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

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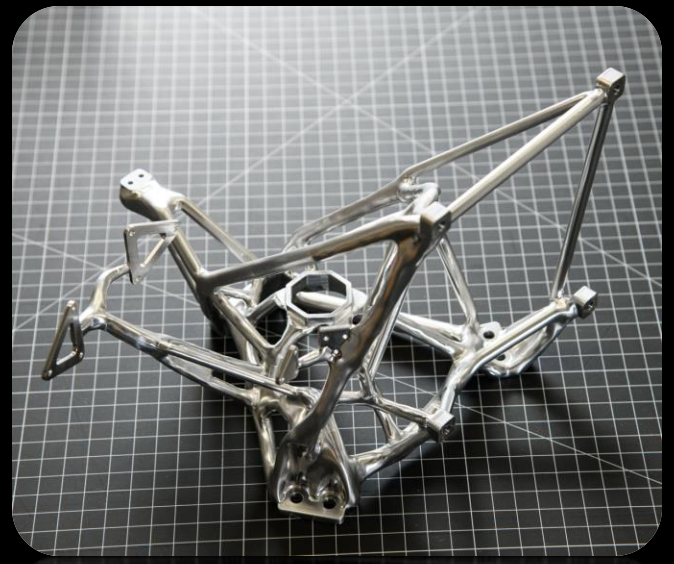


“Research is what I'm doing when I don’t know what I’m doing.”

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

Image source: https://www.artstation.com/artwork/Z5lYJm

Image source: 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?

Image source: https://mobile.twitter.com/aebdigital/status/1079504882393116674

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 ???

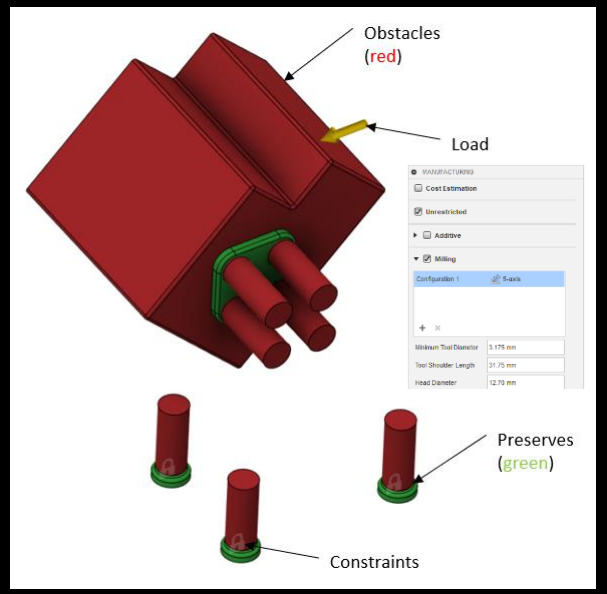
"astronaut seated in an armchair in the shape of an avocado, on the surface of the moon during the Apollo moon landings, by Salvador Dali, blue earthrise in the background"

Evolved Structures: Prompt Engineering for Structures

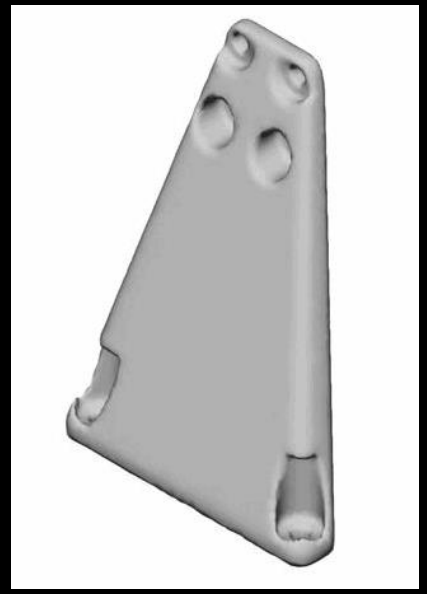
(1) Create a prompt to digitally encode structure requirements into software
- Follow written *Evolved Structures Guide for NASA applications*

(2) Use Generative Design AI to evolve optimal designs meeting requirements
- Using COTS software adapted for GSFC needs

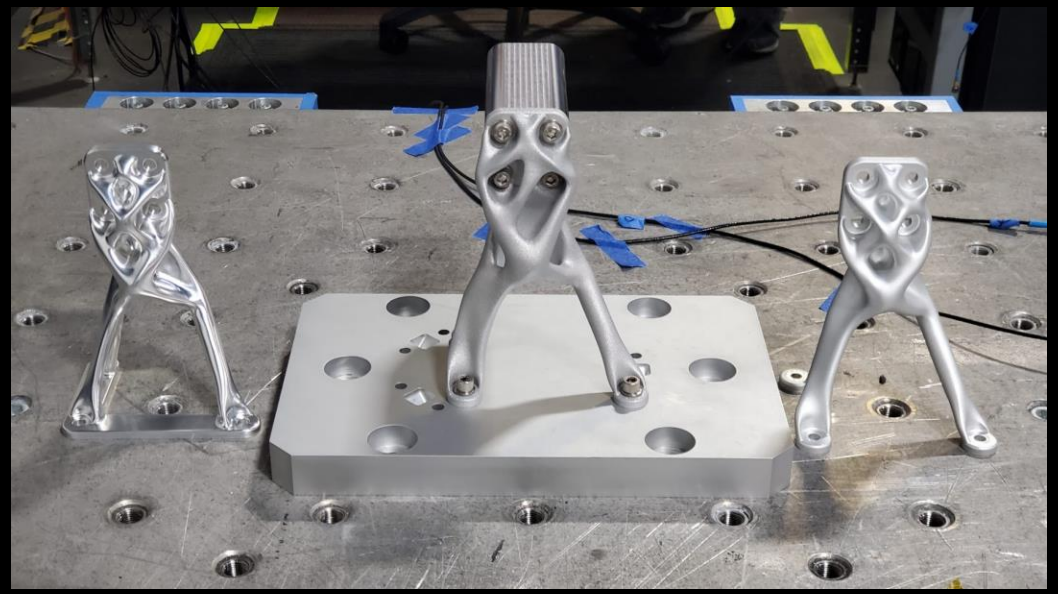
(3) Fabricate parts directly from Generative Design output using Digital Manufacturing (software + robots)
- Using industrial processes such as automated CNC and Additive Manufacturing (AM)



Encode Requirements
~1 hr



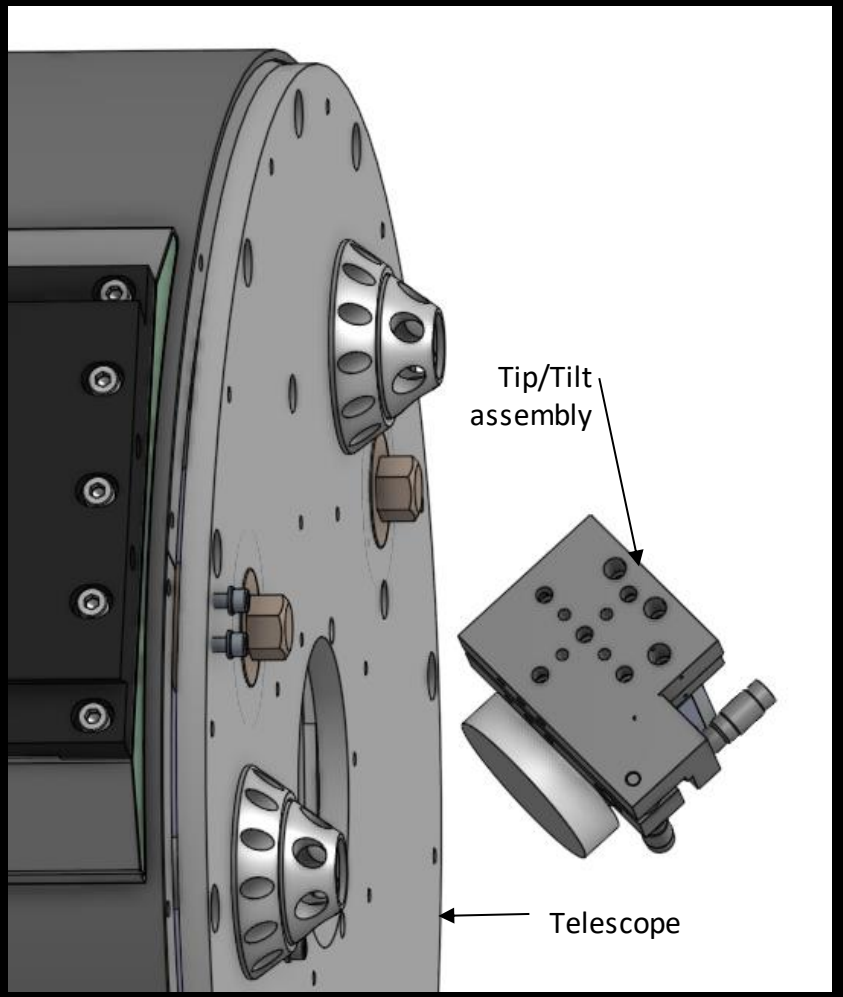
Evolve Designs
~1 hr



Fabricate Parts
1 day – 3 weeks

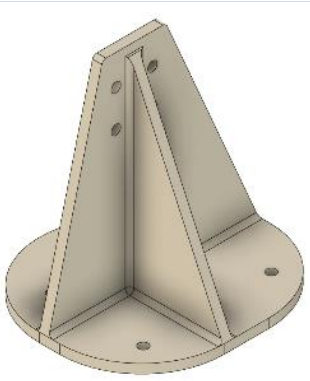
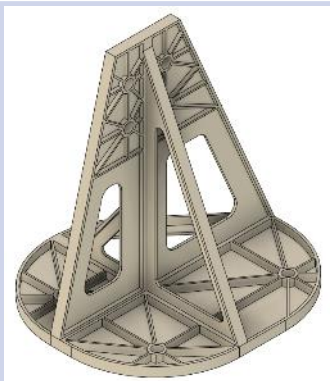
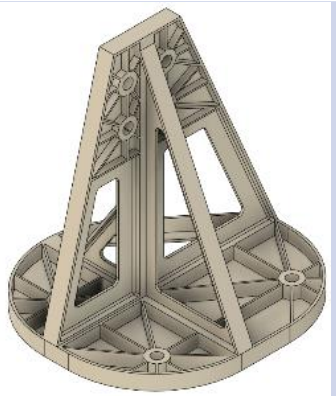
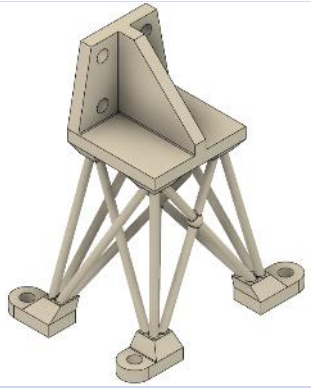
Application Example: EXCITE Tip/Tilt Bracket

- 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

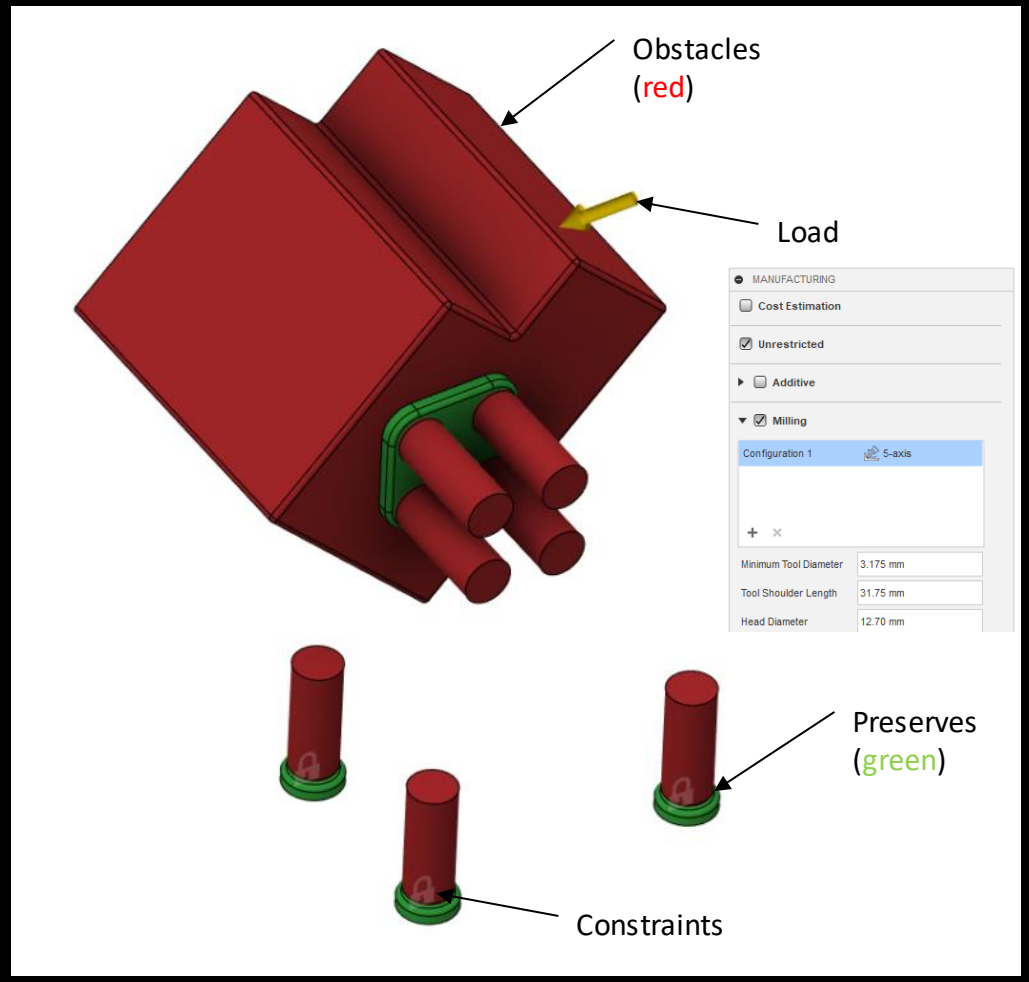


Application Example: Human Design

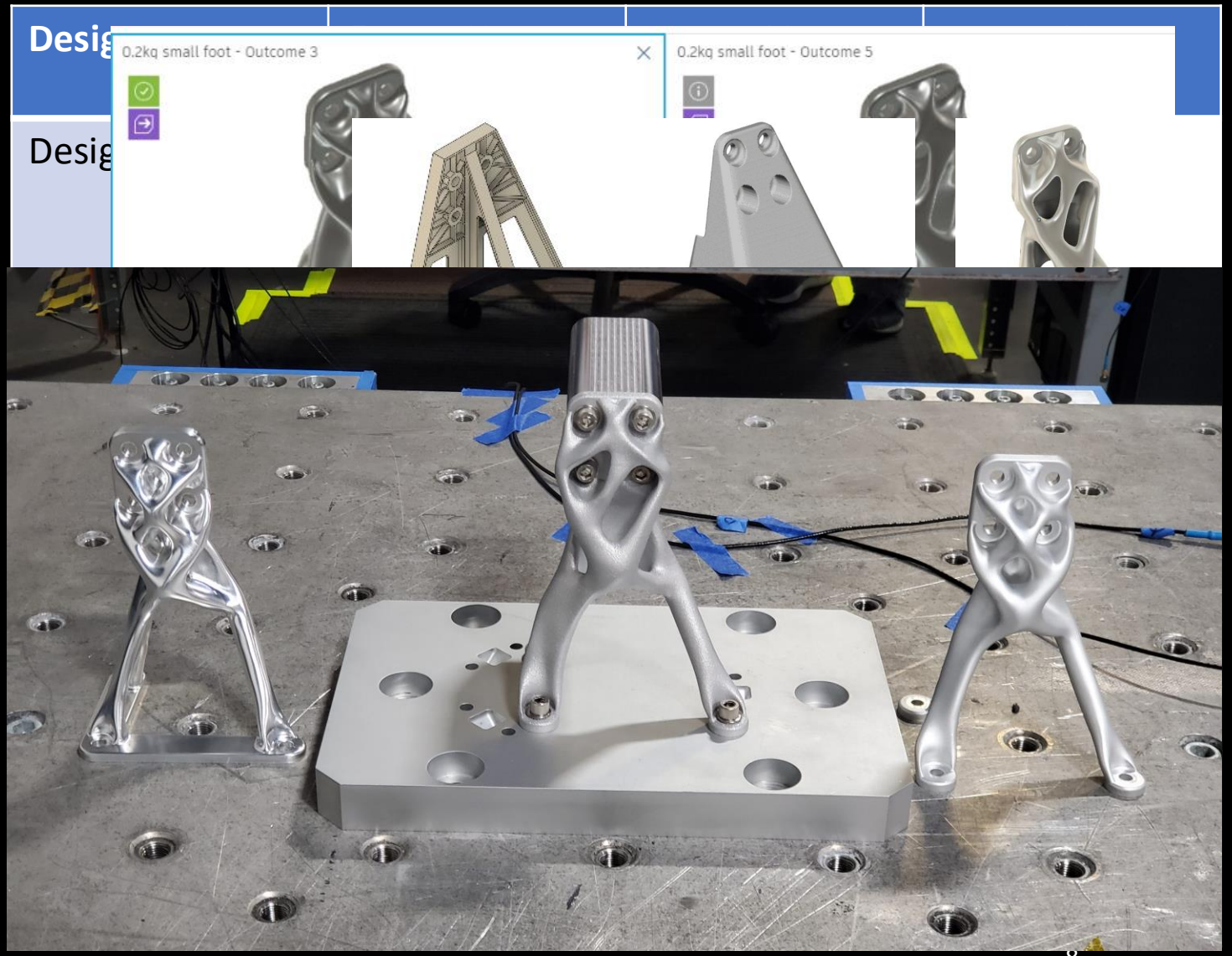
- Design problem given to senior design engineer
- Finite Element Analysis (FEA) done my me
  - Design improved with iteration
- No manufacturable design meets the mass target
- Elapsed time: 2 days

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

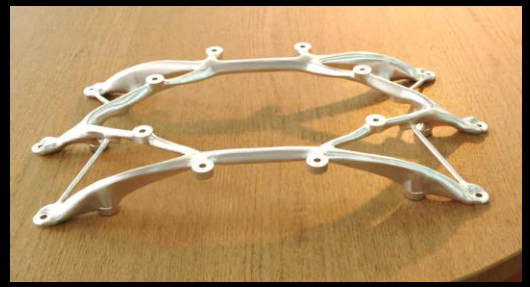

EXCITE: Tip/Tilt mount


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

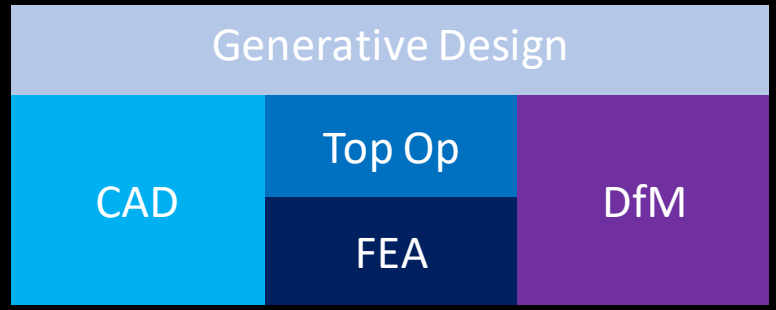
How is this possible?

- 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)

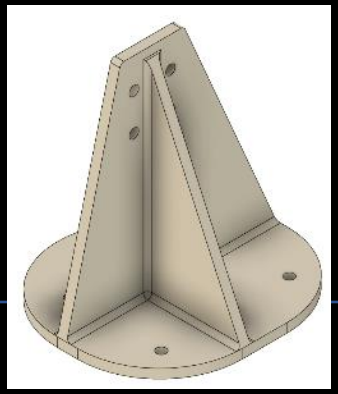
Enable *more science per dollar* by reducing the development time/cost and increasing the performance of spaceflight structures.

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

Design requirements and goals → Designer creates CAD model → Analyst checks against requirements → Designer generates drawing → Machinist evaluates drawing → Fabrication → Inspection → Qualification → Flight

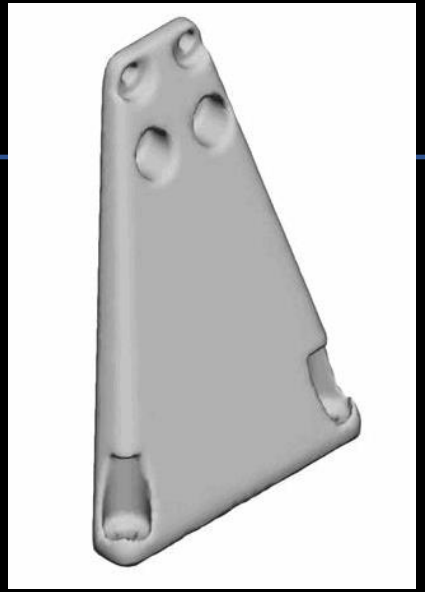
Months-Years

Evolved Structures Process

Design requirements and goals → AI Generates Designs; checks requirements and fabrication → Digital Manufacturing → Inspection → Qualification → Flight

Engineer focuses on requirements

Hours-Days



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

How it works

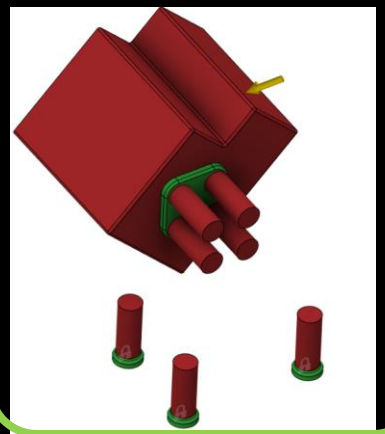
AI Generates Designs; checks requirements and fabrication

Hours-Days

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

User inputs

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



Create voxel mesh of design space

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

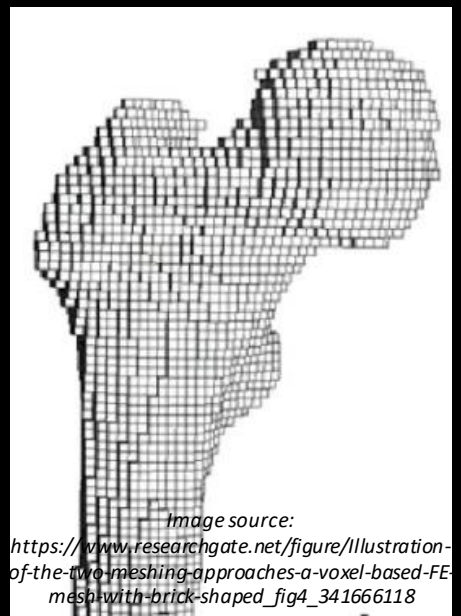


Image source: https://www.researchgate.net/figure/Illustration-of-the-two-meshing-approaches-a-voxel-based-FE-mesh-with-brick-shaped_fig4_341666118

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

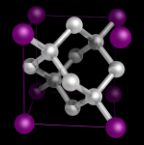
- Organize for simple user interaction
- Recommendation engine (mass, stress, cost)
- Reconstructed design preview

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

Digital Manufacturing: Robots turning bits to atoms

Bits



Atoms

Digital Manufacturing

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

- 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 ≠ 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

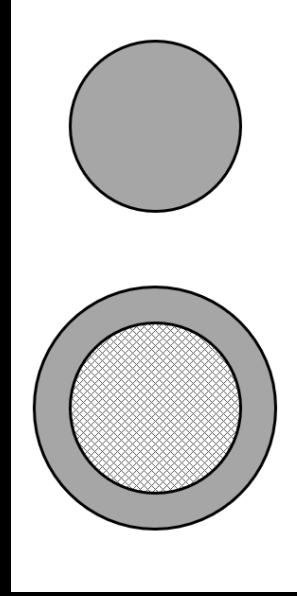
Image source: https://www.protolabs.com/services/cnc-machining/

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

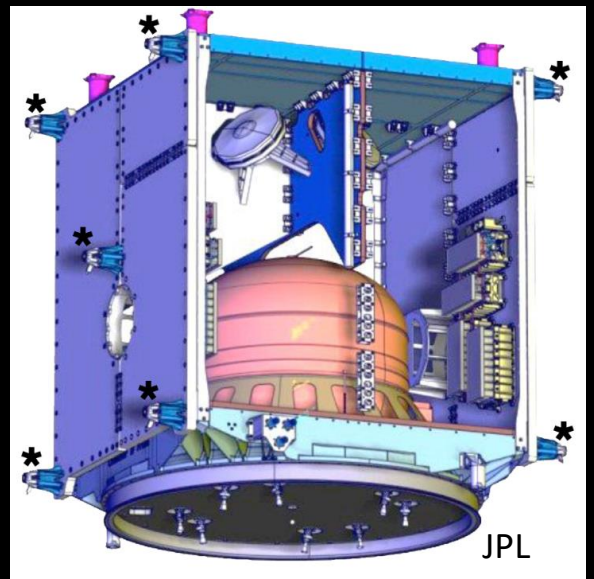
Image source: https://www.ge.com/news/reports/these-engineers-3d-printed-a-mini-jet-engine-then

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



JPL

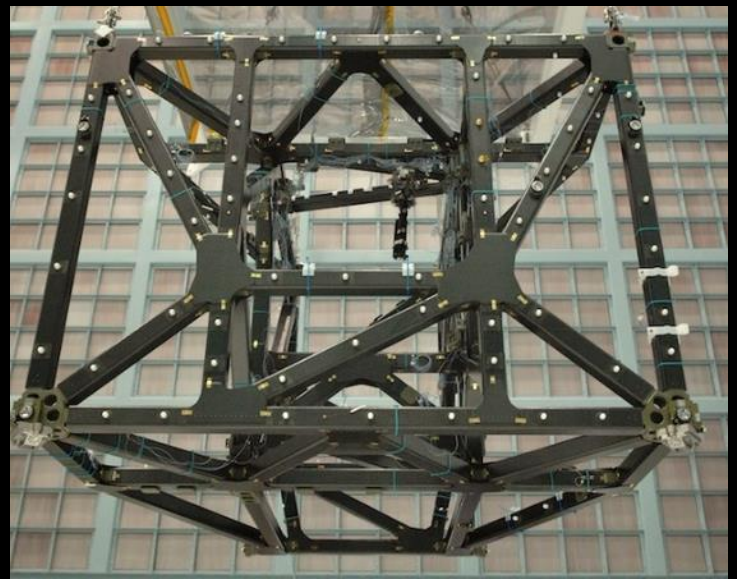


Image source: https://www.wired.com/story/massive-ai-powered-robots-are-3d-printing-entire-rockets/

Relativity Space

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

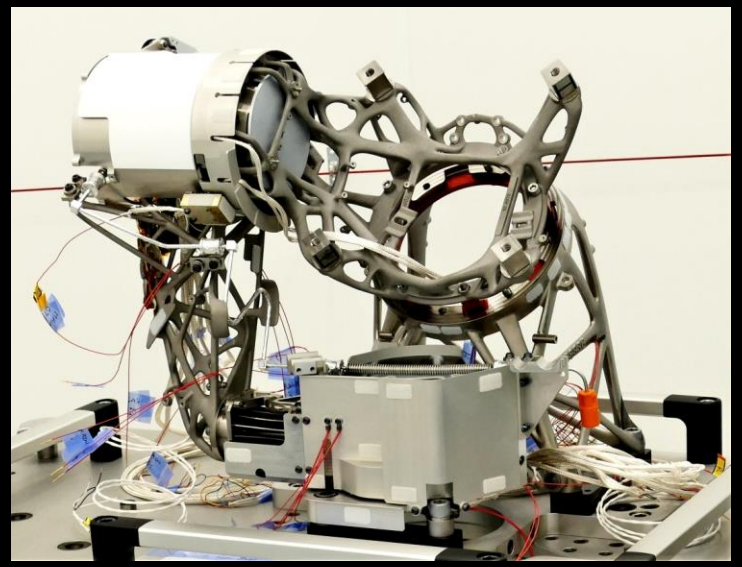


Image source: https://www.thalesgroup.com/en/worldwide/space/news/ethm-3d-printed-electrical-thruster-mechanism

"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
- Connect with me via LinkenIn