Lunar Surface Innovation CONSORTIUM

NASA

JOHNS HOPKINS APPLIED PHYSICS LABORATORY

LSIC Excavation & Construction Focus Group

Monthly Meeting

March 27th, 2024

Sarah Hasnain & Jibu Abraham

LSIC Excavation & Construction Focus Group Co-Facilitators

LSIC E&C Focus Group

Athonu Chatterjee
Jibu Abraham
Sarah Hasnain
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Michael Nord
Gus Terlaje

Agenda

1. LSIC Sign-Ups & Call for Speakers – Email Jibu.Abraham@jhuapl.edu and Sarah.Hasnain@jhuapl.edu
2. Opportunities & Conferences
3. Leveraging AI & Robotics for Excavation & Construction
    1. Ryan McClelland (NASA – Goddard) – Evolved Structures: Generative Design and Digital Manufacturing at NASA
    2. Tom McCarthy (Motiv Space Systems) – Autonomous Robotic Construction
4. Breakout Discussions (30 mins)

    Integrating AI into Excavation & Construction on the lunar surface – Opportunities and Risks

Opportunity: DARPA SHALE

Respond by April 15 / Six Hypotheses for Accelerating the Lunar Economy (SHALE) RFI

"The LunA-10 study has identified six key hypotheses where, if revolutionary improvements in technology can be made, a direct acceleration to the fielding of a lunar economy is likely to occur. To address these, the DARPA Strategic Technology Office (STO) is requesting information related to actionable technical insights and new methods by which disruptively large (at least one order of magnitude or greater) improvements in these areas may be made. This RFI seeks responses that address the following topics of interest:

1) Centralized thermal rejection and generation as a service,
2) Widespread orbital lunar prospecting and surveying,
3) Creating large silicon wafers for microsystems on the Moon,
4) Biomanufacturing to accelerate lunar construction,
5) New concepts to increase refinement rates in low gravity,
6) New concepts for Lunar position, navigation and timing."

https://sam.gov/opp/64eebf6ce73b48a098796a3196b6db5c/view

Opportunity: NASA Space Technology Art Challenge

Respond by April 15 / NASA Space Technology Art Challenge: Imagine Tomorrow

"The NASA Innovative Advanced Concepts (NIAC) Program wants you to show the world the future of space technology. The NIAC Program is looking for posters that help people better understand these visionary aerospace concepts that might be used in future NASA missions . . . These images will inspire vast audiences by creating effective visualizations of cutting-edge technologies. All selected images will be uploaded to the NIAC website, shared widely, and available for free digital download. Credit will be given to all artists' work."
https://www.nasa.gov/directorates/stmd/stmd-prizes-challenges-crowdsourcing-program/center-of-excellence-for-collaborative-innovation-coeci/the-nasa-space-technology-art-challenge-imagine-tomorrow/

Image Credit: NASA

Upcoming Conferences

April 15-18 / ASCE Earth & Space 2024

American Society of Civil Engineers (ASCE) Aerospace Division (ASD) Biennial International Conference on Engineering, Science, Construction and Operations in Challenging Environment. Pre-conference short course on *Lunar Geotechnics and Foundation Design*. https://earthspace2024.fiu.edu/

May 21-22 / NASA-USGS Workshop on Planetary Subsurface Exploration for Science and Resources

NASA and USGS are hosting the 2nd workshop on Planetary Subsurface Exploration for Science and Resources on Tuesday-Wednesday, May 21-22, 2024, in Moffett Field, California at the Moffett Field Auditorium facilities. Agenda and registration coming soon!

June 4-7 / Space Resources Roundtable

The Space Resources Roundtable (SRR) will convene its 24th meeting on June 4-7, 2024. The meeting will be held in person on the campus of the Colorado School of Mines in Golden, CO, USA. https://learn.mines.edu/srr/

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SAVE THE DATE

LSIC 2024 Spring Meeting | April 23 – 25

Johns Hopkins Applied Physics Laboratory,
Kossiakoff Center, Laurel, MD (hybrid)

This spring, our focus is engaging our community on how to get back to the Moon together including NASA's plans and updates, infusion paths, partnerships, current technology investments, and more!

Registration opens
February 16th

Abstract Portal open until
March 1st

Ryan McClelland (NASA – Goddard)

Ryan McClelland is a Research Engineer in NASA GSFC's Instrument Systems and Technology Division, he pursues the development and implementation of digital engineering technologies for space-flight missions. Ryan is particularly excited about the potential of Artificial Intelligence, Virtual Reality, Generative Design, and Digital Manufacturing to accelerate space systems development.

With a diverse background in technology development, Ryan's previous research encompasses lightweight X-ray optics, aluminum foam core optical systems, and the investigation of non-linear effects in kinematic mechanisms. In addition to his research, Ryan has played a significant role in various flight missions, including designs currently on orbit aboard the Hubble Space Telescope and International Space Station. Recently, he served as the Roman Space Telescope Instrument Carrier Manager. Ryan holds a B.S. in Mechanical Engineering, summa cum laude, from the University of Maryland.

Tom McCarthy (Motiv Space Systems)

Tom McCarthy is the VP of Business Development and Co-Founder of Motiv Space Systems located in Pasadena, CA. Motiv Space Systems is a disruptive technology driven small business dedicated to the art of motion control and robotics and their numerous applications in space flight systems.

Tom began his career as an electrical engineer at the Jet Propulsion Laboratory designing flight computing architectures and embedded motion control solutions to enable some of NASA's most exciting exploration challenges. Those challenges included developing roving platforms for exploring Mars, the Moon and asteroids which required operations in extremely harsh environments. Tom has since built upon those experiences to work with future visionaries interested in utilizing robotics for the expansion of commerce in space. Tom, along with his Motiv colleagues, continue to build partnerships and develop new technologies to enable future flight missions.

Breakout Discussions

Integrating AI into Excavation & Construction on the lunar surface: Opportunities and Risks

Guiding Questions:

What existing terrestrial AI systems could be applicable to lunar E&C applications?
(Share links to GitHub repos, papers, articles, podcasts, etc. in chat!)

What computational resources are needed to support AI-enabled lunar E&C?
What might this look like for early infrastructure vs. a more sustained presence?

What risks are there to implementing AI in lunar E&C efforts?
Consider environmental (ex: dust, lighting, terrain) and resource (ex: data, power, computing) factors.

How might Generative AI be utilized in designing modular and interoperable structures?


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Evolved Structures:
Generative Design and Digital Manufacturing at GSFC

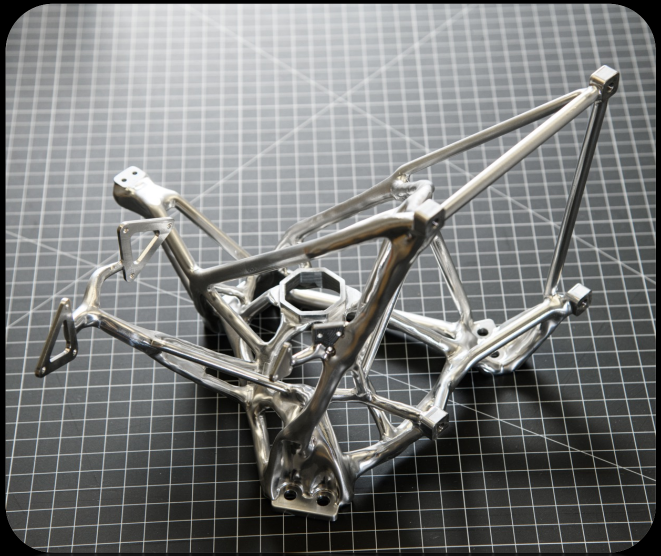
Ryan McClelland

Research Engineer

Instrument Systems and Technology Division

(ISTD, 550)

NASA Goddard Space Flight Center (GSFC)



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 and proposals: CCRS, DraMS, DAVINCI, EXCITE, LEXA, HWO, STRIVE, etc
- Goals of this presentation
  - Enable missions to improve the mass/stiffness/strength of structures by 2x-4x while reducing development time/cost by ~10x
  - Inform stakeholders on how to identify promising applications
  - Help GSFC win missions and deliver on commitments
  - Share lessons learned for successful mission infusion

"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

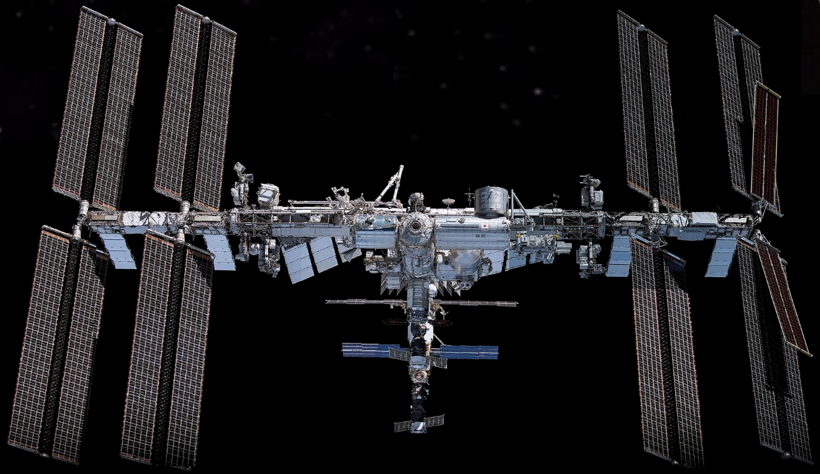


Image source: https://mobile.twitter.com/aebdigital/status/1079504882393116674

Evolved Structures Process

(1) Digitally encode structure requirements into software

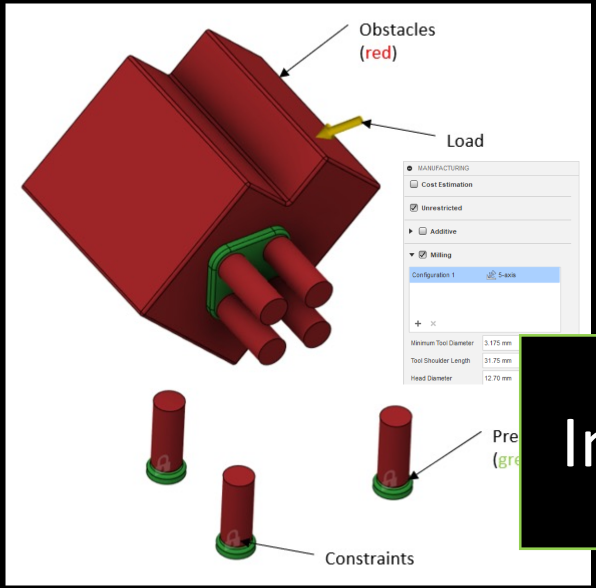
- Follow written *Evolved Structures Guide for NASA applications*

(2) Use Generative Design AI to evolve optimal designs meeting requirements

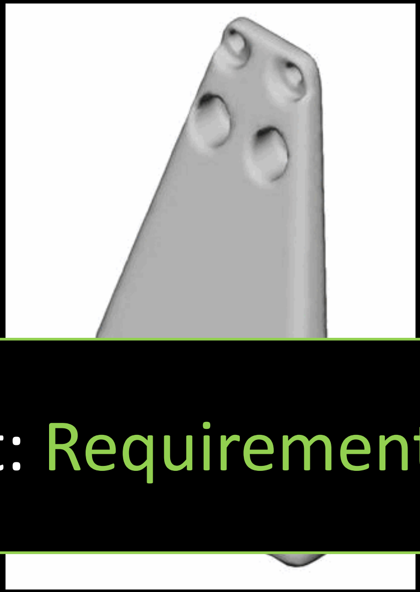
- Using COTS software adapted for GSFC needs

(3) Fabricate parts directly from Generative Design output using Digital Manufacturing (software + robots)

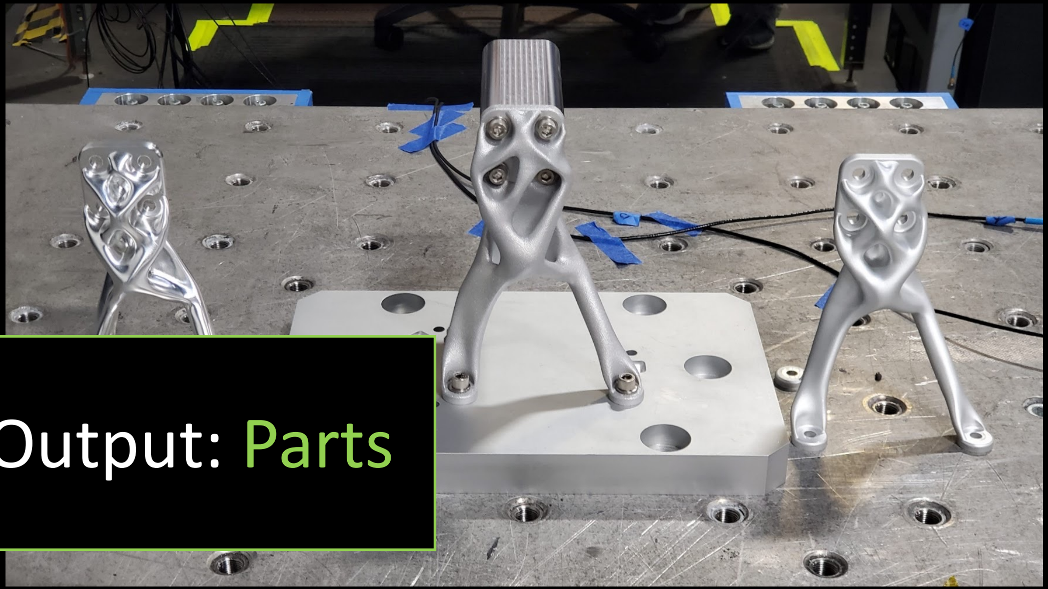
- Using industrial processes such as automated CNC and Additive Manufacturing (AM)



Encode Requirements
~1 hr



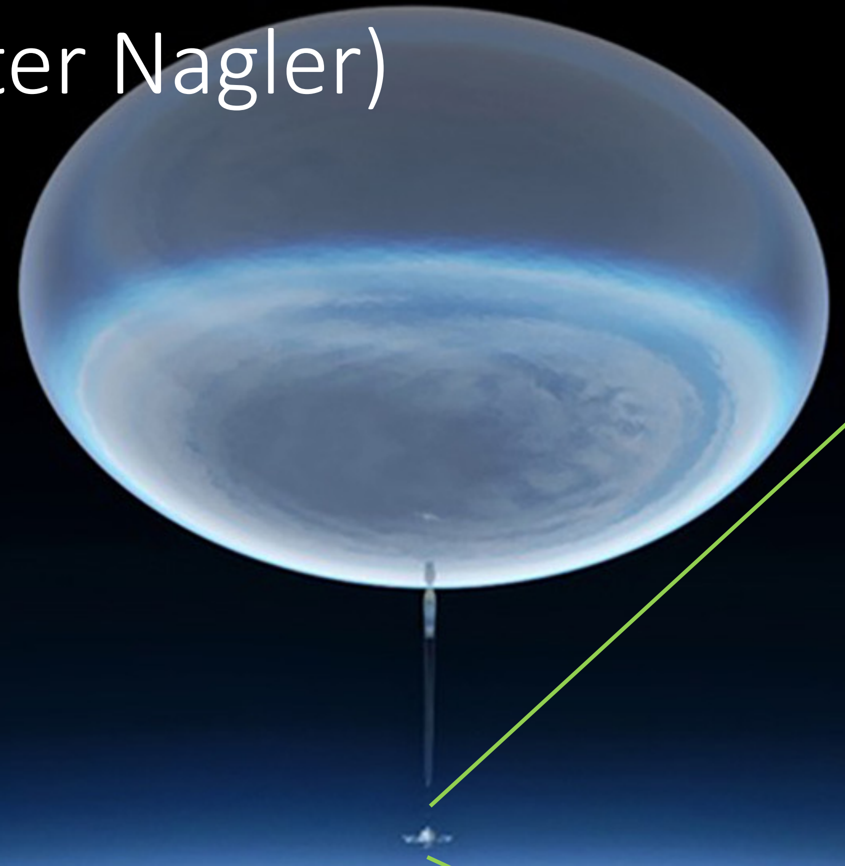
Evolve Designs
~1 hr



Fabricate Parts
1 day – 3 weeks

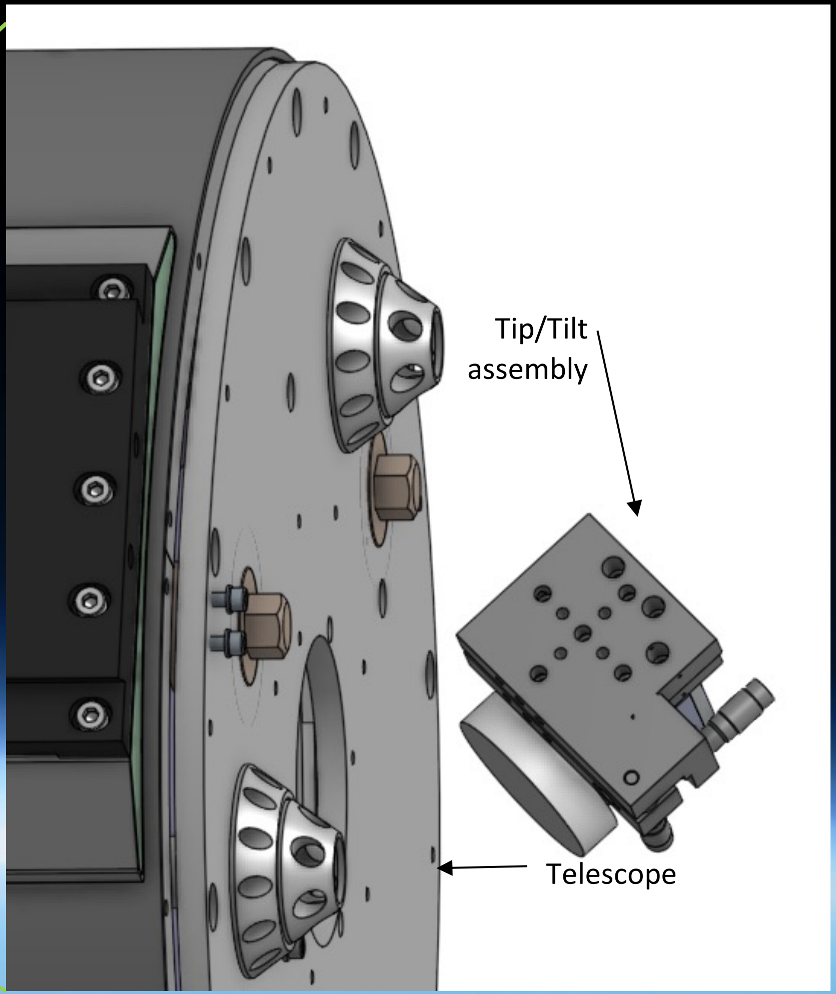
Input: Requirements ▶ Output: Parts

NASA EXoplanet Climate Infrared Telescope (EXCITE, PI: Peter Nagler)



40 km

above Earth's surface

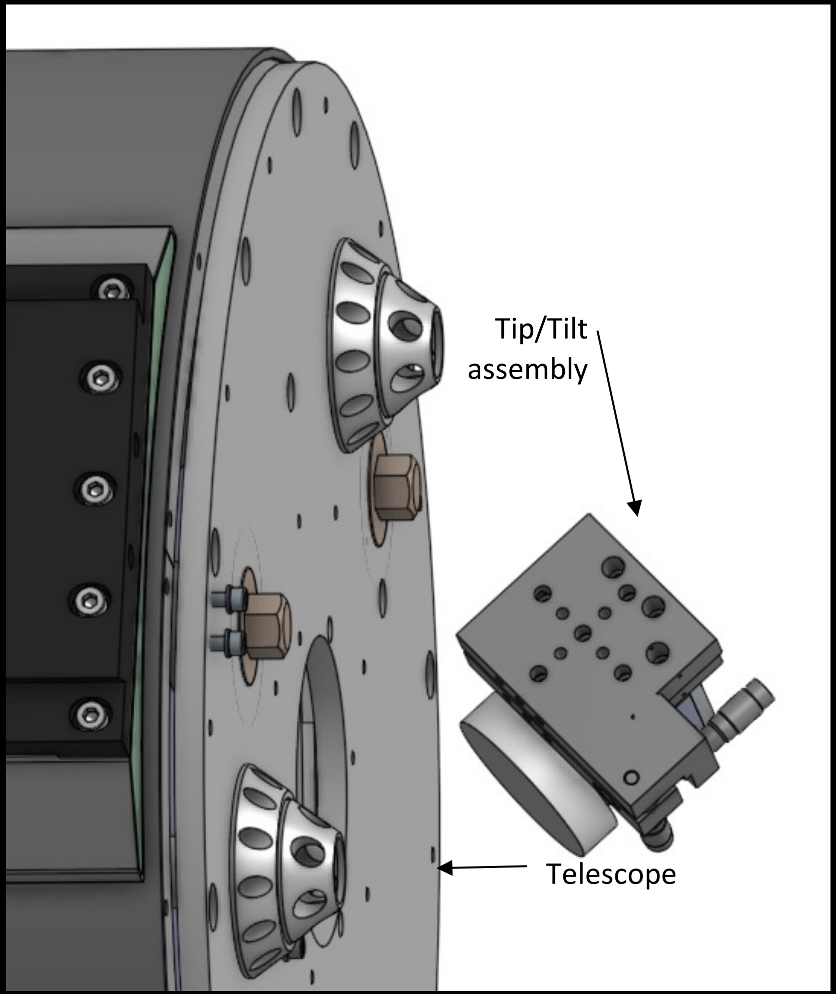


Illustration

Image Source: https://www.jpl.nasa.gov/news/nasa-mission-will-study-the-cosmos-with-a-stratospheric-balloon

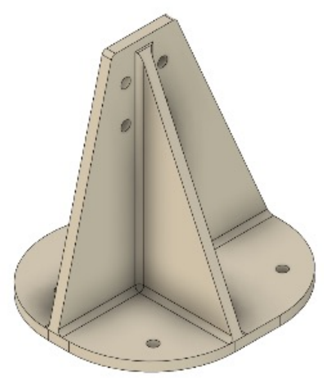
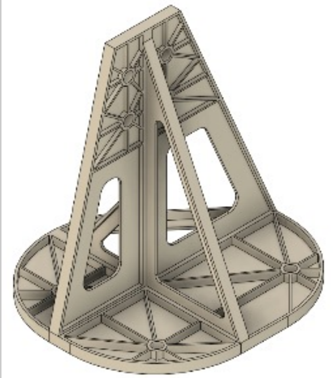
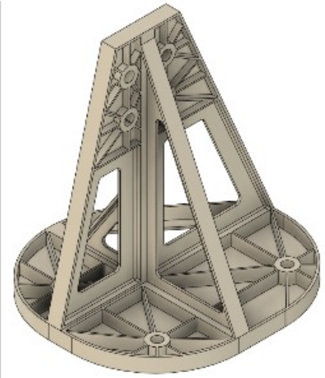
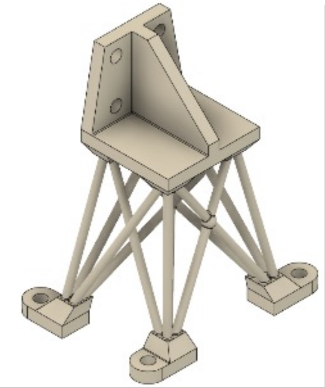
Application Example: EXCITE Tip/Tilt Bracket

- 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

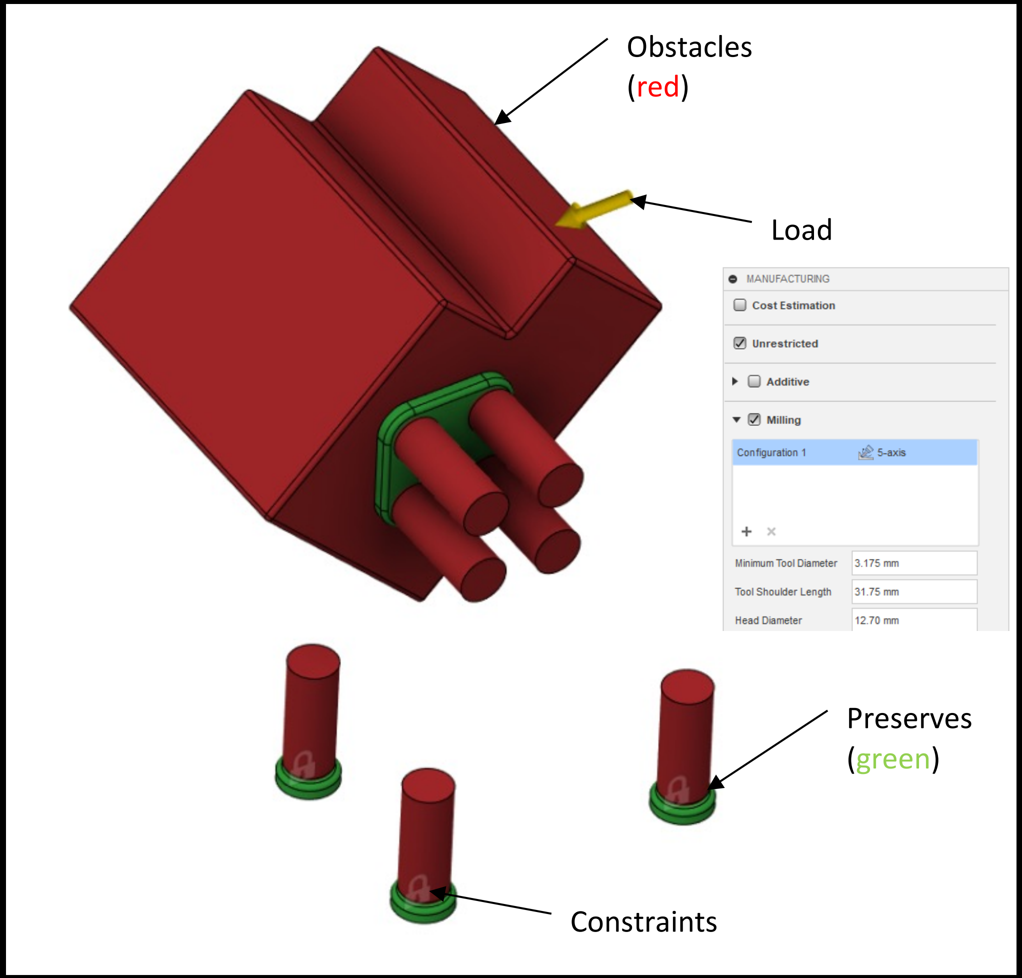


Application Example: Human Design

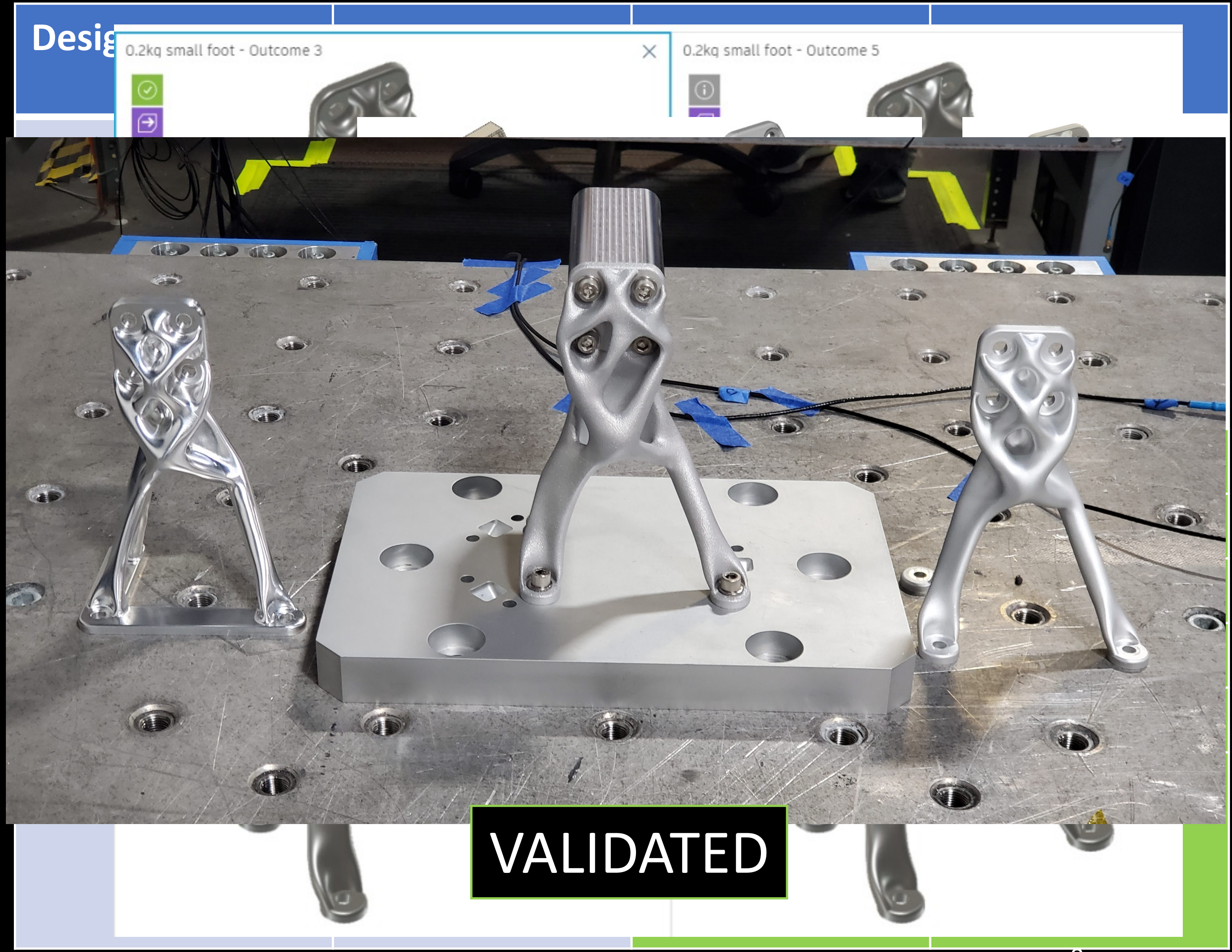
- Design problem given to senior design engineer
- Finite Element Analysis (FEA) done my me
  - Design improved with iteration
- No manufacturable design meets the mass target
- Elapsed time: 2 days

Human Designer Iteration	1	2	3	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 Design

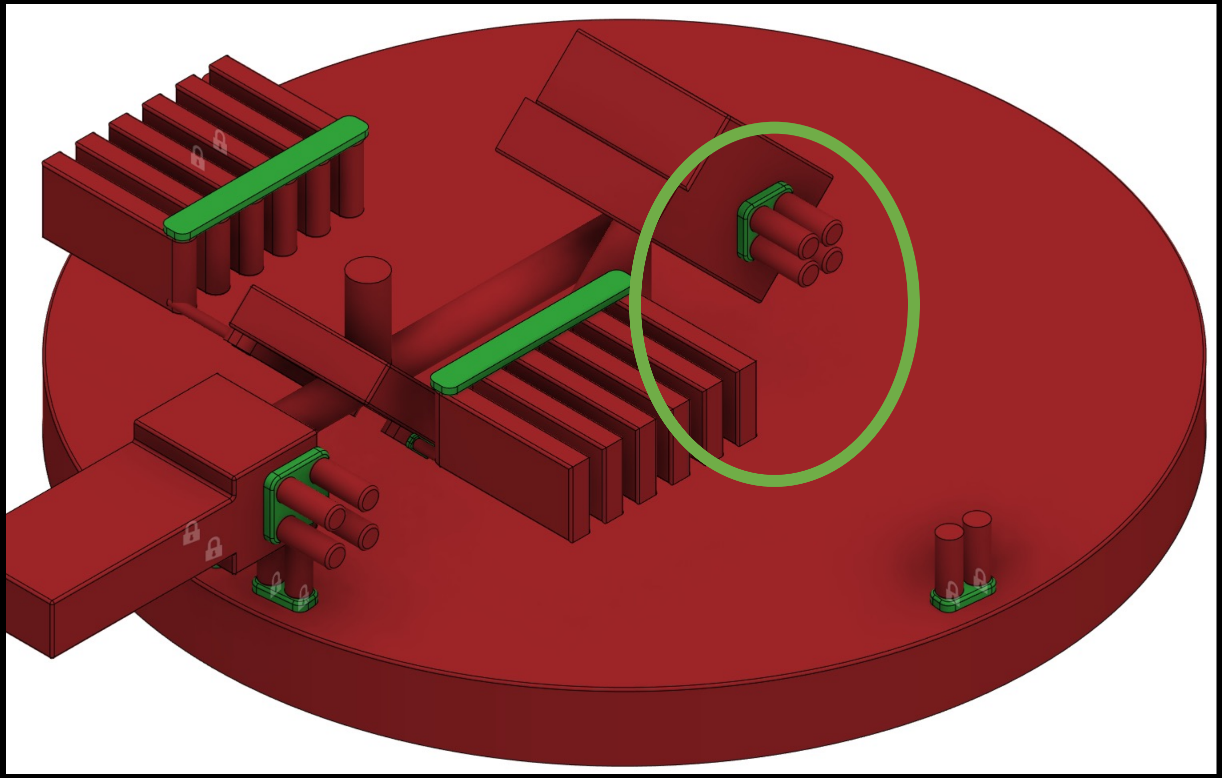


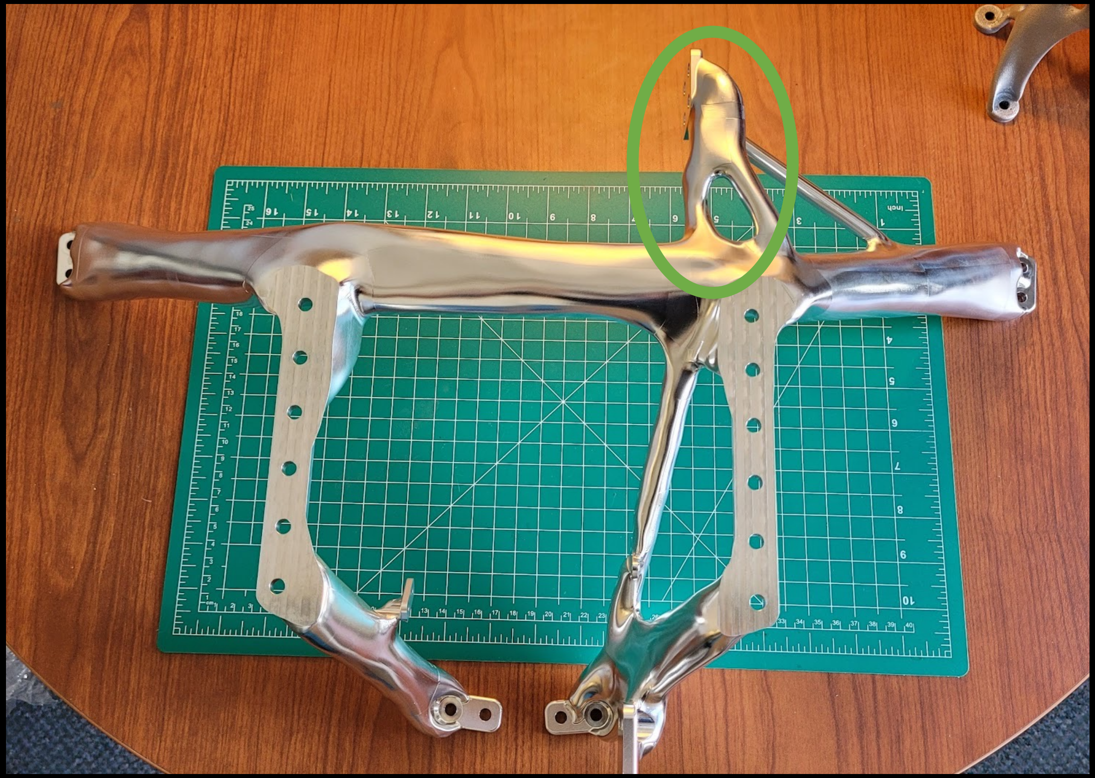
Inputs



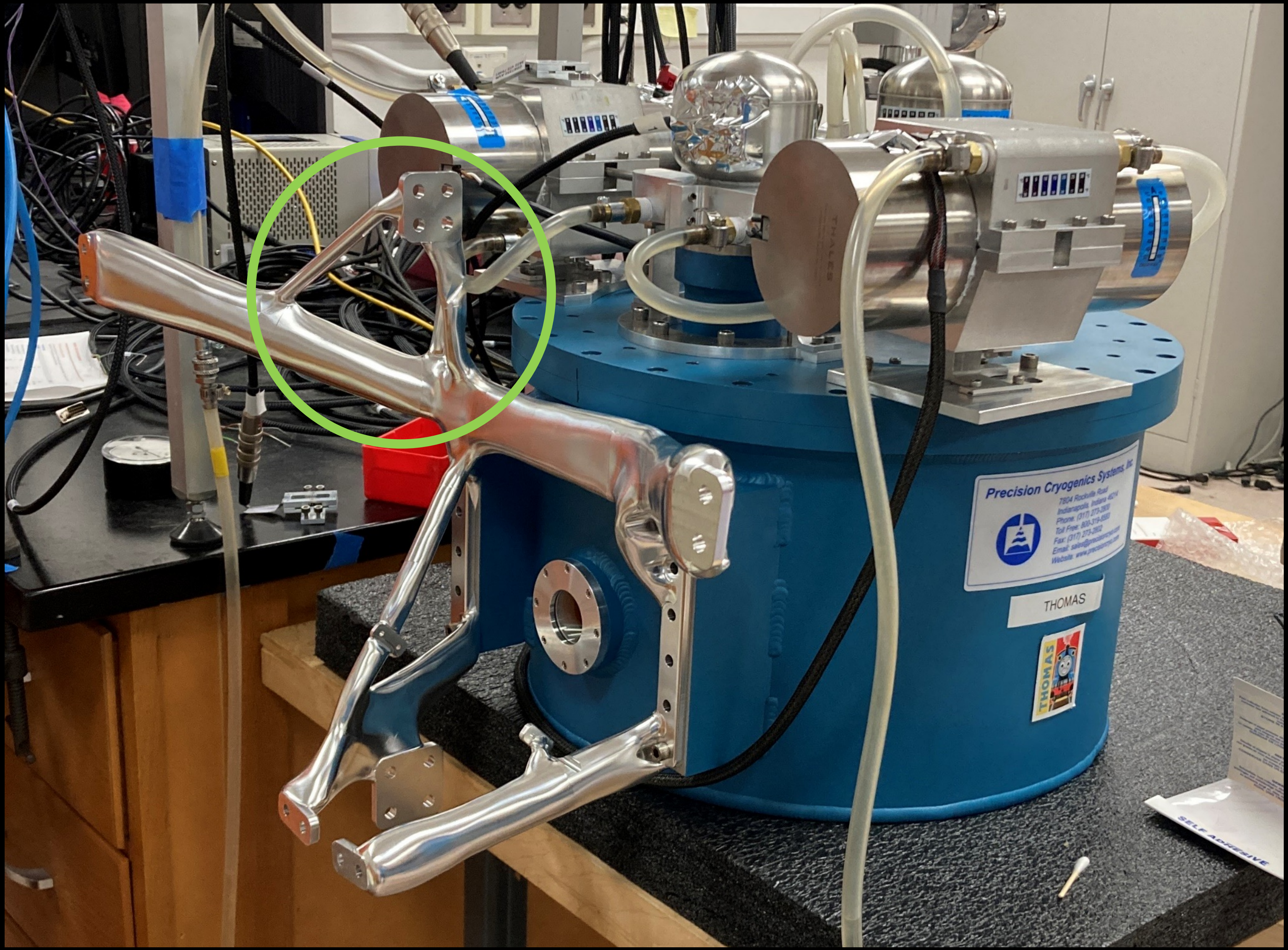
Outputs

Case Study: EXCITE Evolved Optical Bench





Case Study: EXCITE Evolved Optical Bench



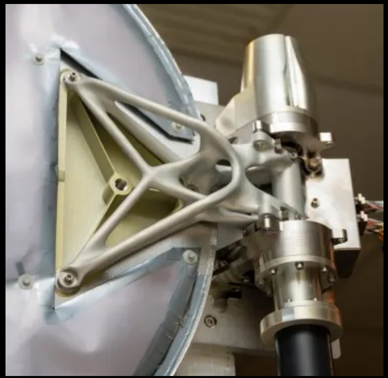
Application Examples

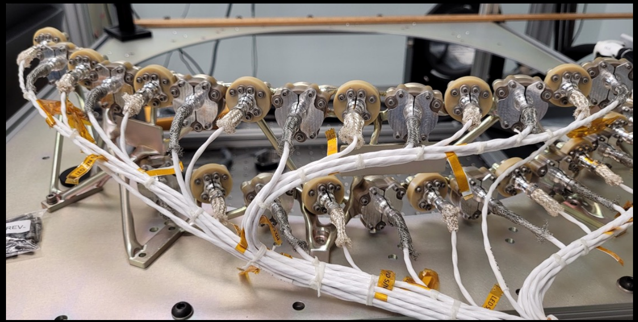
"The trick to having good ideas is not to sit around in glorious isolation and try to think big thoughts. The trick is to get more parts on the table."
- Steven Johnson


EXCITE: Tip/Tilt mount


EXCITE: Radiator mount


EXCITE: Detector mount


MSR-CCRS: Capture Lid

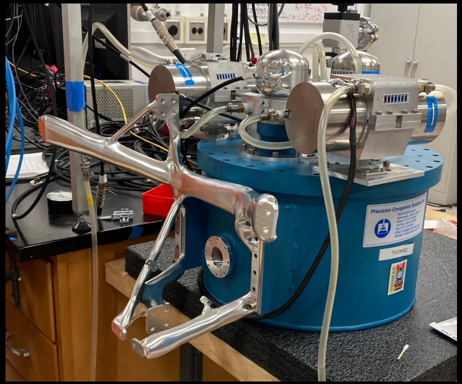

MSR-CCRS: Capture Sensor Bracket


DraMS Carousel Base

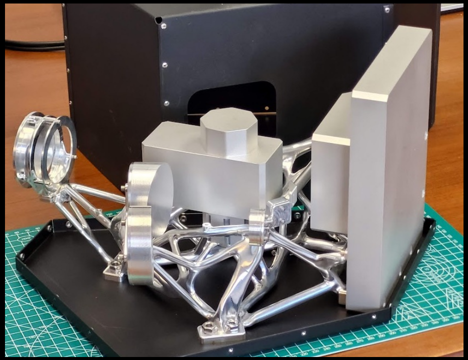

LEXA: Lunar Spectrometer


Optical Bench


CCRS: LTM Paddle

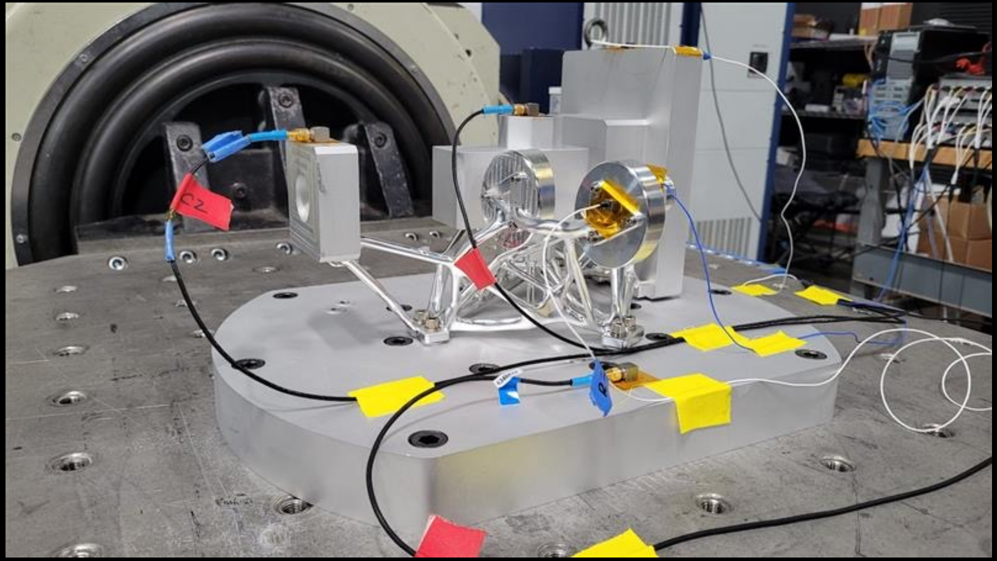

EXCITE: Optical Bench


Venus lander

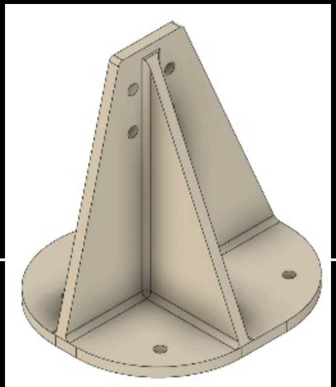

Optical Bench

Case Study: ALICE Evolved Optical Bench

- Earth Science Instrument for STRIVE mission
- Radically lightweight structure
  - Reduced from 3.6 kg to 610 gms!
- Consolidates 10 parts from the original design
  - CNC machined from a single block of Aluminum
- Successfully vibration tested to GEVS standards
- Demonstrates Evolved Structures as an enabling technology for future instruments
  - Reducing mass creates a virtuous cycle, enabling other parts of the system to be lighter and reducing power consumption, all of which ultimately reduce cost
- Next step: reduce entire instrument mass to fit on a smaller mission class



Generative Design: Paradigm Shift



Current GSFC Process

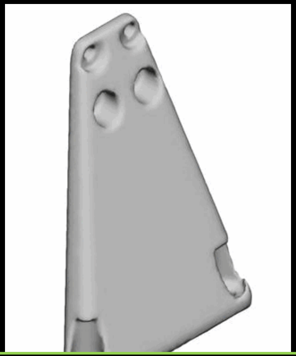
Design requirements and goals → Designer creates CAD model → Analyst checks against requirements → Designer generates drawing → Machinist evaluates drawing → Fabrication → Inspection → Qualification → Flight

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



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

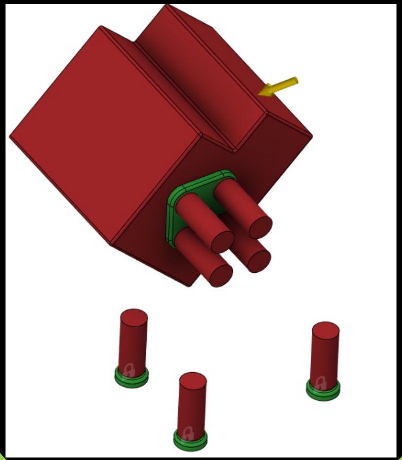
Generative Design: How the process works

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

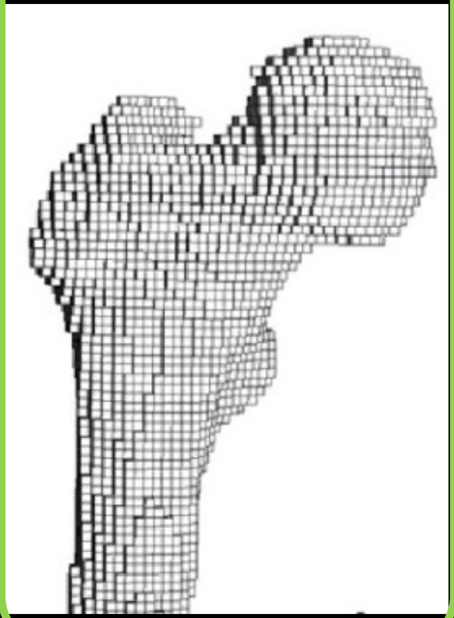
AI Generates Designs; checks requirements and fabrication

Hours-Days

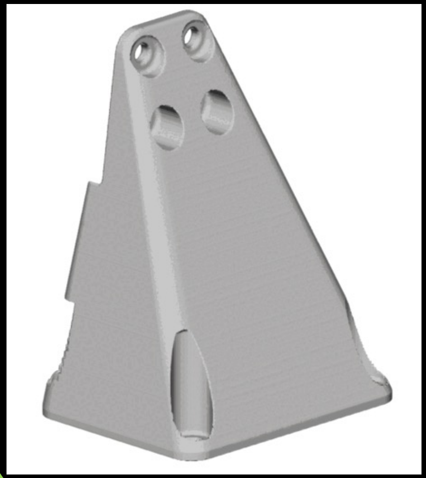
User inputs



Create voxel mesh of design space



Run Topology Optimization

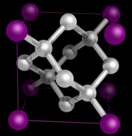


Output results for user review

Reconstruct CAD model of selected outputs

Digital Manufacturing: Robots turning bits to atoms

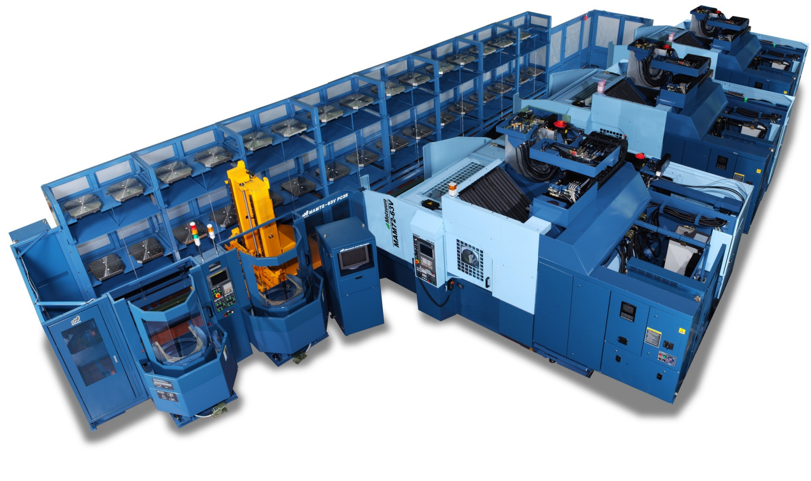
Bits

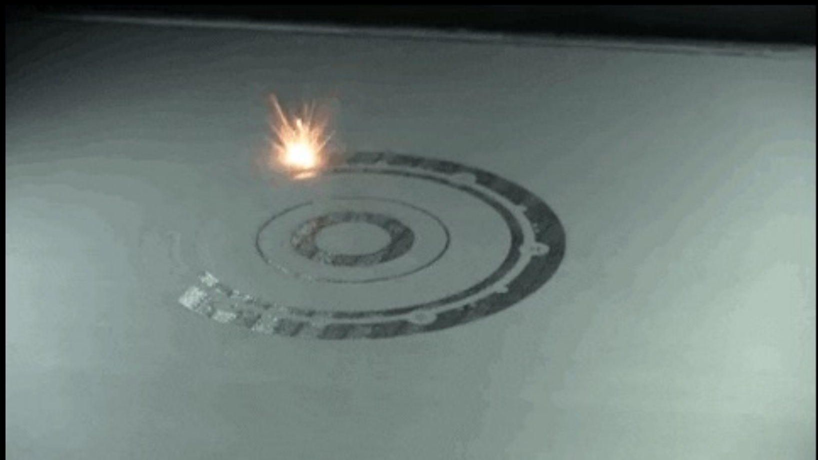


Atoms

Digital Manufacturing

- CAD ▶ CAM ▶ Code ▶ Robot ▶ Part
- Most of the time CNC is best
  - Generative Design creates parts that are fundamentally stiff and machinable
  - Commercial CNC capabilities far exceed most engineer's expectations
  - Material properties superior to AM
    - More ductile, more predictable
  - Vendor suggestions: [CNC 5-axis Machine Shop Master List.xls]
- AM (3D Printing) advantages and costs
  - More design freedom ▶ greater performance (~10%-20%)
  - Fabrication cost lower for expensive-to-machine materials
    - Titanium, Inconel, etc
  - Material properties are process dependent
  - But: Additional verification and documentation required
    - NASA-STD-6030 – depends on mission class





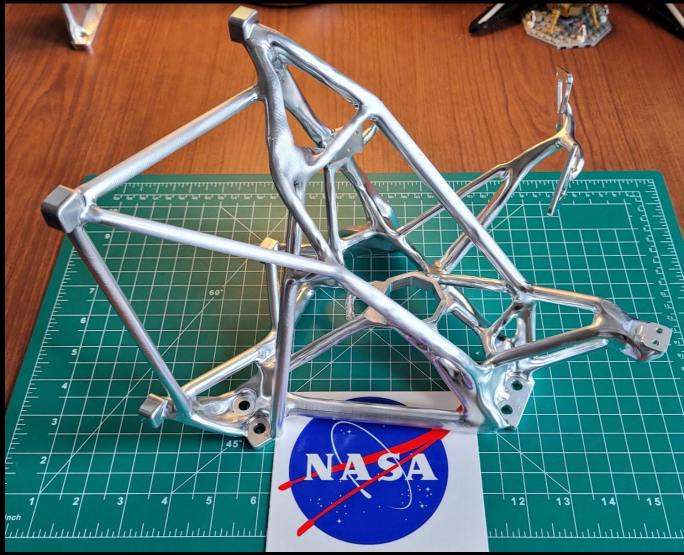
Summary and Future Work

- Evolved Structures process:
  - Design requirements are digitally encoded
  - Generative Design AI evolves optimal structures
  - 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
  - Integrate LLMs to create inputs
- Connect with me via LinkenIn

Backup

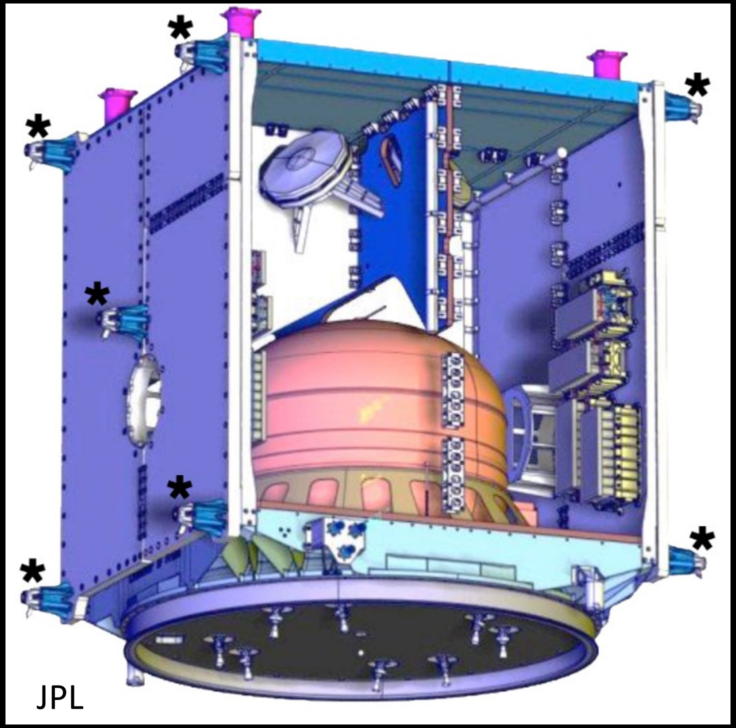
CNC vs. AM for Evolved Structures (Today)

- 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
- Need a compelling reason to use AM
  - Unmachinable features like internal voids and channels



AM for Evolved Structures (Future)

- Cost and schedule will improve due to mature technologies, marketplace, and standards
- Generative Design and AM will enable large monolithic structures
  - Vastly improved performance
  - Vast reduction in part count



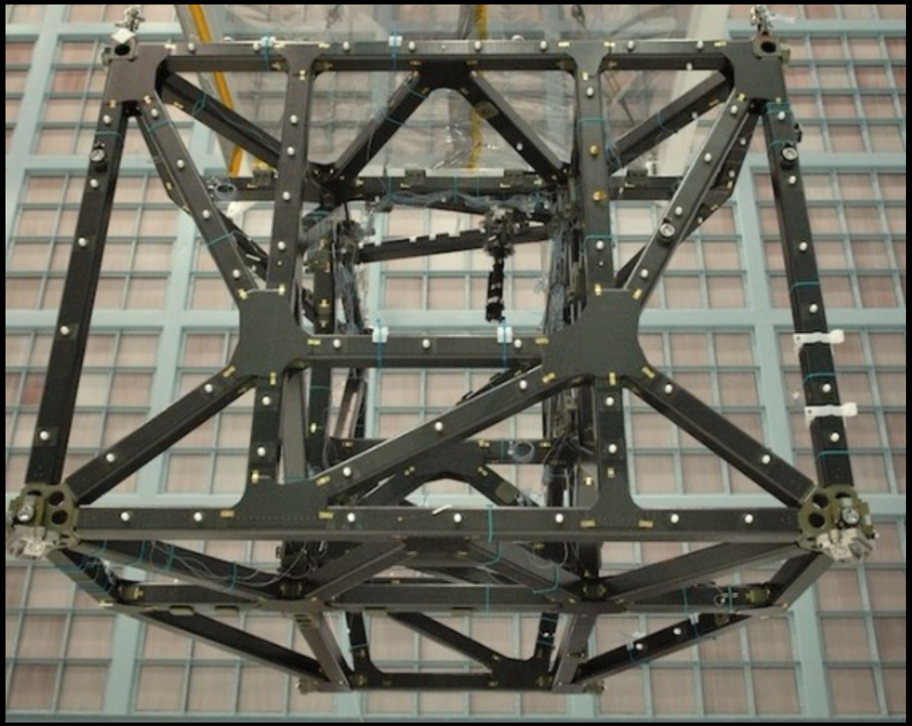
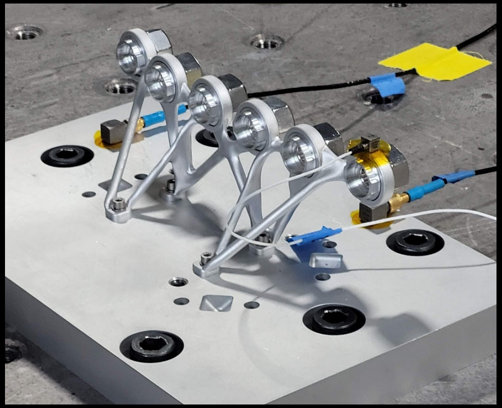
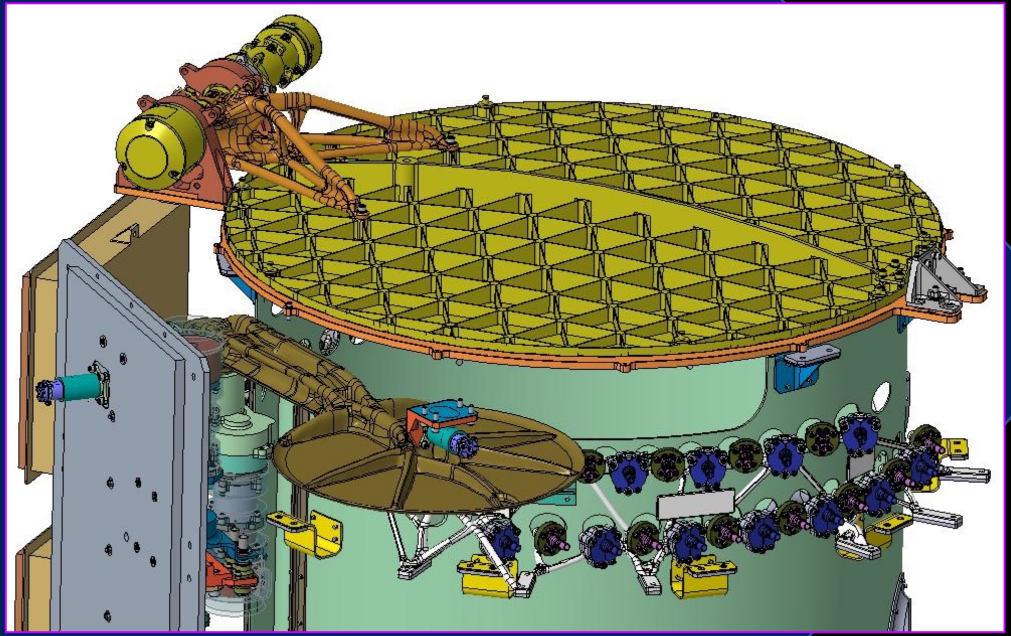
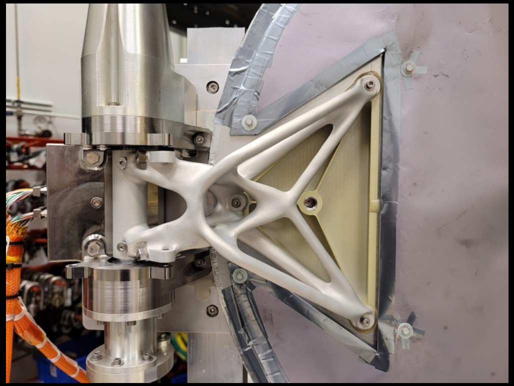


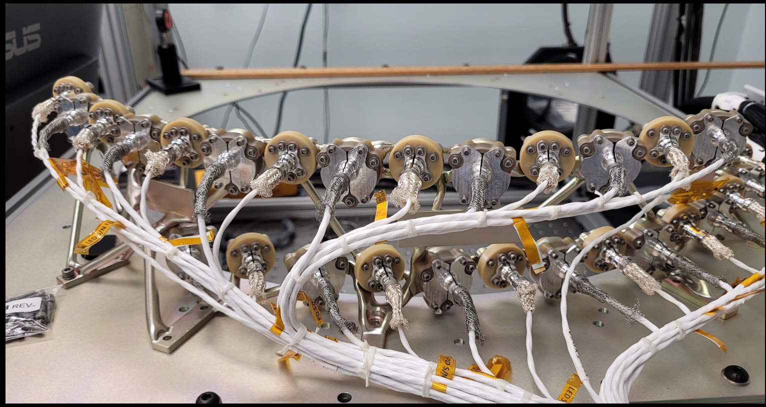
Image source: https://www.wired.com/story/massive-ai-powered-robots-are-3d-printing-entire-rockets/

Project Infusion: Prototype to Baseline



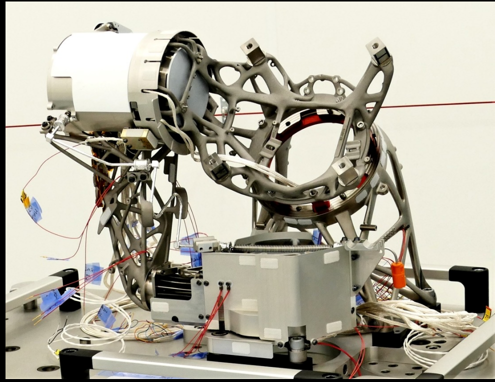


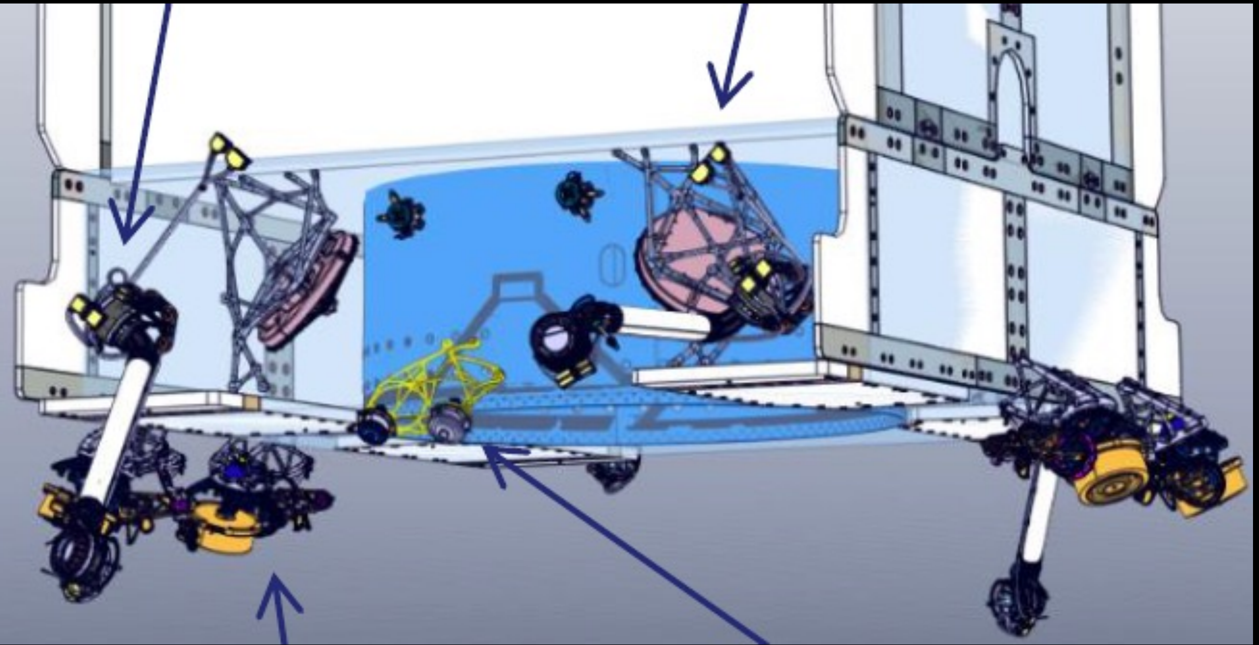


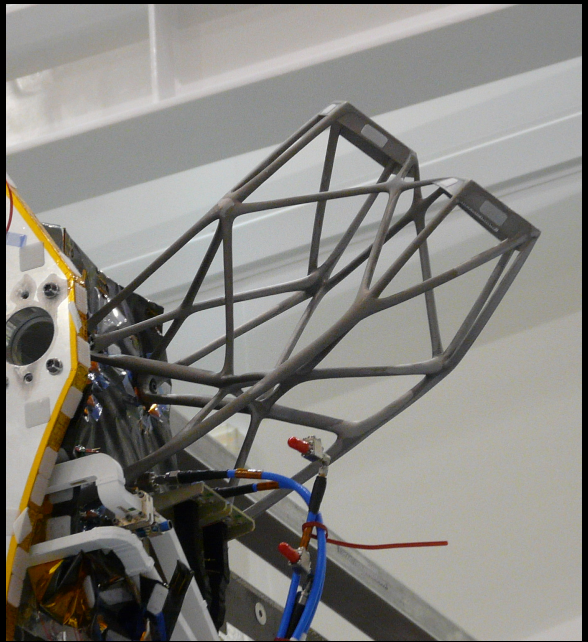


Heritage

- Topology Optimization techniques developed in the 80s with commercial software integration in the 90s
  - Altair OpiStruct
- Thales has flown many Generatively Designed parts
  - Hundreds flown on commercial missions
  - Large antenna brackets flown on NASA SWOT
- JPL cable bracket for Europa Clipper
  - Qualified for flight (2024 launch)
- SpaceX uses Generative Design commonly







Software Packages

- All major CAD/CAE packages are developing Generative
  - Altair, Ansys, Autodesk, Dassault, PTC, MSC, Solidworks, nTopology, ParaMatters, NX
- Performed market research and benchmark testing on available software
- Primarily using Autodesk Fusion 360 (assessed and cleared for NASA use)
  - ✓Allows the use of gravity loaded remote masses (e.g., CONM2+RBE3)
    - Conservative representation of mounted components
  - ✓Directly creates manufacturable/editable CAD geometry (e.g., not tessellated)
  - ✓Allows direct editing of organic shapes generated
    - Critical for tuning the geometry, e.g., to optimize for 3D printing
  - ✓Manufacturing constraints for CNC machining
    - Enables designs that can be made with GSFC's traditional materials and processes (e.g. milling from Aluminum, Titanium, Stainless Steel, and Invar)
  - ✓Easy to use for the non-Finite Element Analysis (FEA) specialist
    - Penn State students reduced mass of an expert design by 3x
  - ✓Rapid improvement – updates every ~6 weeks (scrum schedule)

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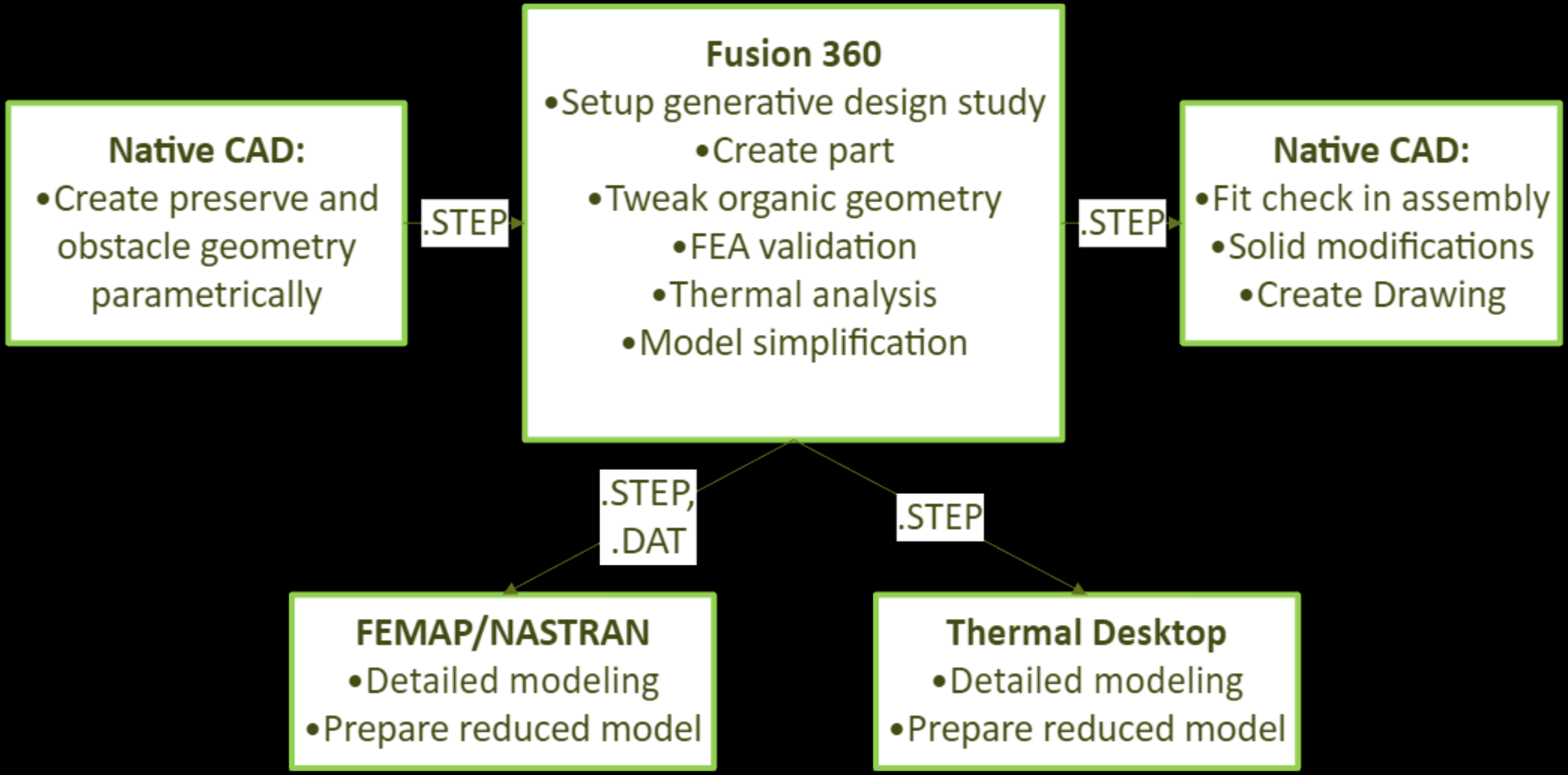
Generative Design in the Engineering Toolbox



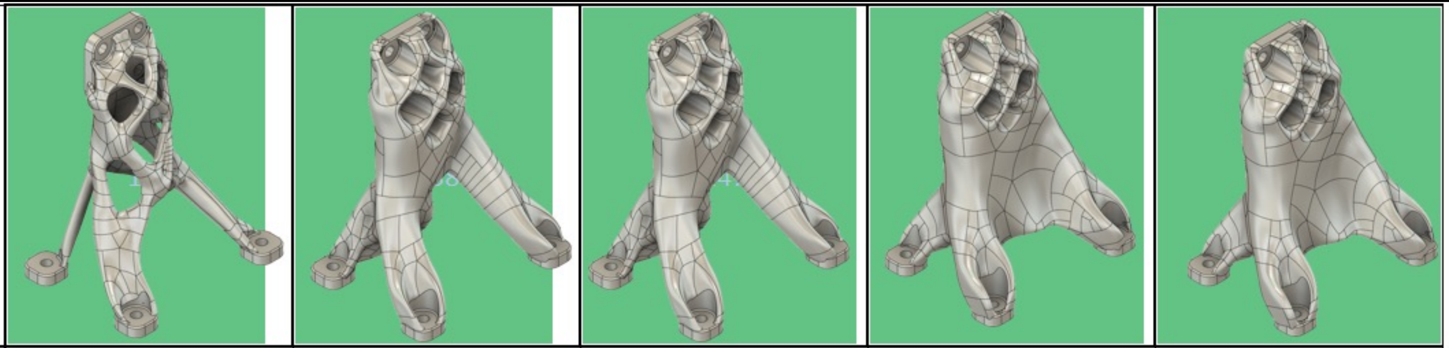
TRL and Risk

- There is less risk in Generative Design compared to human designs
  - Generative Designs have higher stength due to better stress distribution
  - Generative Design uses known and predictable algorithms
  - Humans use unknown and unpredictable algorithms
    - Give 10 different designers the same requirements, get 10 different designs
  - Current design validation techniques can be used: e.g., NASTRAN/FEMAP
  - Fewer mistakes from stove-piping of design, analysis, and manufacturing
    - Common failure mode – game of telephone
  - NASA requirements and standards can be encoded into Generative Design
    - E.g. bolt edge distance, tool clearance, factor of safety, loads and modes
- There is no additional risk in Digital Manufacturing compared to traditional techniques
  - Current verification techniques can be applied: e.g., inspection and test
  - NASA-STD-6030 defines requirements for flying AM parts
    - 11 AM parts on Perseverance Rover (JPL)
  - Early optimized design encourages early prototypes to reduce risk: hardware rich

Lattice for Optimized Structures

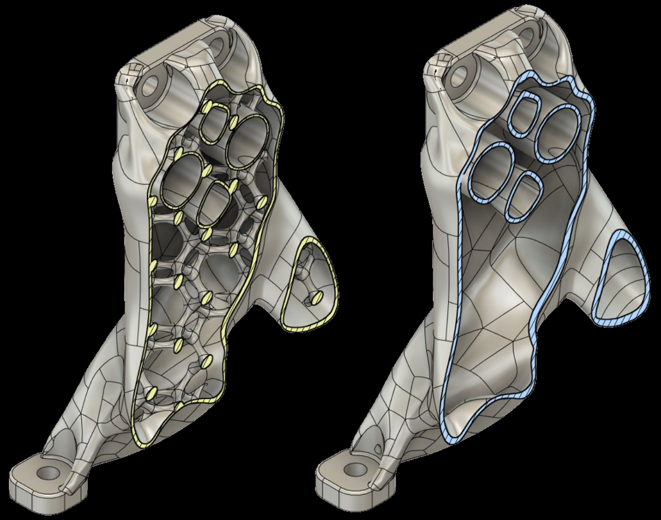
Image source: https://www.ntop.com/resources/blog/optimizing-the-mass-and-natural-frequency-of-the-nasa-excite-bracket-with-field-optimization-or-ntop/

- For pure structural performance (mass/stiffness/strength) minimal benefit of Lattice vs. solid Generative Designed parts
  - ~10% stiffness improvement in tested applications
  - Currently researching potential benefits on vibration damping
  - May see benefits of Lattice in impact absorption, heat transfer, and bio-compatibility
- Currently no automated workflow for optimization, design, analysis, powder removal, and inspection of Latticed parts
  - About 10x longer to develop compared to solid Generatively Design parts



Design	Solid	Lattice 1	Hollow 1	Lattice 2	Hollow 2
Mass (gm)	139	141	139	141	139
1st Mode (hz)	138	138	147	147	152

Data source: Design for Internal Lattice Structures with Application in Additive Manufacturing Donald Palomino CSUN Thesis 5/2023

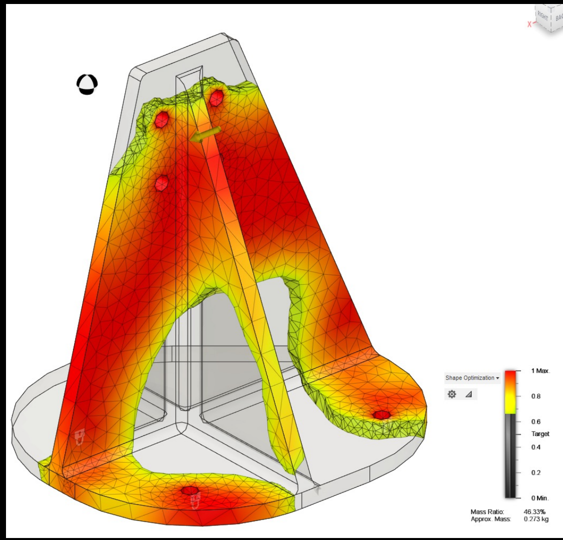


Cross sections of EXCITE bracket Latticed (left) and Hollow (right)

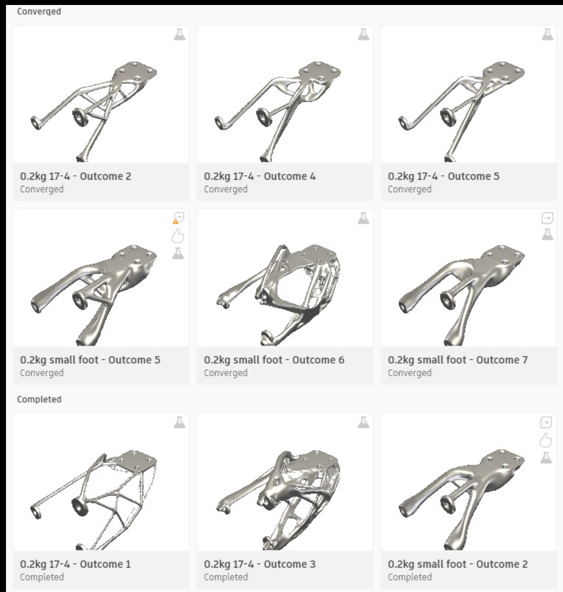
Generative Design: Supercharging Topology Optimization

- Traditional Topology Optimization (Top Op) generally refers to the NASTRAN-SIMP (solid isotropic microstructure with penalization) density-based method of optimization
  - Start with a human design and find areas to lightweight
  - Low stress elements are “removed” by lowering their density
  - Penalty function pushes elements toward density of 0 or 1
  - Result is relative density of finite elements
- Generative Design: Industry term used to signal advanced capabilities build on top of Topology Optimization
  - Creation of real CAD models (not tessellated) from Top Op results
  - Including of DfM ➡️ ensure results can be fabricated
  - Simultaneous exploration of multiple materials and fabrication processes
  - Better algorithms e.g. Level Set compliance minimization
- See Tony Abbey’s excellent Top Op primers:
  - Part 1: https://www.digitalengineering247.com/article/topology-optimization
  - Part 2: https://www.digitalengineering247.com/article/topology-optimization-methods/
  - Part 3: https://www.digitalengineering247.com/article/topology-optimization-2

Top Op



Generative Design



“Perfection is achieved, not when there is nothing more to add, but when there is nothing left to take away.” - Antoine de Saint-Exupery

Tom McCarthy
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Motiv Space Systems

Robotics and Motion Control

Integrated multidisciplinary team

- Electrical Engineering
- Mechanical Engineering
- Software Engineering
- Systems Engineering
- Robotics Engineering
- Hardware development and delivery

Qualifications

- Space flight hardware developed for a range of environments
  - Destinations include LEO, GEO, Deep Space, Lunar and planetary surface investigations

Motiv Space Systems

- **Formed in 2014**
- **Located in Pasadena, CA**
- **Qualifies as a Small Business**
  - Class 10,000 Clean Room (ISO 7)
  - Environmental test facilities
  - Robotic integration lab
  - CMM inspection facility
  - Avionics test and assembly facility
  - Machine shop for assembly and finish machining

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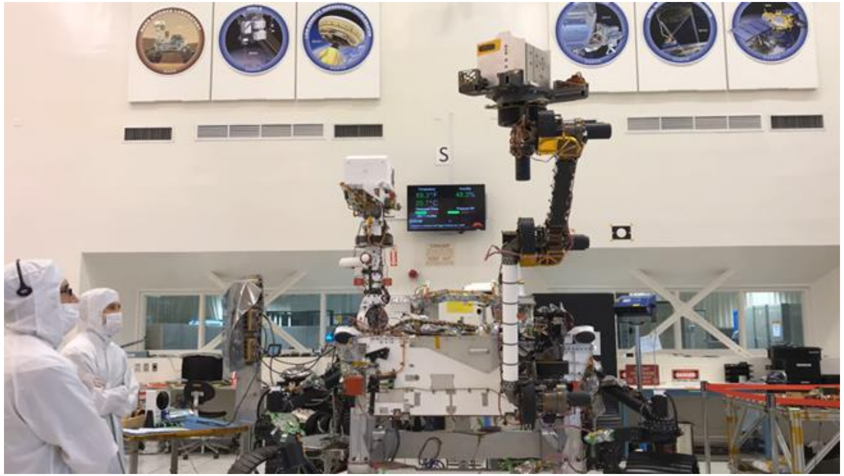
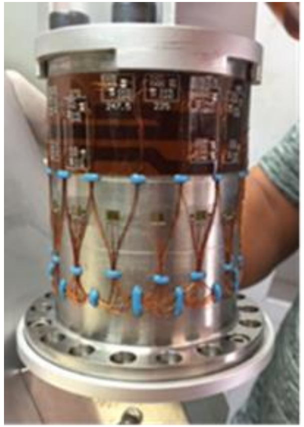
Robotics for Lunar Sustainability

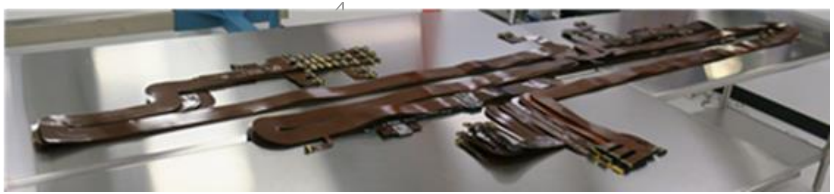
LSIC Excavation and Construction – March 2024

Mars 2020 Robotic Arm - Heritage

- Most capable robotic arm ever for Mars!
- 5-DOF arm, 45kg payload
- Custom 6-DOF force-torque sensor







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Extreme Environment Technologies
Survive and Operate Through the Lunar Night

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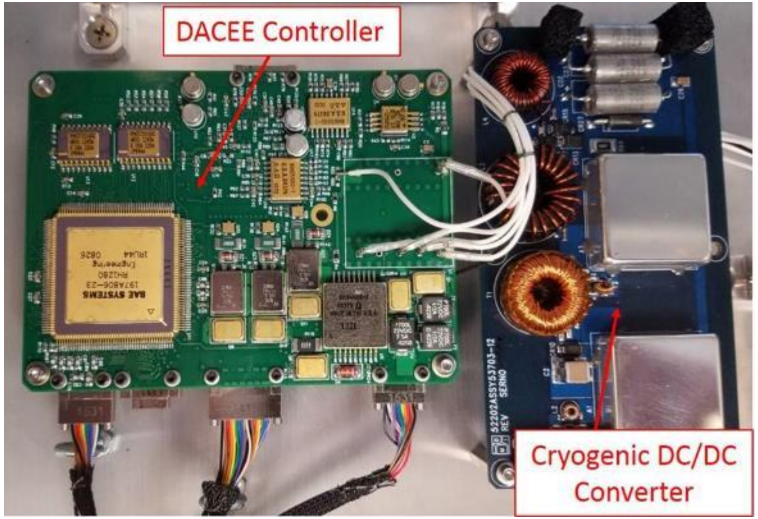
Technology to Survive & Operate Through the Night

- Motiv 2015 SBIR Phase I/II – Dual Axis Controller for Extreme Environments (DACEE)
    - Demonstrate -180°C operations without survival heaters
- Partnered with JPL to demonstrate applications of cryogenic technology developments
- JPL Bulk Metallic Glass Gear Technology – GCD Program
    - Evaluate BMG solution for extreme environments without lubricants



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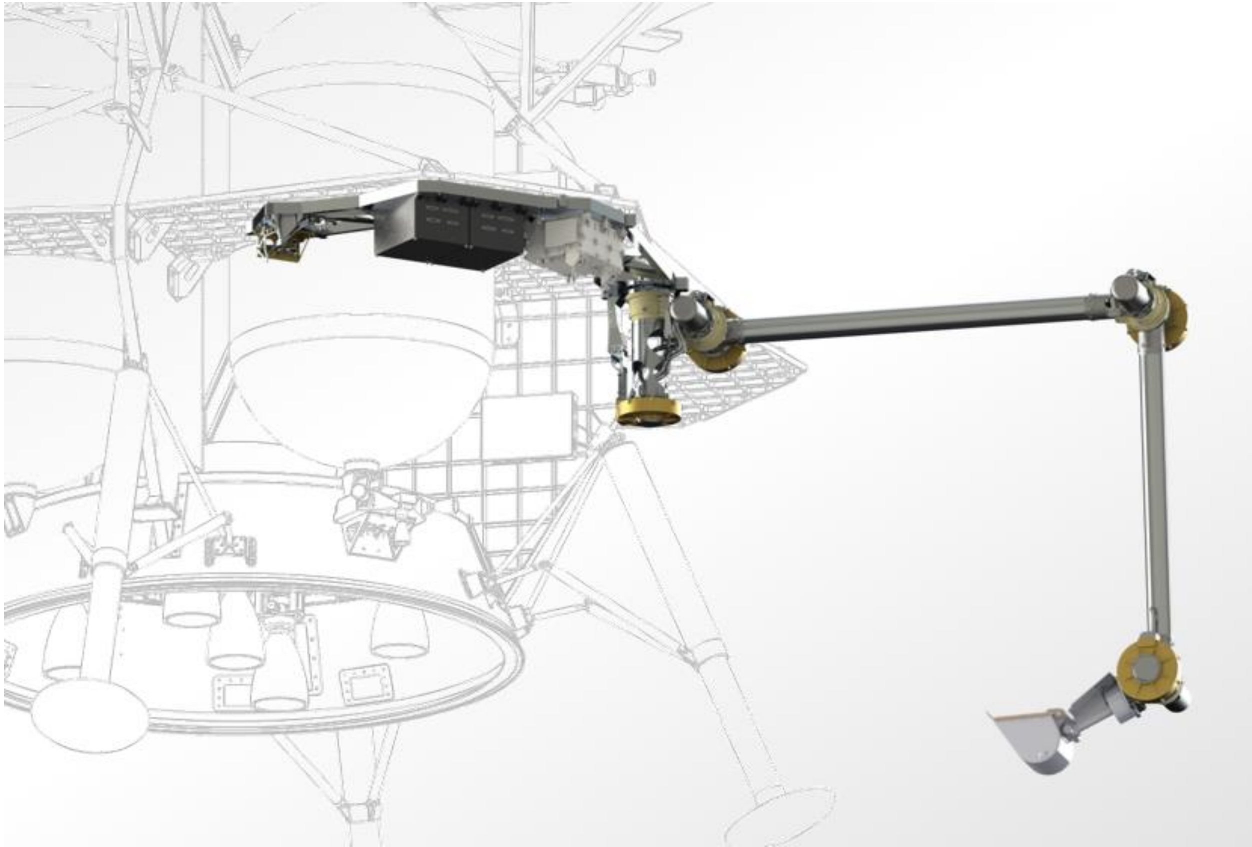

Cold Operable Lunar Deployable Arm (COLDArm) System

Shown integrated on notional CLPS lander

Manipulator designed to be scalable and modular to easily integrate with most CLPS providers.

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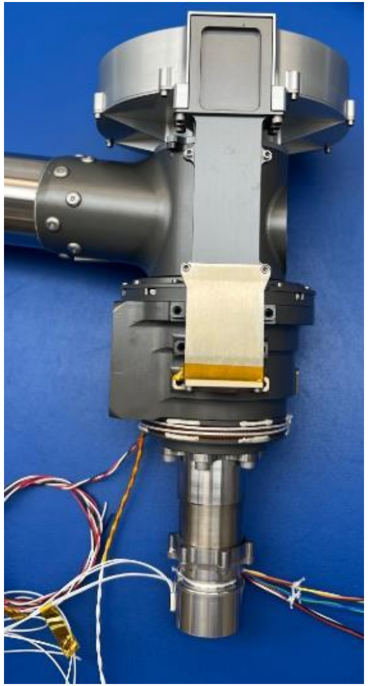
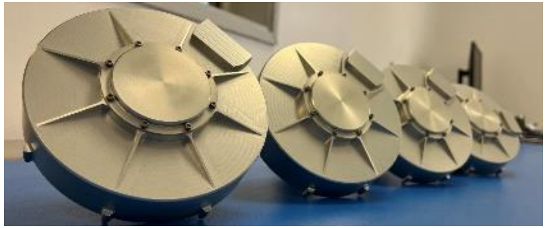
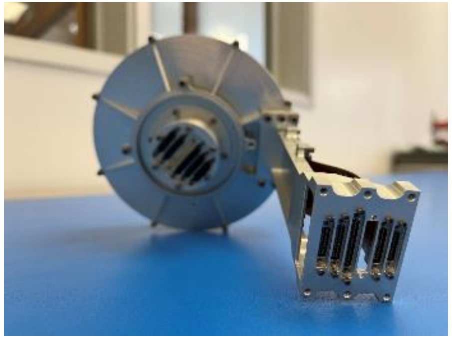
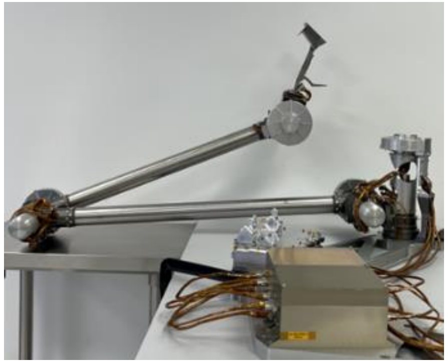






- 4-DOF, 1.7m Robotic Arm – TRL 6!
- Operates at -180°C – *No Heaters!*
- Qualified via TVAC and Vibe
- Dust tolerant to lunar environment
- Modular Construction
    - Adjustable for a variety of future CLPS or small landers



COLDArm

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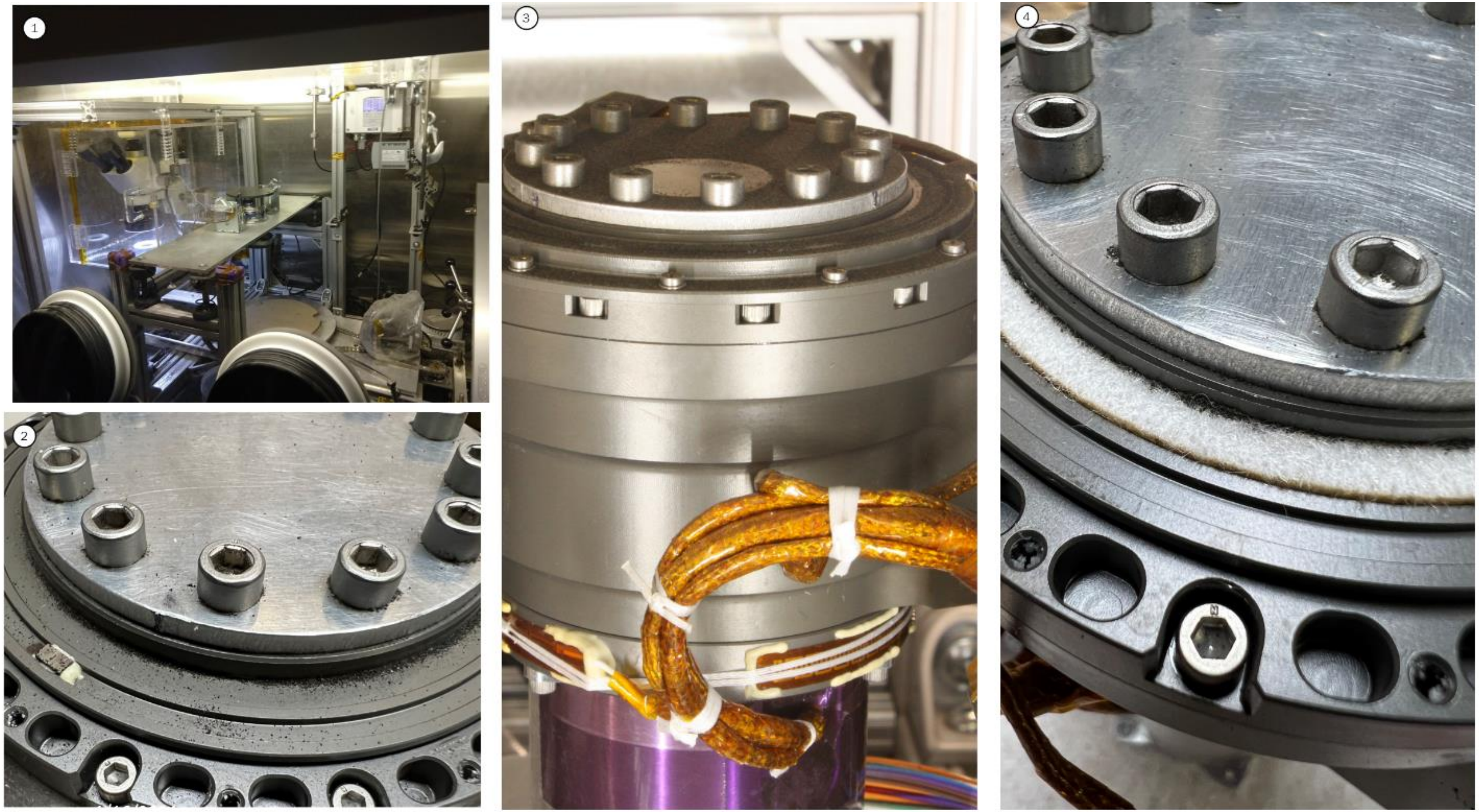

COLDArm Regolith Testing. (1) Test Venue (2) Actuator Output (3) Deposited Dust (4) Felt Seal

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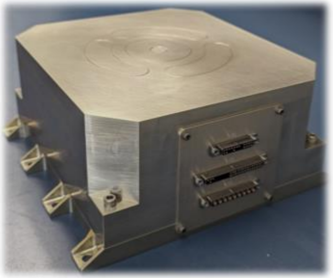
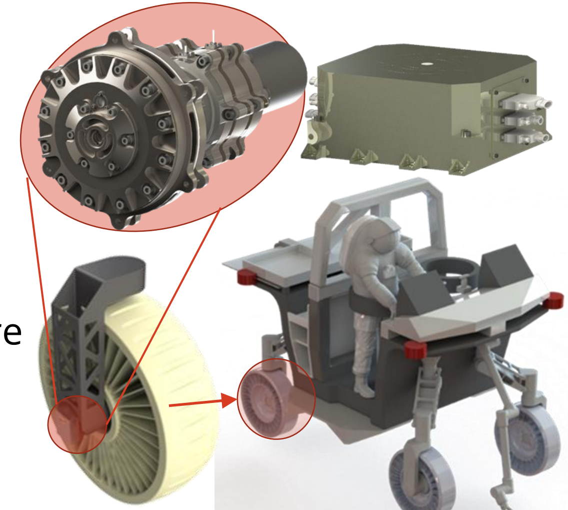
High Power and Torque Systems

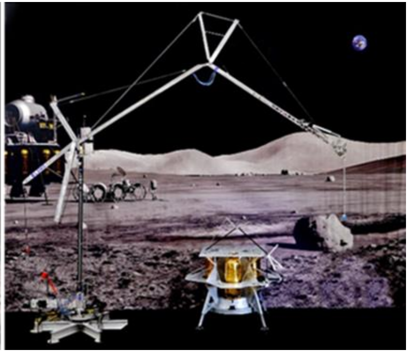
Extreme Environments

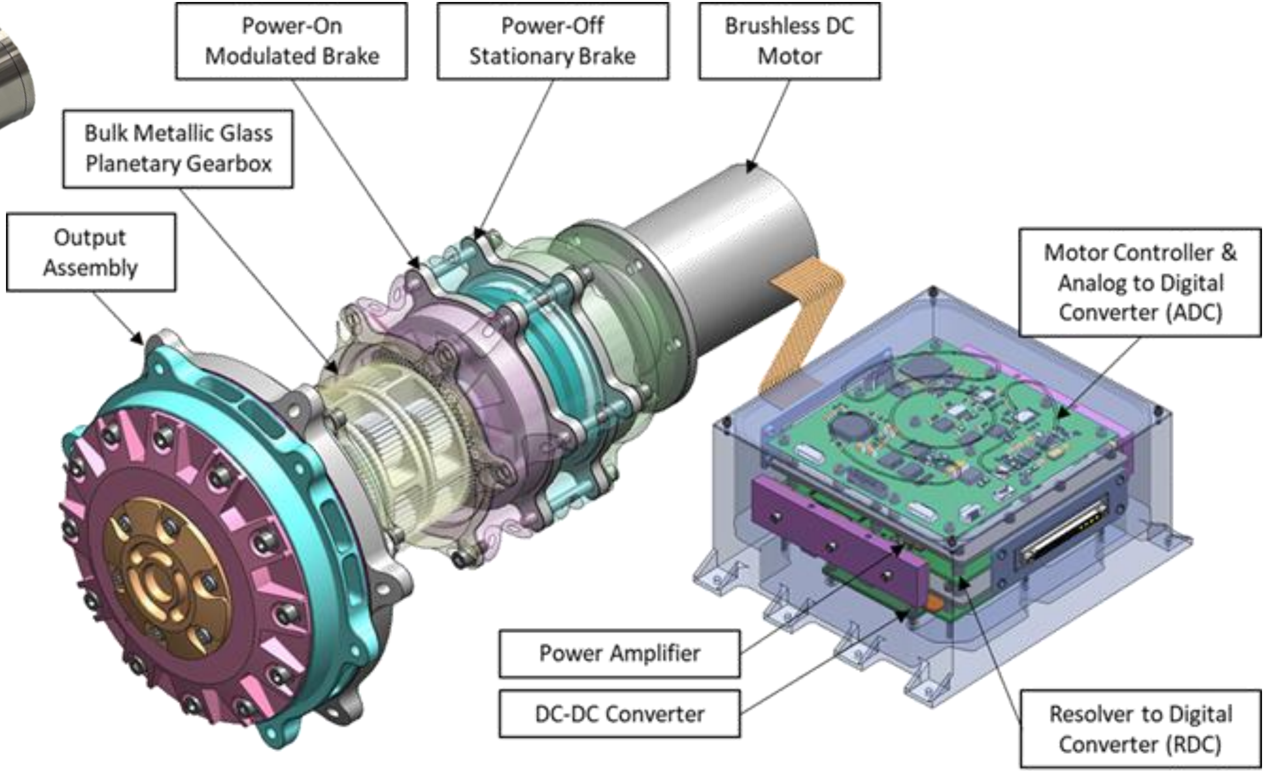
- Survive & Operate through the Night
- Cryo Operations
- Distributed Actuation for Logistics and Infrastructure





LTV Mobility & Suspension





Unit will be on display during LSIC Spring Meeting

Distributed Extreme Environments Drive System - DEEDS

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Regolith Life Testing on Motiv's LTV Actuator

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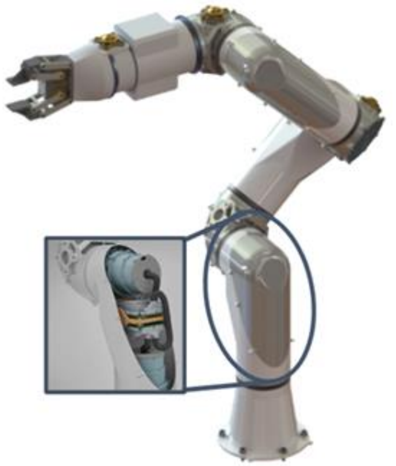
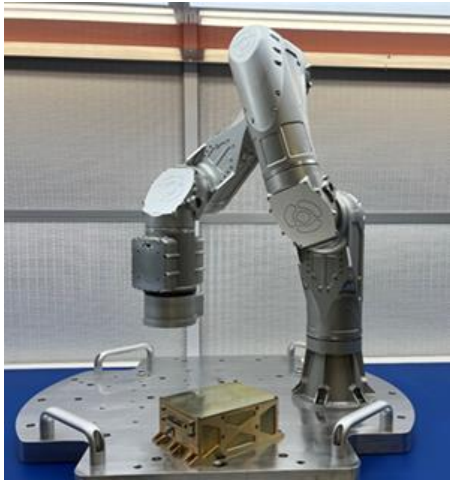
Dexterous Manipulation for Construction / Outfitting

xLink Robot Tech for Lunar Applications



xLink Robotic Arm

- Modular Manipulator Architecture
- Distributed Control Solution
- Integrated Force-Torque Sensor



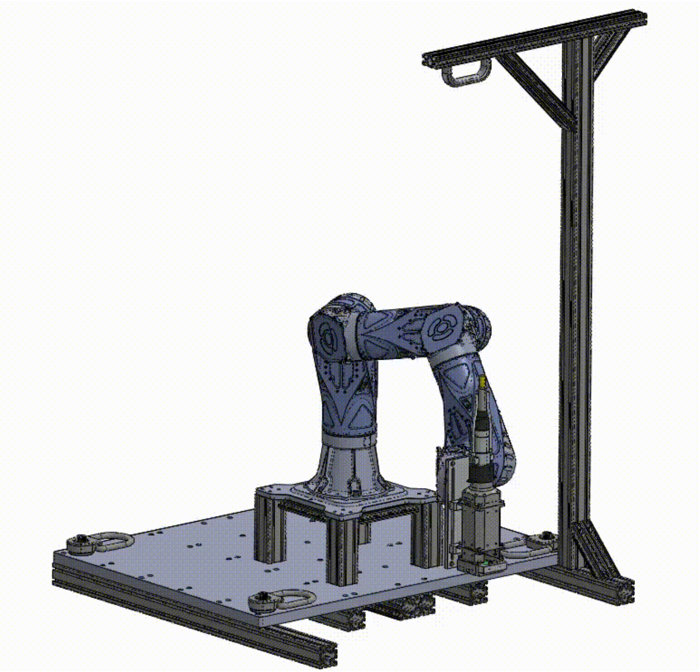
Qualified - xLink Robotic Arm

- Developed for OSAM-2 Flight demonstration Mission
- 1.3M in Length / 7-DOF

xLink Robotic Arm

- Lab grade system developed for satellite servicing activities
- Architecture scale appropriate for LTV requirements
- 2.3M in Length / 7-DOF

Tools for Lunar Additive Manufacturing / Outfitting



New Robotic Platforms to Deliver Laser and Welding Tools / EE Tolerant to Lunar Environments

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Creating the Tools to Enable Long Term Lunar Sustainment

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Thank you