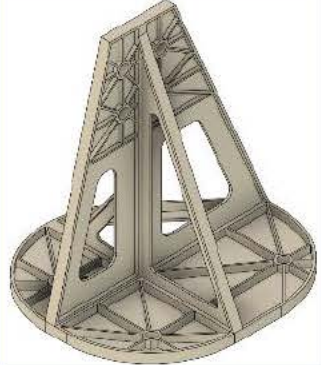
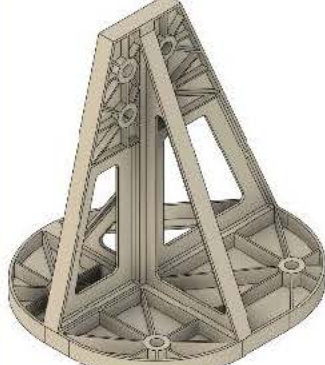

# Application Example: EXCITE Tip/Tilt Bracket

- **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

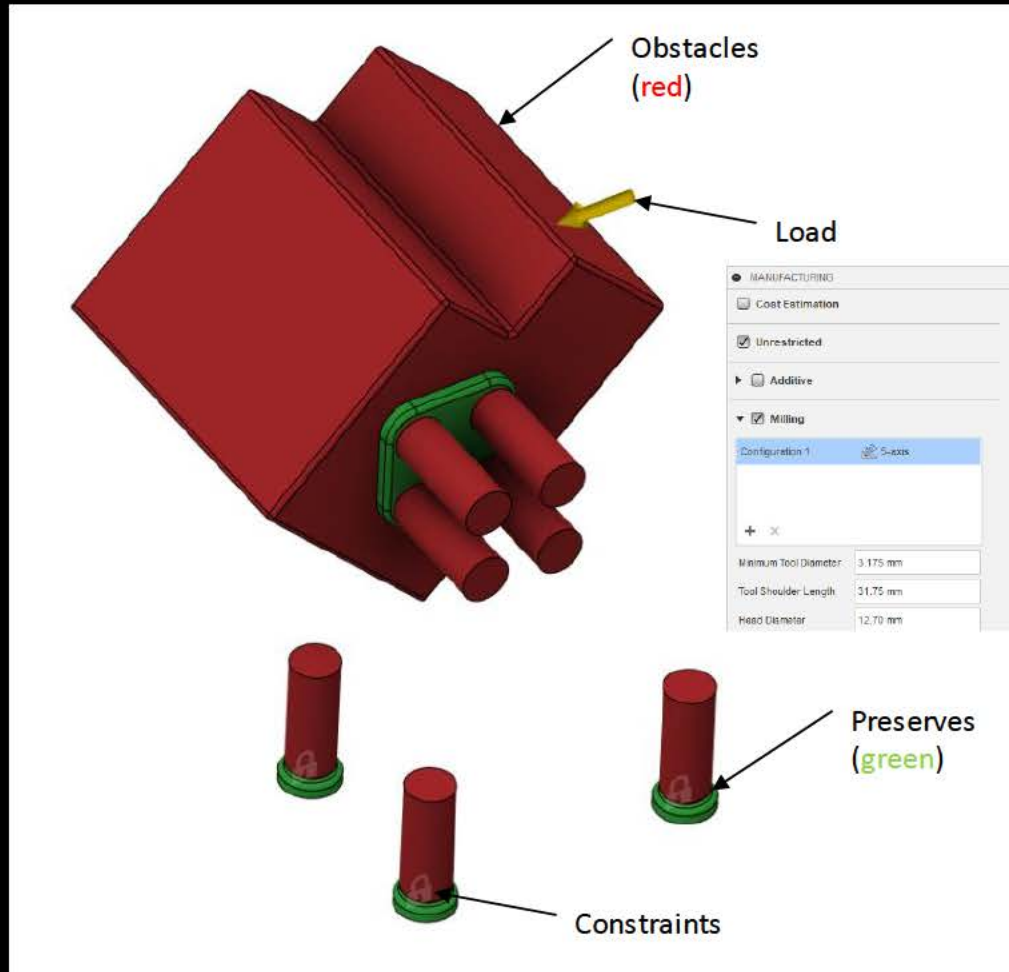


# Application Example: Human Design

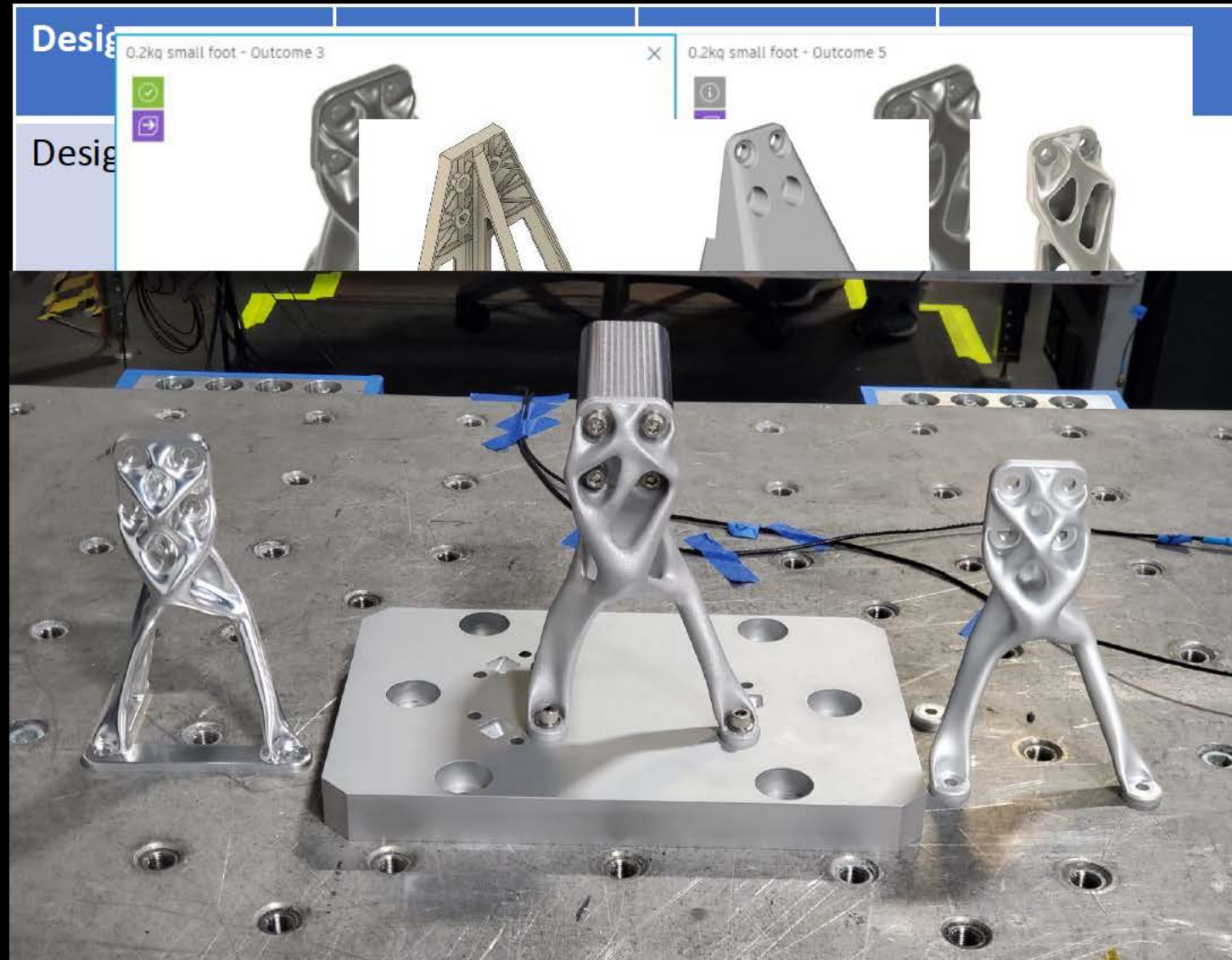
- Design problem given to senior design engineer
- Finite Element Analysis (FEA) done by me
  - Design improved with iteration
- **No manufacturable design meets the mass target**
- Elapsed time: 2 days

Designer / Iteration	Drew 1	Drew 2	Drew 3	Drew 4
Design (Aluminum)				
Mass (kg)	0.59	0.18	0.27	0.18
1 <sup>st</sup> 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



ALICE: Optical Bench



CCRS: LTM Paddle



Dragonfly: Carousel base



Venus lander



Lunar Spectrometer

# How is this possible?

- Generative Design and Digital Manufacturing leverage the massive advances in Information Technology
  - Pro/Engineer (e.g., Creo) released 1987
  - NASTRAN released 1968
  - Computing power has increased **>10,000x since 1990!**
    - Enables a **step-change** in Computer Aided Engineering (CAE) capability
    - Cloud computing allows practically unlimited compute for FEA
- Generative Design can be considered an abstraction layer on top of:
  - Computer Aided Design (CAD)
  - Finite Element Analysis (FEA) i.e., simulation
  - Design for Manufacturing (DfM)

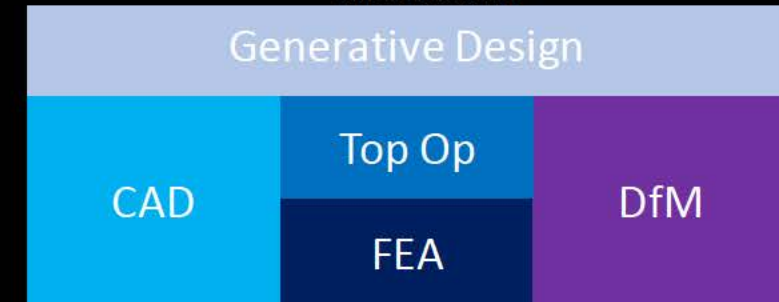
Enable *more science per dollar* by reducing the development time/cost and increasing the performance of spaceflight structures.



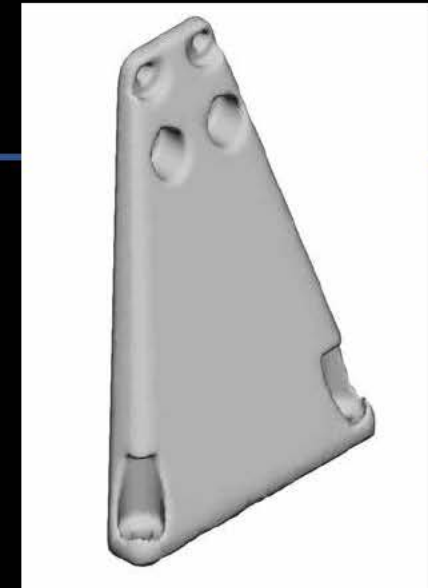
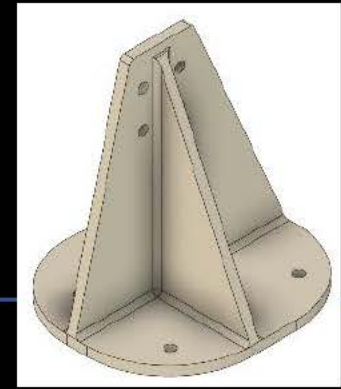
Image source: <https://www.vintagecomputing.com/index.php/archives/772/retro-scan-of-the-week-computer>



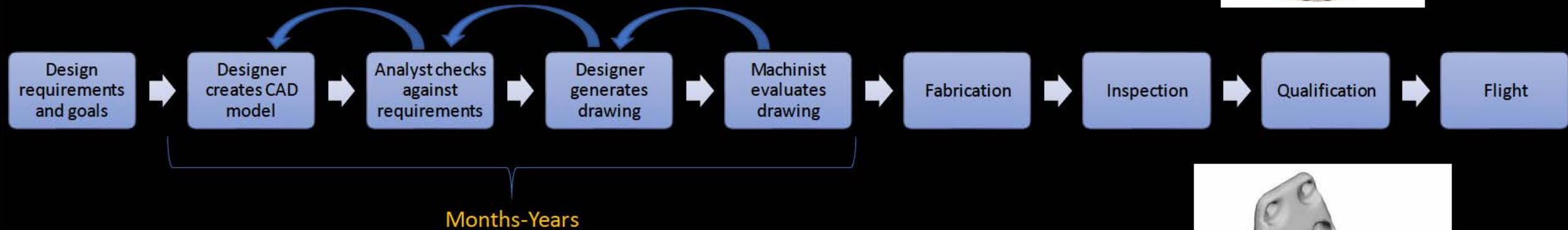
Image source: <https://elements.envato.com/cloud-computing-datacenter-server-room-servers-rac-62XTEN5>



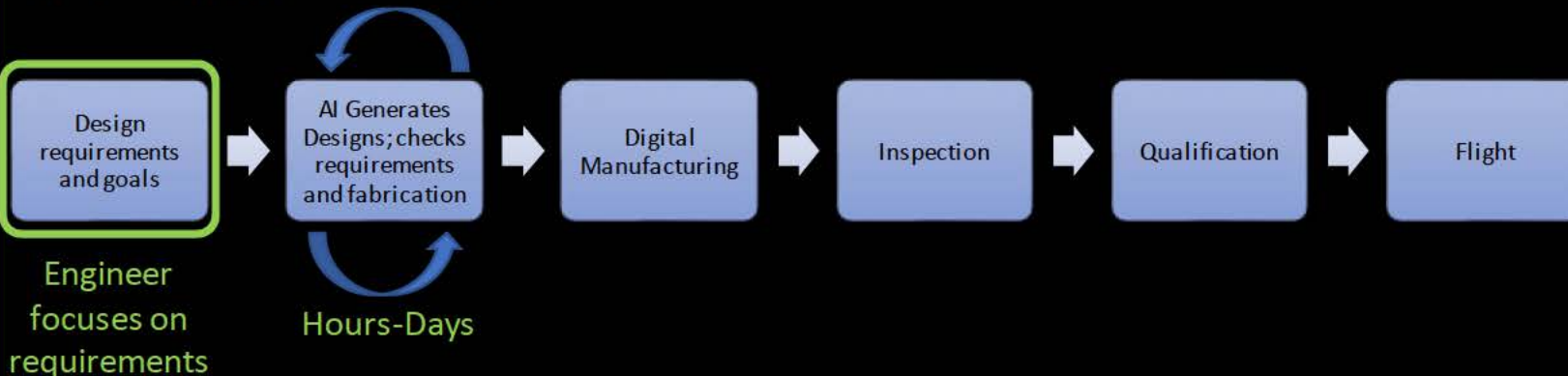
# Generative Design: Paradigm Shift



## 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

Create voxel mesh of design space

Run Topology Optimization

Output results for user review

Reconstruct CAD model of selected outputs

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



- 3D version of a pixel
- Can represent any geometry at any level of detail
- Also used in medical field

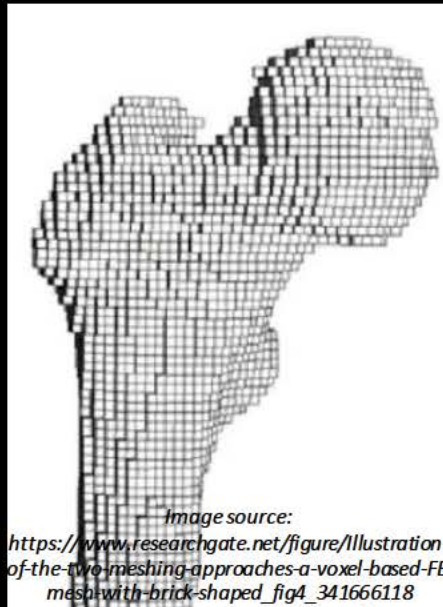


Image source:  
[https://www.researchgate.net/figure/Illustration-of-the-two-meshing-approaches-a-voxel-based-FE-mesh-with-brick-shaped\\_fig4\\_341666118](https://www.researchgate.net/figure/Illustration-of-the-two-meshing-approaches-a-voxel-based-FE-mesh-with-brick-shaped_fig4_341666118)

- 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)



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



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



# Digital Manufacturing: Robots turning bits to atoms



Bits



Atoms

# Digital Manufacturing

- Manufacturing processes that can **make parts from CAD files** with minimal human intervention
  - Software creates machine code (e.g., gcode) from CAD
  - Robot runs the code and makes the part
- **Digital Manufacturing  $\neq$  Additive Manufacturing**
- **Automated CNC**
  - Computer Aided Manufacturing (CAM) creates gcode from CAD with some human input
  - CNC robot runs the gcode
  - Exception: Protolabs – automated machine shop
    - 500+ HaaS CNC machines and no traditional machinists
- **Additive Manufacturing (AM, 3D printing)**
  - Slicer software generates gcode from CAD
  - AM robot runs the machine code – e.g. L-PBF
  - Post-process machining, heat treatment, support removal

Robot: a machine capable of carrying out a complex series of actions automatically, especially one programmable by a computer



Image source: <https://www.protolabs.com/services/cnc-machining/>  
Speed: 16200 RRM

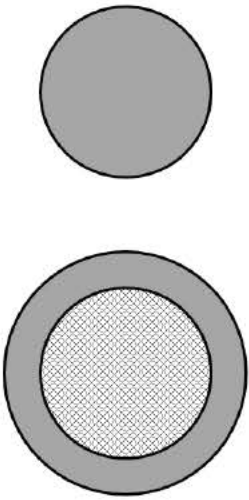
Image source: <https://www.youtube.com/watch?v=Byj1ON4x4vY>



Image source: <https://www.ge.com/news/reports/these-engineers-3d-printed-a-mini-jet-engine-then>

# AM for Evolved Structures (Future)

- Cost and schedule will improve due to mature **technologies, marketplace, and standards**
- Generative Design and AM may enable hollow bone-like structures with **vastly improved performance**
- Generative Design and AM will enable **large monolithic structures** to be designed and fabricated unlocking game-changing cost/schedule improvements
  - Vast improvement in structure performance
  - Vast reduction in part count and assembly labor
  - Print entire monolithic spacecraft primary structure
  - Print monolithic telescope structures



Same area but  
3x bending  
stiffness

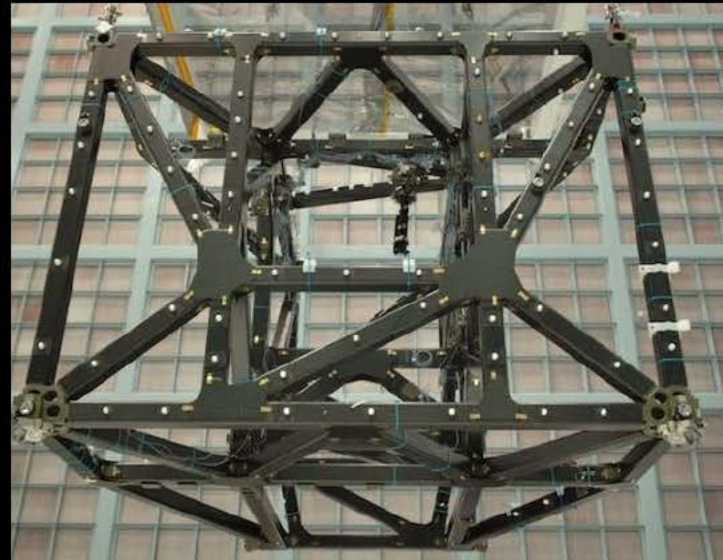
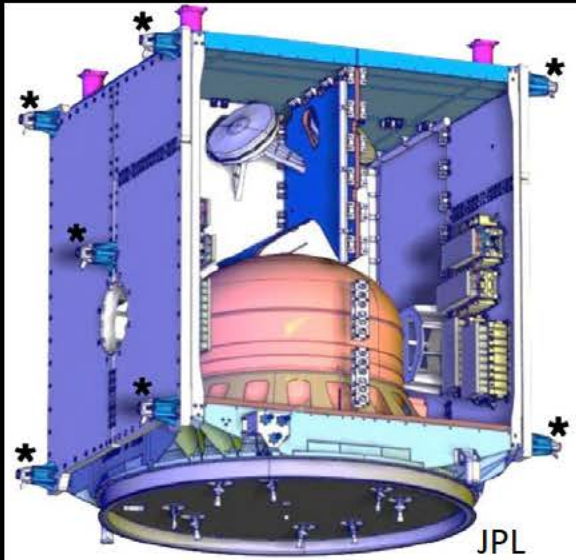


Image source: <https://www.wired.com/story/massive-ai-powered-robots-are-3d-printing-entire-rockets/>



# Pitfalls and Barriers to Adoption

- Skills gap: Design, Analysis, AND Manufacturing skills required
  - Currently **stove-piped** into different organizations
  - Generalist, not specialist level skills required
  - **Achieve through training**
  - May produce “**10x engineers**”
- Cultural inertia: general resistance to change
  - The parts **look weird** and alien
    - Get feedback and buy in from stakeholders
    - **Build, test, and fly** lots of hardware
  - Fear of being replaced by AI
    - Encourage **win-win** mentality: achieve more
    - Encourage **growth mindset**: fun to learn new tools!
- GiGo (Garbage in / Garbage out): need to get the requirements right
  - Also, a problem for human designs: **no more robust** against unplanned loads
  - Human intuition: from a lifetime of training, we know what “**looks right**”

Thales Aerospace / 3D Systems

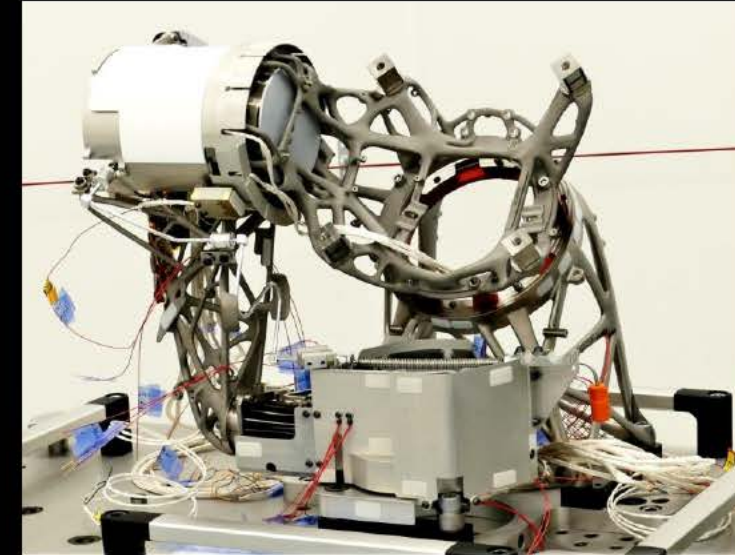


Image source: <https://www.thalesgroup.com/en/worldwide/space/news/ethm-3d-printed-electrical-thruster-mechanism>

*“When I am working on a problem, I never think about beauty but when I have finished, if the solution is not beautiful, I know it is wrong.” - R. Buckminster Fuller*

# Summary and Future Work

- Evolved Structures process:
  - Design requirements are **digitally encoded**
  - Generative Design AI **evolves optimal structures**
    - Iterative design, analysis, and fabrication simulation
  - Digital Manufacturing robots **fabricate parts from CAD**
- Typical metallic structures – **now automated**
  - Requirements → parts for fab in **1-2 days**
  - Parts **~3x stiffer/lighter/stronger** than human designs
  - Demonstrated by **test**
- The Future
  - Make all structure development **10x faster/cheaper**
  - Trusses, flexures, lightweight optics
  - Look for opportunities to automated development in **other disciplines**

