OPTICAL INSTRUMENT MOUNTING BRACKET – NASA JPL

RELEVANT BACKGROUND

Design challenge posted by NASA JPL in Aug 2020

Optical instrumentation systems are among the most common NASA and JPL flown instruments in space

To function properly, optical instruments have tight pointing deviation requirements

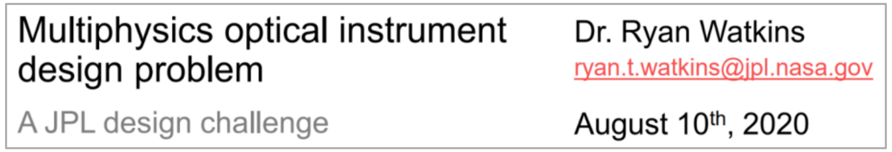
Angular deviation from the central axis of the cone of the optical instrument is highly undesirable

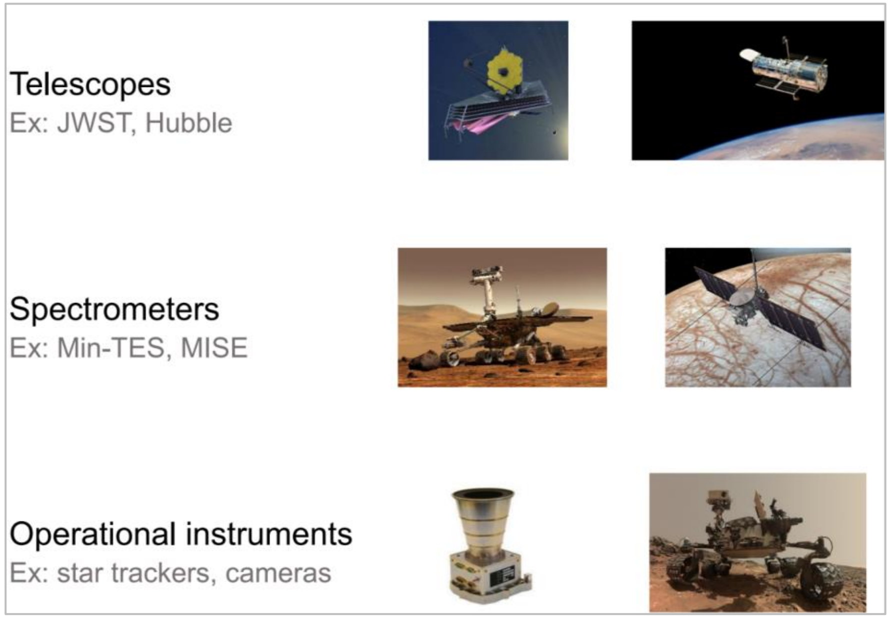
Pointing requirements are difficult to achieve due to extreme temperature conditions in space

Differing CTEs between materials are amplified by extreme thermal gradients from direct sunlight or shade

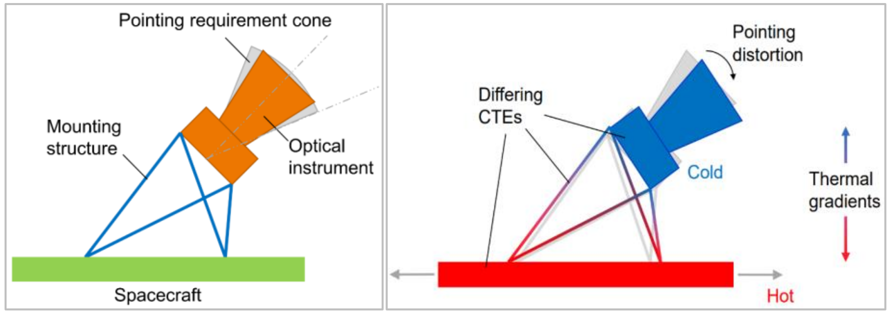
Consortium of universities/research groups/industry partners have attempted to provide a valid design

<u>**No valid design has been attained**</u>





Examples of optical instrumentation systems



Pointing deviation due to thermal gradients

OBJECTIVE

Design the mounting structure for a prototypical star tracker

Develop a simple workflow capable of consistently passing requirements under multiphysics loading

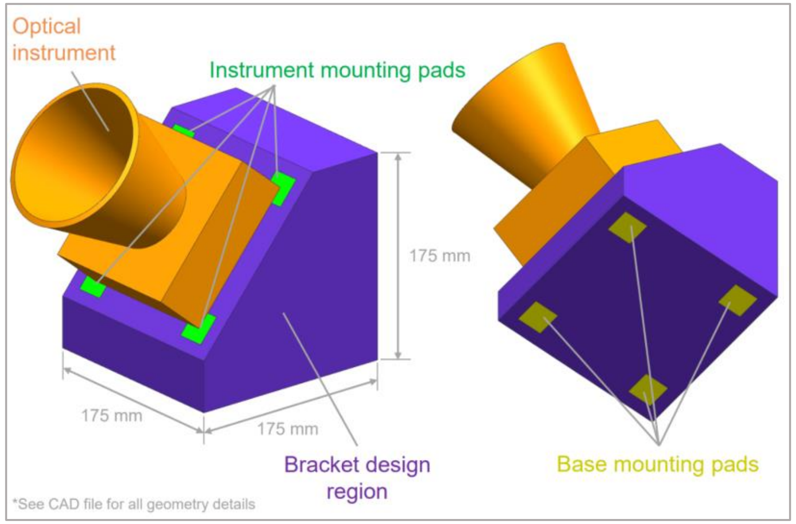
SYSTEMS ENGINEERING APPROACH

Stakeholder Needs

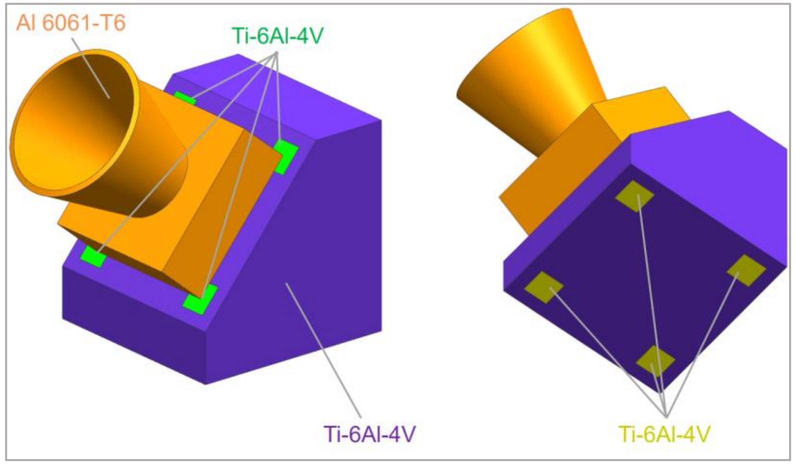
1. Provide a mounting bracket to mount a star tracker to spacecraft
2. Bracket design volume is restricted to fit within the bracket design region
3. Material of the mounting bracket must be Ti6Al4V
4. Material of the star tracker must be Al6061-T6 (modified)
5. Optical assembly (including bracket) must pass requirements

Material Properties

Ti-6Al-4V	**Al6061-T6**
E = 110 GPa (16 Msi)	E = 68 GPa (9.9 Msi)
ν = 0.31	ν = 0.33
ρ = 4430 kg/m^3	ρ = 9555* kg/m^3
α = 8.8 ppm/°C	α = 22.2 ppm/°C
κ = 6.9 W/(m °C)	κ = 152.3 W/(m °C)
σ_y = 827 MPa (120 ksi)	σ_y = 276 Mpa (40 ksi)
σ_u = 896 MPa (130 ksi)	σ_u = 310 MPa (45 ksi)



Geometry definition and relevant components



Material designation

*To achieve the appropriate instrument mass of 3 kg (without including concentrated masses), the material density has been scaled up.

Concept exploration

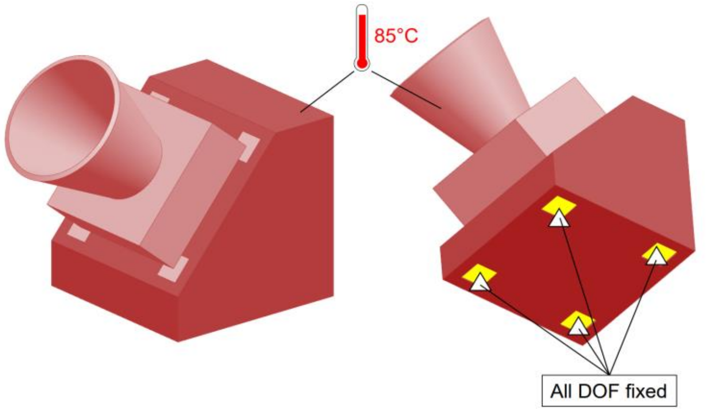
Systems engineering timeline

TECHNICAL REQUIREMENTS DEFINITION

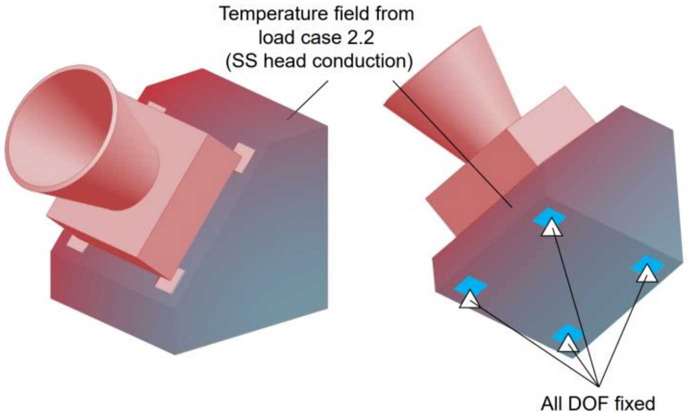
Relevant load cases

1. Launch: 3 sub cases
   - Boundary conditions: fixed base
   1. 2,000 N load in the x direction
   2. 2,000 N load in the y direction
   3. 2,000 N load in the z direction
2. Thermal: 3 sub cases
   - Boundary conditions: fixed base
   - Initial condition: uniform temperature of 20°C
   1. Thermoelastic bulk soak at 85°C
   2. Steady state (SS) heat conduction
   3. Thermoelastic deformation from SS heat conduction temperature field
3. Normal modes
   - Boundary conditions: fixed base

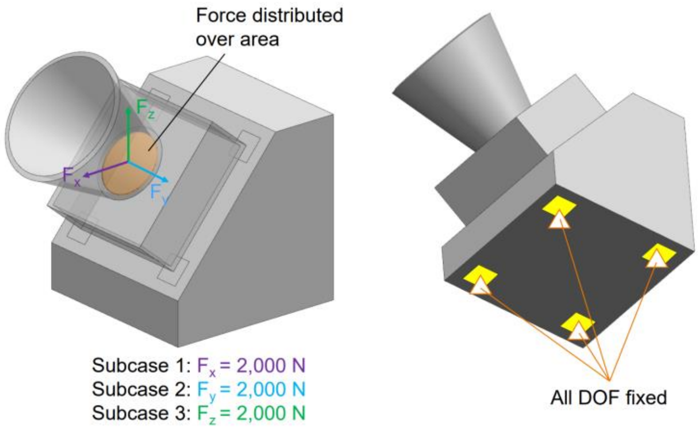
Load case 2.1: bulk temperature soak



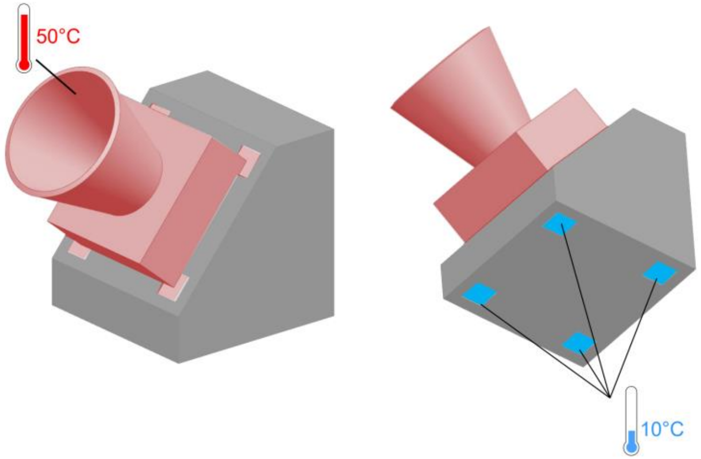
Load case 2.3: thermoelastic deformation from SS heat conduction temperature field



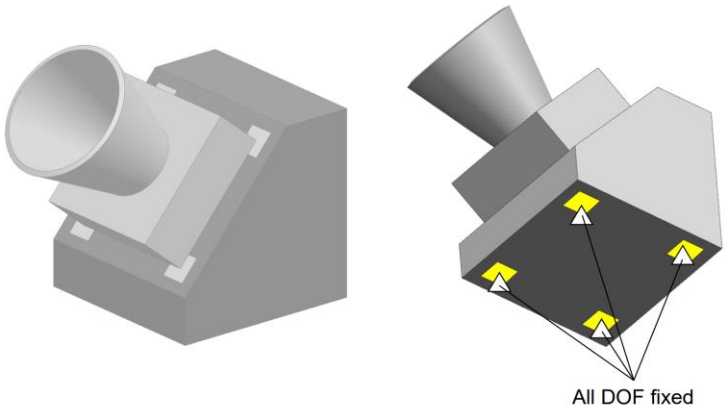
Load case 1.1-1.3: launch



Load case 2.2: steady state heat conduction



Load case 3: normal modes



LOGICAL DECOMPOSITION OF REQ'S

Goal: Minimize mass

Priority
- Must have
- Nice to have
- Extra credit

Requirements

Minimum member size
$t > 1mm$

Base interface shall not slip
$F_{shear} < 1{,}500$ N (each mounting pad)
Load cases: 1.1-1.3, 2.1, 2.3

Fundamental frequency
$\lambda > 200$ Hz
Load case: 3

Instrument interface shall not slip
$F_{shear} < 1000$ N (each mounting pad)
Load cases: 1.1-1.3, 2.1, 2.3

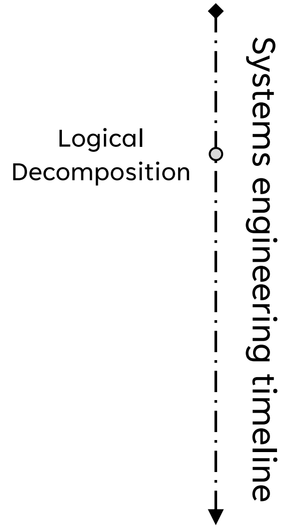
Structure shall not yield
$1.25\ \sigma_{von\ mises} < \sigma_y$
Load cases: 1.1-1.3, 2.1, 2.3

Structure shall not buckle
$2\ p < p_{crit}$
Load cases: 1.1-1.3, 2.1, 2.3

Minimal pointing deviation
$|\theta| < 0.001°$ (cone central axis best fit)
Load case: 2.3

Minimal heat loss through base interface
$\oint\!\!\oint_A q\ dA < 4$ W (over all base mounting pads)
Load case: 2.2

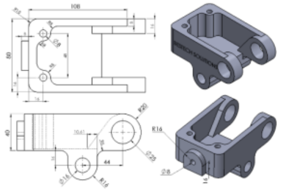
Requirements logical decomposition

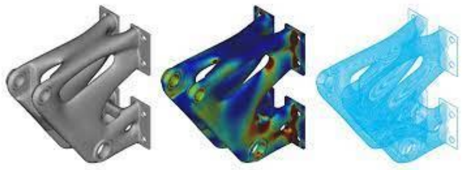


DESIGN SOLUTION DEFINITION

Commercially-available design methodologies:

CAD	GENERATIVE DESIGN (GD)	TOPOLOGY OPTIMIZATION (TO)
Pros: Well-established Highly robust Cons: Low efficiency Manual process Time-consuming	Pros: Improved efficiency and speed Increased design creativity and diversity Cons: Limited physics High manufacturing cost High risk of non-compliance	Pros: Weight reduction Shorter implementation Some flexibility to multiphysics Cons: Limited software High manufacturing cost



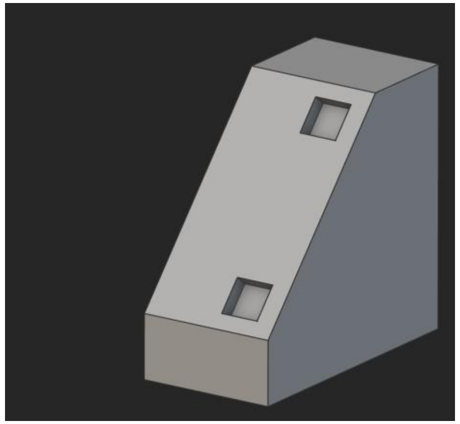


Design Solution Definition

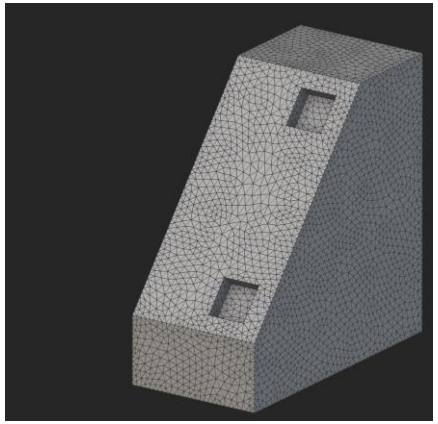
Systems engineering timeline

DESIGN SOLUTION DEFINITION

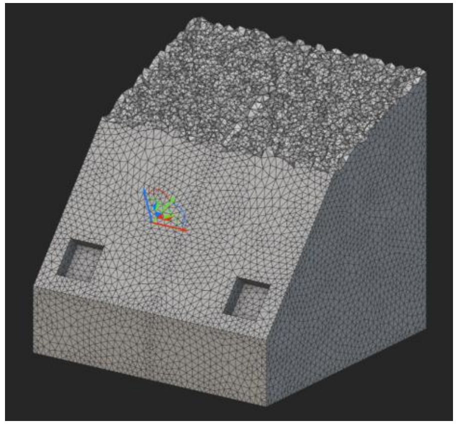
Topology optimization (TO) implementation: nTopology



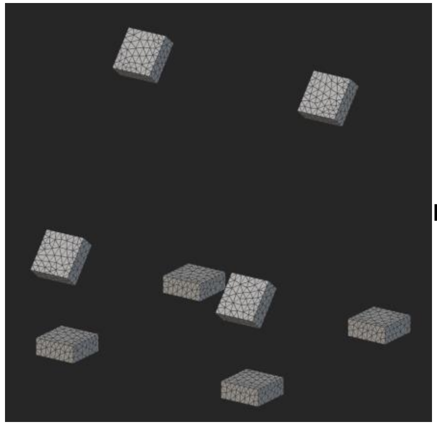
Import Bracket (half)



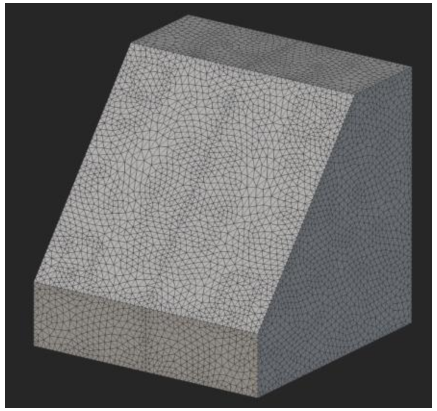
Surface Mesh



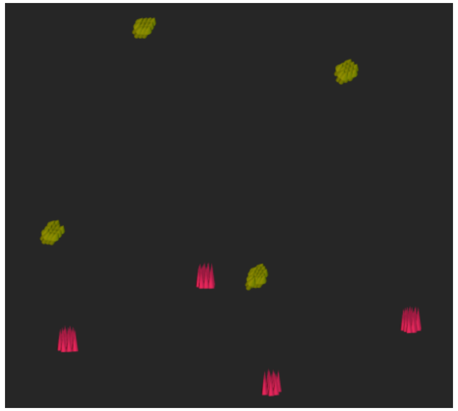
Volume Mesh (mirrored)



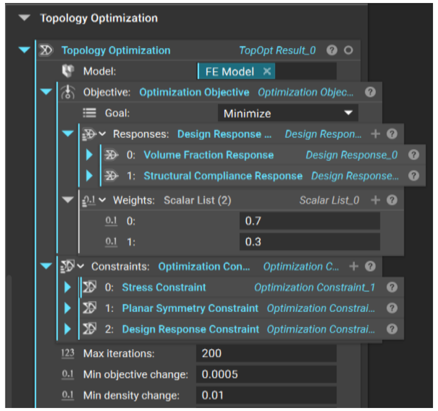
Mesh mount interfaces



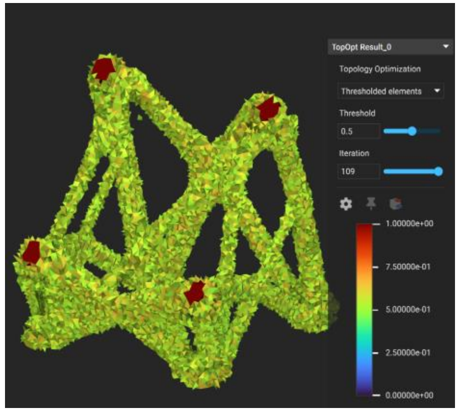
Merge meshes



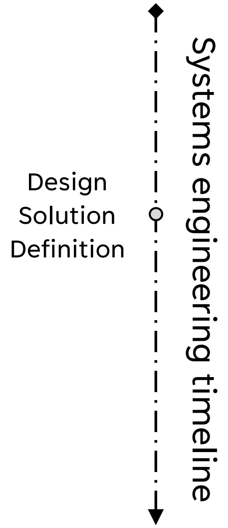
Apply structural loads



Define TO process inputs

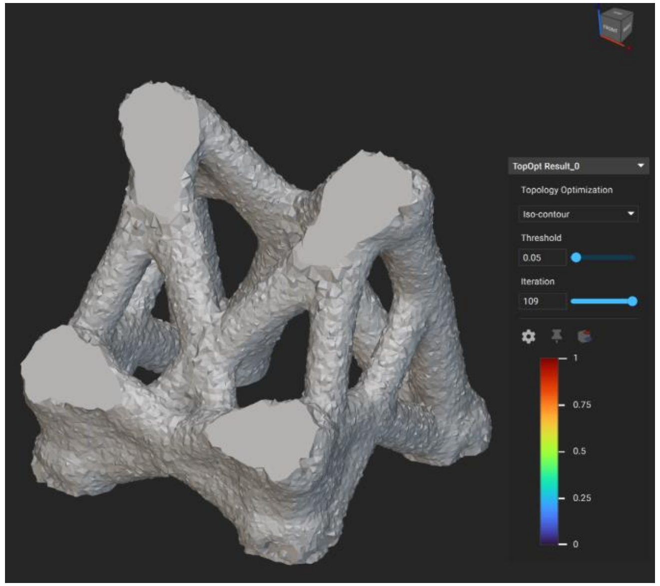


Obtain TO result

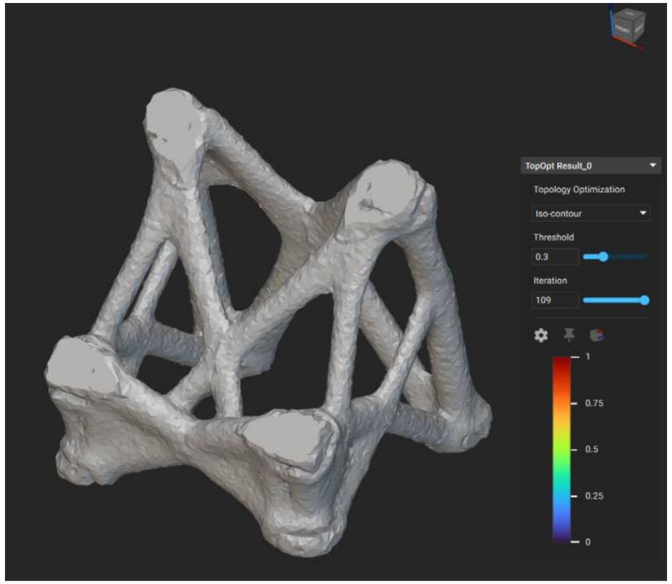


DESIGN SOLUTION DEFINITION

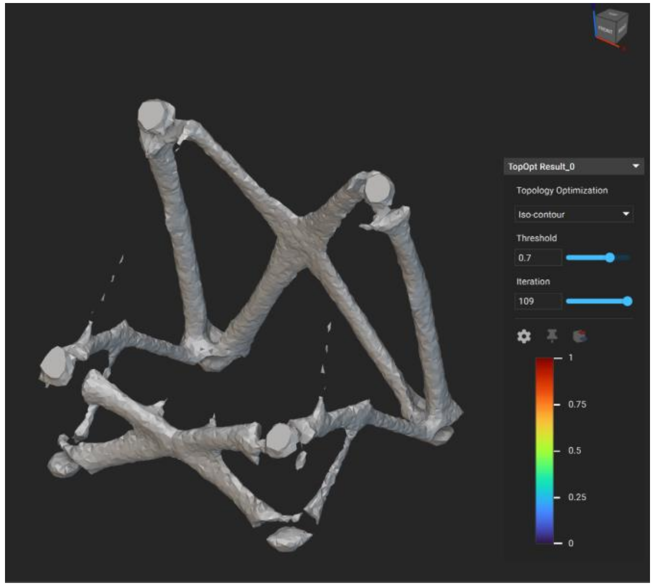
Topology optimization (TO) implementation: nTopology



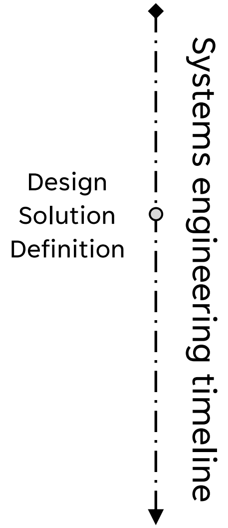
0.05 threshold



0.3 threshold

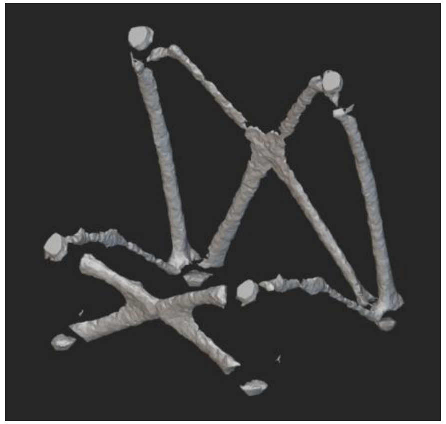


0.7 threshold

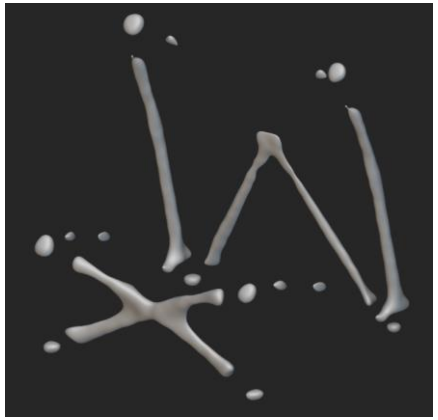


DESIGN SOLUTION DEFINITION

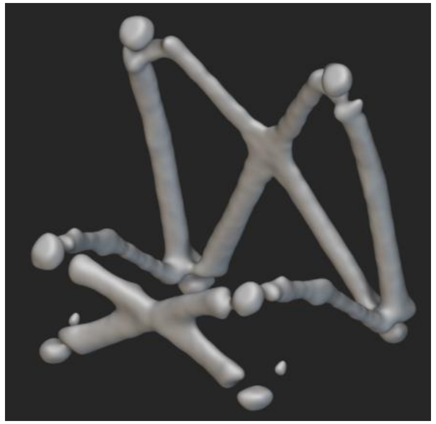
Topology optimization (TO) implementation: nTopology



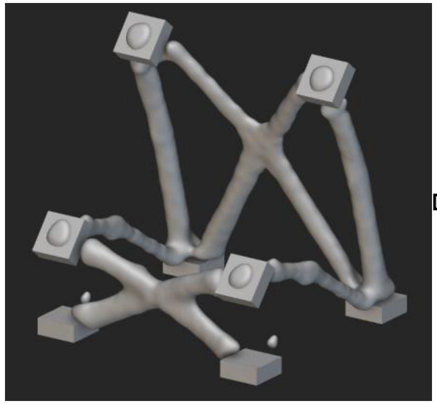
Resulting TO implicit body



Smoothening

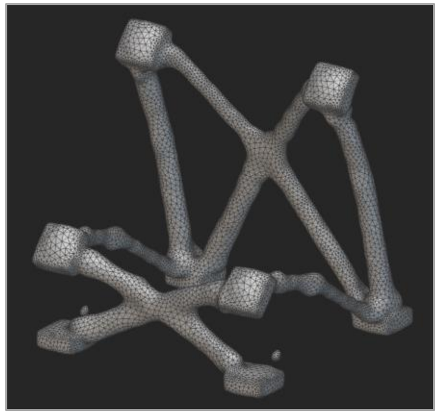


Thickening

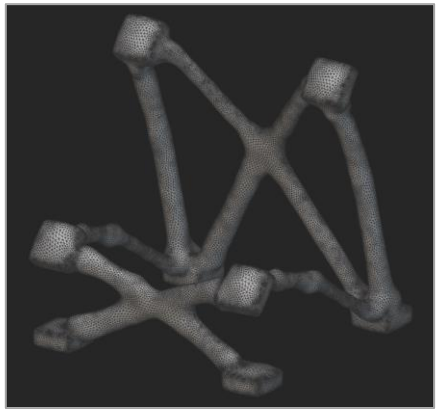


Boolean union

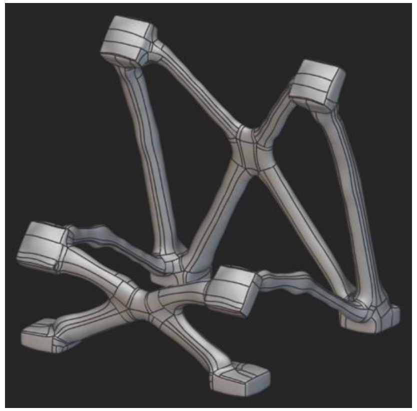
Smoothening and export



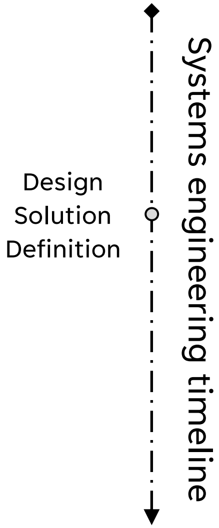
Coarse surface mesh



Fine surface mesh

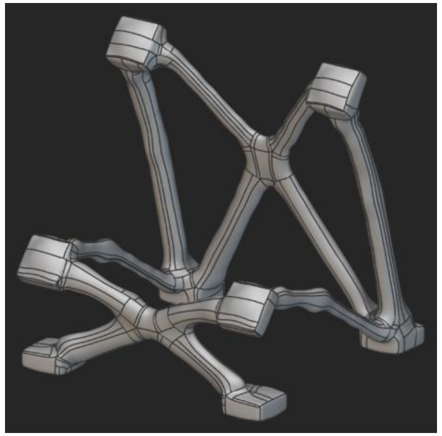


Export as .step file



PRODUCT INTEGRATION

Implementation and integration of TO result: AUTODESK® FUSION 360™

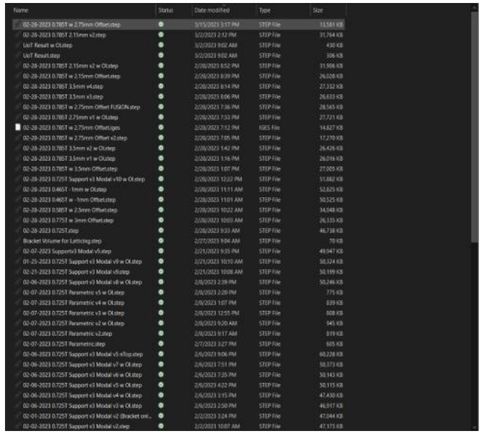


Obtain .step file

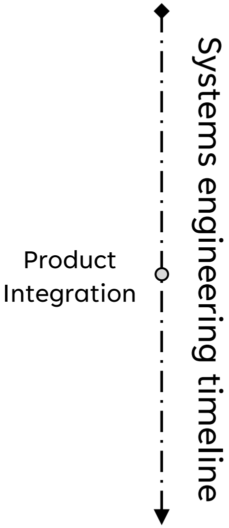
Import to Fusion and clean-up

*

Re-assembly and integration of OI*



Export assembly as .step file

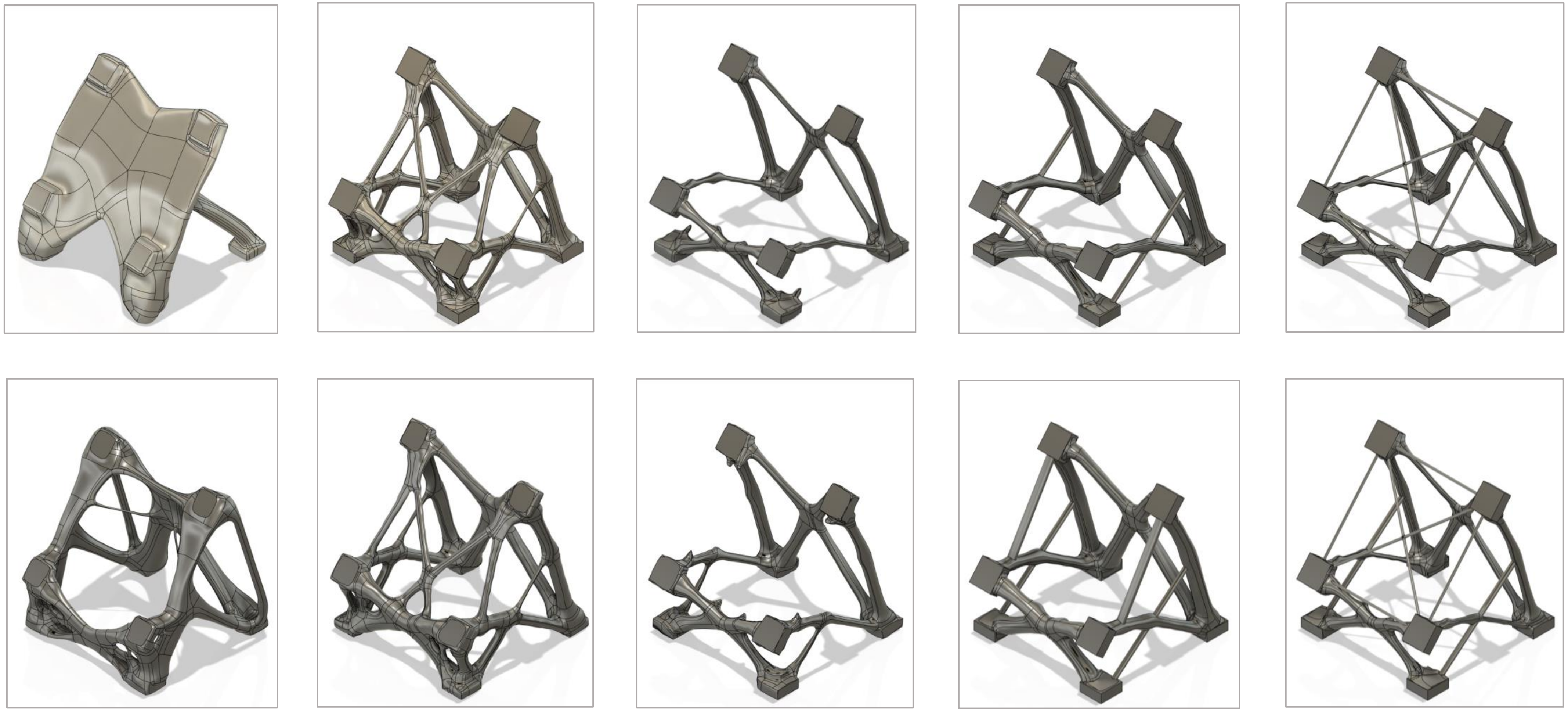


***Note:**

Additional iterations after TO were necessary to get closer to compliance against pointing deviation and natural frequency requirements

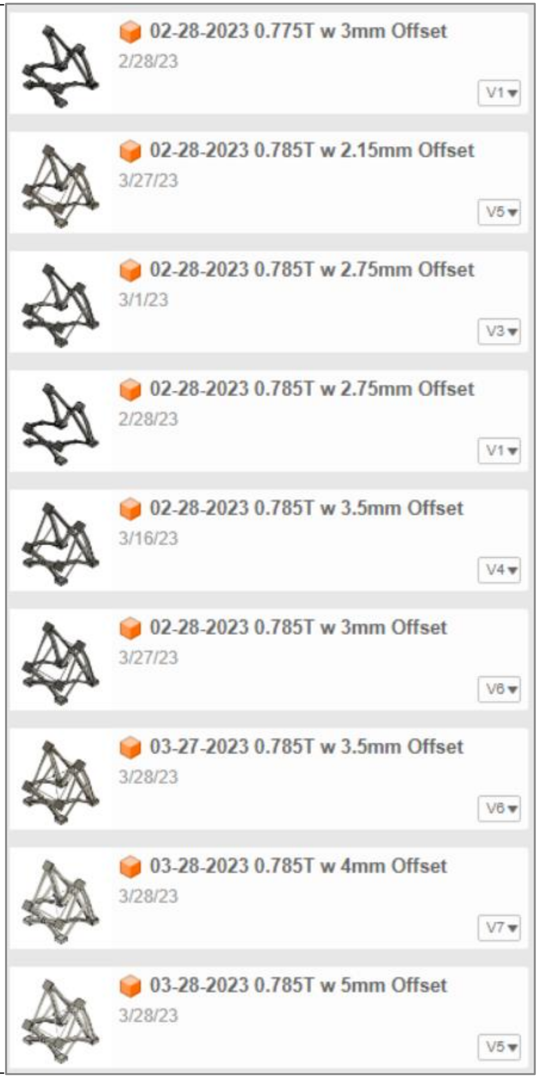
ITERATIONS

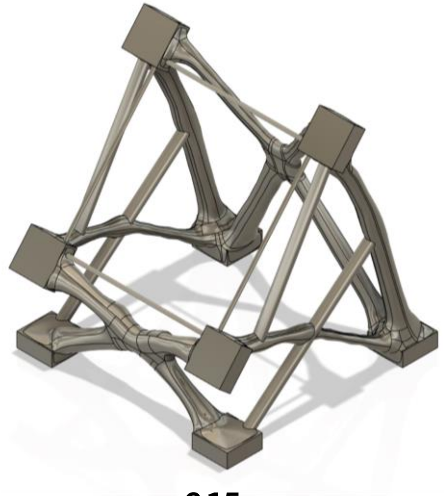
Examples of the many iterations required:



ITERATIONS BY THICKENING

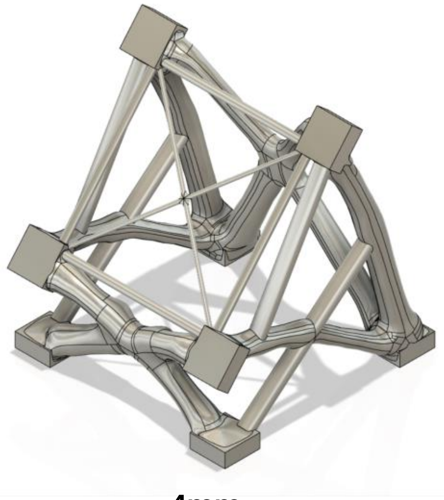
2.15-5mm



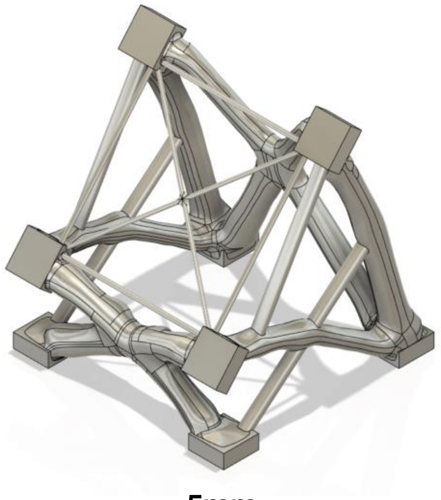


2.15mm

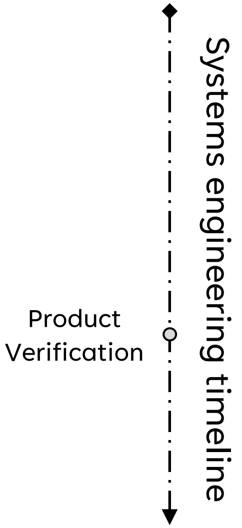
3mm



4mm



5mm

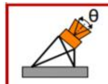


PRODUCT VERIFICATION

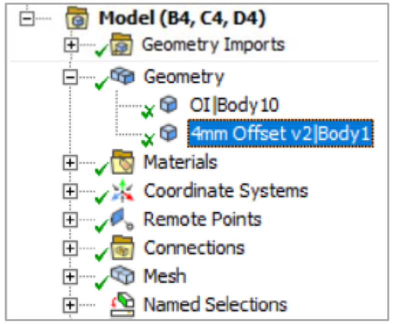
Verification against requirements was performed with FEA: Ansys

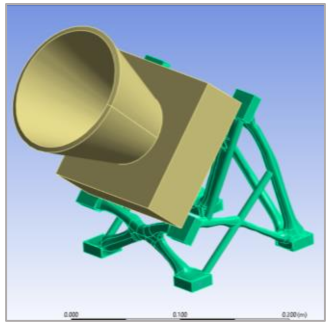
Preliminary verification is with load case 2.3 (thermal gradient with fixed base)

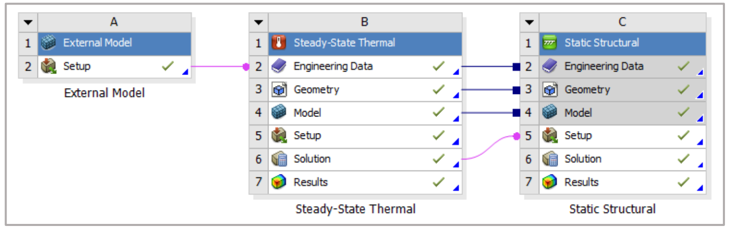
P.D. is the most difficult requirement to meet:



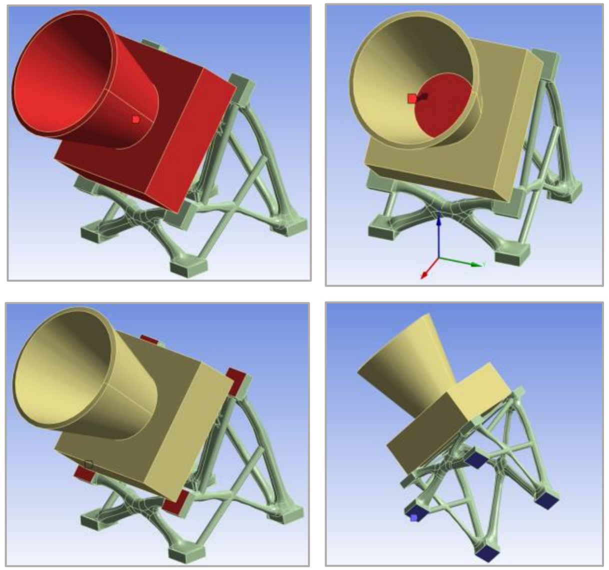
Minimal pointing deviation
|θ| < 0.001° (cone central axis best fit)
Load case: 2.3



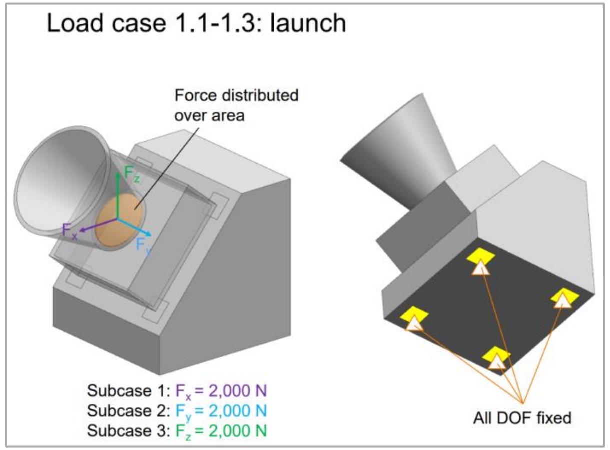




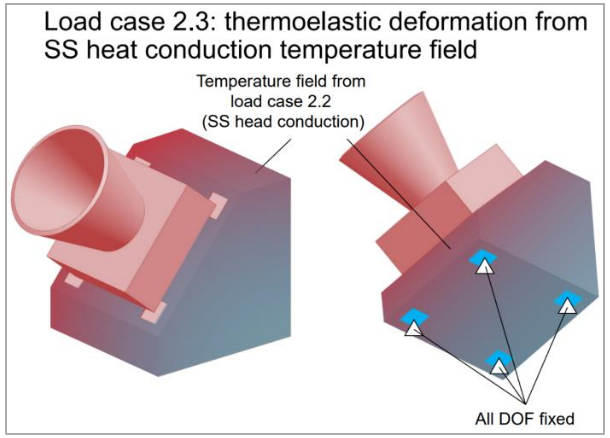
Import External Model (geometry, materials)



Set up boundary conditions (Load cases 1.1-1.3, 2.3)

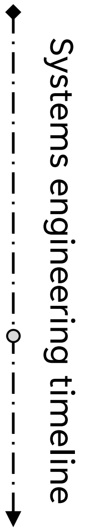


Structural forces load case



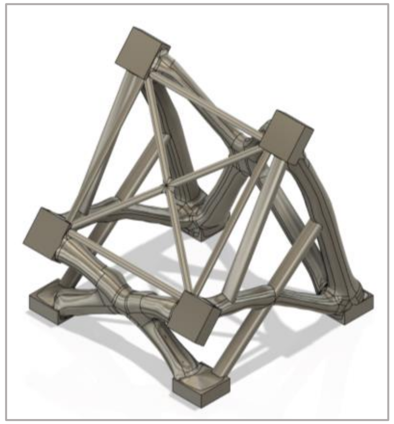
Thermoelastic deformation load case

Product Verification



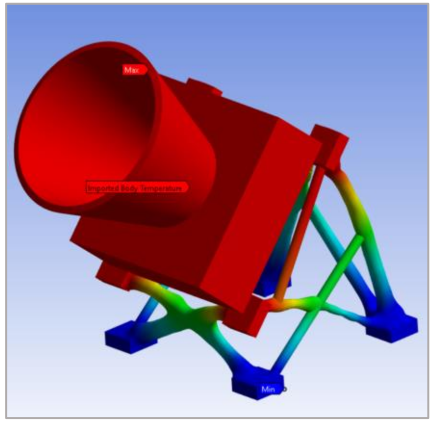
PRODUCT VERIFICATION

Verification against requirements was performed with FEA: Ansys



Latest bracket design

Mesh (1.4M elements)



Temperature gradient

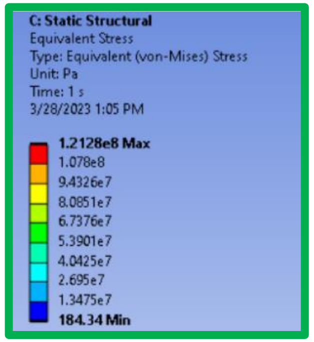
Definition	
Type	Flexible Rotation
Location Method	Remote Points
Remote Points	Remote Point
Suppressed	No
Options	
Result Selection	X Axis
Display Time	End Time
Results	
Maximum Value Over Time	
X Axis	-8.6242e-004

Pointing deviation results

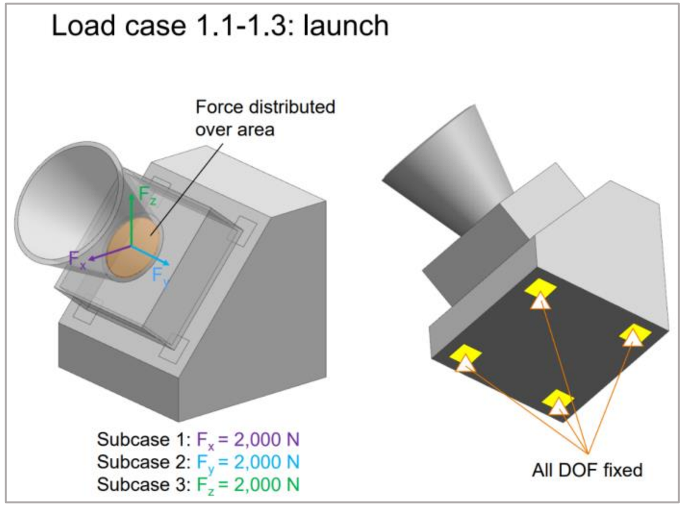
Tabular Data

	Mode	Frequency [Hz]
1	1.	214.72
2	2.	222.61
3	3.	389.52
4	4.	511.27
5	5.	670.92
6	6.	683.38

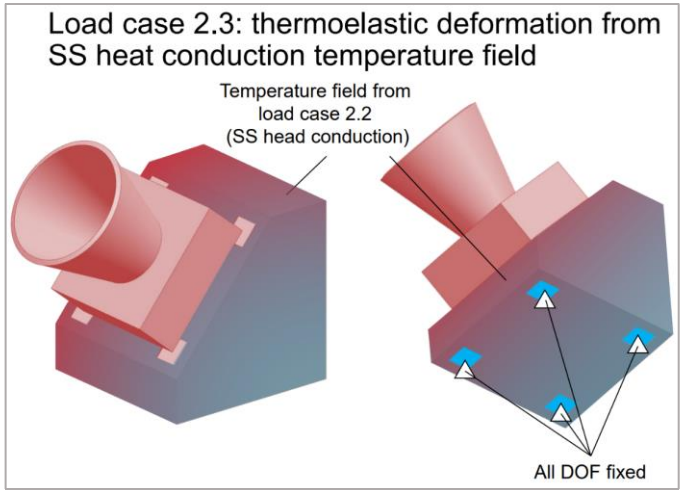
Natural frequency results



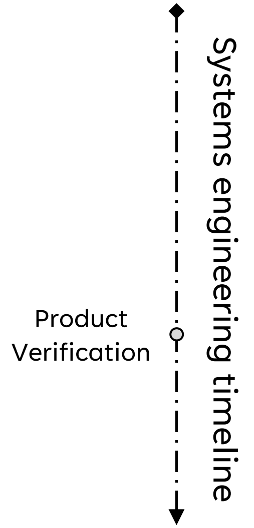
Von Mises stress results



Structural forces load case



Thermoelastic deformation load case



PRODUCT VERIFICATION

Requirements verification comparison with Hypermesh (NASA JPL):

Ansys

Requirement	To meet or exceed	Result	Pass/Fail
Pointing deviation	$\|\theta\| < 0.001°$	$\|\theta\| = 0.0008624°$	✓
Fundamental frequency	$\lambda > 200$ Hz	$\lambda = 214.72$ Hz	✓
Von Mises stress	$\sigma_{max} < 660$ MPa	$\sigma_{max} = 121.28$ MPa	✓
Member size	$t_{min} > 1$ mm	$t_{min} = 1.5$ mm	✓

Altair | HyperWorks

Requirement	To meet or exceed	Result	Pass/Fail
Pointing deviation	$\|\theta\| < 0.001°$	$\|\theta\| = 0.0001333°$	✓
Fundamental frequency	$\lambda > 200$ Hz	$\lambda = 200.80$ Hz	✓
Von Mises stress	$\sigma_{max} < 660$ MPa	$\sigma_{max} = 125.72$ MPa	✓
Member size	$t_{min} > 1$ mm	$t_{min} = 1.5$ mm	✓

Product Verification

Systems engineering timeline

Design passes verification in both models

Final mass: 0.92 kg (94% reduction of mass)

PRODUCT VERIFICATION

Requirements verification comparison with Hypermesh (NASA JPL):

Mass
- Full system mass: 4.17403 kg
- Bracket only (excluding mounting pads): 0.9140300000000003 kg

Fundamental Frequency
- ✓ Min frequency: 200.8 Hz (ref > 200 Hz)

Minimum pointing deviation
- ✓ Pointing X: 0.00013337884512850434 deg (ref < 0.001 deg)
- ✓ Pointing Y: 2.2645612542640414e-05 deg (ref < 0.001 deg)

Bolt slip

LaunchX
- ✓ Instrument bolt shear forces EID 1059584: 515.7 N (ref < 1000 N)
- ✓ Instrument bolt shear forces EID 1059585: 515.8 N (ref < 1000 N)
- ✓ Instrument bolt shear forces EID 1059586: 563.1 N (ref < 1000 N)
- ✓ Instrument bolt shear forces EID 1059587: 571.6 N (ref < 1000 N)
- ✓ Base bolt shear forces EID 1059588: 952.5 N (ref < 1500 N)
- ✓ Base bolt shear forces EID 1059589: 943.3 N (ref < 1500 N)
- ✓ Base bolt shear forces EID 1059590: 572.8 N (ref < 1500 N)
- ✓ Base bolt shear forces EID 1059591: 571.9 N (ref < 1500 N)

LaunchY
- ✓ Instrument bolt shear forces EID 1059584: 110.6 N (ref < 1000 N)
- ✓ Instrument bolt shear forces EID 1059585: 111.0 N (ref < 1000 N)
- ✓ Instrument bolt shear forces EID 1059586: 929.1 N (ref < 1000 N)
- ✓ Instrument bolt shear forces EID 1059587: 929.2 N (ref < 1000 N)
- ✓ Base bolt shear forces EID 1059588: 591.7 N (ref < 1500 N)
- ✓ Base bolt shear forces EID 1059589: 598.6 N (ref < 1500 N)
- ✓ Base bolt shear forces EID 1059590: 860.7 N (ref < 1500 N)
- ✓ Base bolt shear forces EID 1059591: 867.5 N (ref < 1500 N)

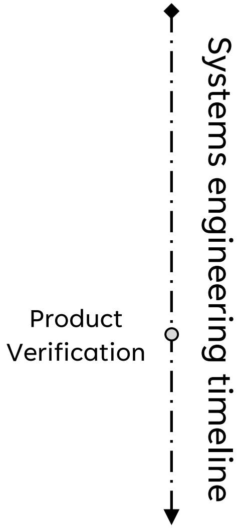
LaunchZ
- ✓ Instrument bolt shear forces EID 1059584: 287.2 N (ref < 1000 N)
- ✓ Instrument bolt shear forces EID 1059585: 289.3 N (ref < 1000 N)
- ✓ Instrument bolt shear forces EID 1059586: 989.0 N (ref < 1000 N)
- ✓ Instrument bolt shear forces EID 1059587: 987.9 N (ref < 1000 N)
- ✓ Base bolt shear forces EID 1059588: 116.7 N (ref < 1500 N)
- ✓ Base bolt shear forces EID 1059589: 102.9 N (ref < 1500 N)
- ✓ Base bolt shear forces EID 1059590: 934.1 N (ref < 1500 N)
- ✓ Base bolt shear forces EID 1059591: 933.3 N (ref < 1500 N)

BulkSoak
- ✗ Instrument bolt shear forces EID 1059584: 1812.1 N (ref < 1000 N)
- ✗ Instrument bolt shear forces EID 1059585: 1783.6 N (ref < 1000 N)
- ✗ Instrument bolt shear forces EID 1059586: 2225.4 N (ref < 1000 N)
- ✗ Instrument bolt shear forces EID 1059587: 2256.9 N (ref < 1000 N)
- ✓ Base bolt shear forces EID 1059588: 652.3 N (ref < 1500 N)
- ✓ Base bolt shear forces EID 1059589: 688.4 N (ref < 1500 N)
- ✗ Base bolt shear forces EID 1059590: 2282.3 N (ref < 1500 N)
- ✗ Base bolt shear forces EID 1059591: 2298.5 N (ref < 1500 N)

ThermoElastic
- ✗ Instrument bolt shear forces EID 1059584: 1094.8 N (ref < 1000 N)
- ✗ Instrument bolt shear forces EID 1059585: 1093.1 N (ref < 1000 N)
- ✗ Instrument bolt shear forces EID 1059586: 1273.7 N (ref < 1000 N)
- ✗ Instrument bolt shear forces EID 1059587: 1272.3 N (ref < 1000 N)
- ✓ Base bolt shear forces EID 1059588: 290.7 N (ref < 1500 N)
- ✓ Base bolt shear forces EID 1059589: 290.0 N (ref < 1500 N)
- ✓ Base bolt shear forces EID 1059590: 179.3 N (ref < 1500 N)
- ✓ Base bolt shear forces EID 1059591: 181.3 N (ref < 1500 N)

Buckling
- ✓ Launch X: 24.69765 (ref > 2)
- ✓ Launch Y: 15.15197 (ref > 2)
- ✓ Launch Z: 18.44882 (ref > 2)

Heat loss through base interface
- ✓ Heat flux: 0.24 W (ref < 4 W)



FUTURE WORK

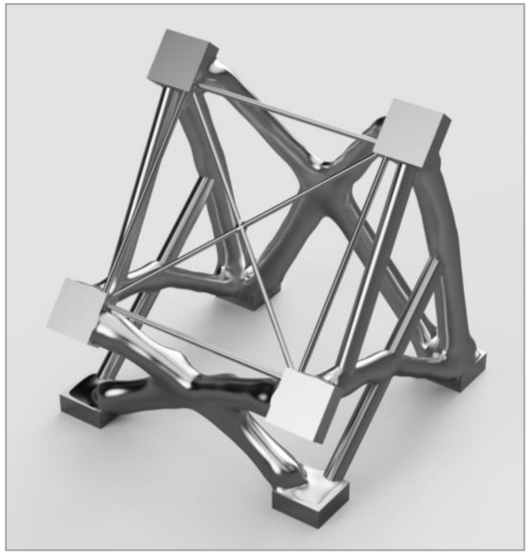
Pending validation based on additive manufacturing

Bracket design would be printed through LPBF in Ti6Al4V

Material validation testing is also necessary

Coupon and tensile specimen would be added to the same print job

Tensile and thermal expansion testing would be performed

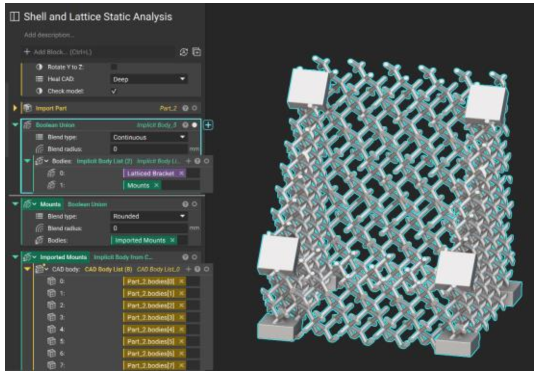


SV2023
(SV 0.785T w 2.15mm Offset)

Implementation of lattice generation as mass reduction method

Lattices can be tailored to increase stiffness, thermal performance, minimize mass, etc.

nTopology was designed to work with lattices and complex geometries



Current lattice work

Product Validation

Systems engineering timeline