Jet Propulsion Laboratory
California Institute of Technology

Jet Propulsion Laboratory
California Institute of Technology

Designing optical instruments for space applications

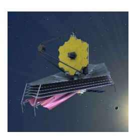
Multiphysics topology optimization

Ryan Watkins
Adam Duran, Jenny Hua, Josh Ravich

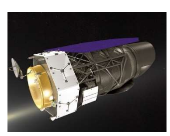
November 19th, 2019

Optical instruments are one of the most common instruments flown by JPL and NASA

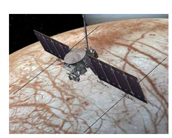
Telescopes
Ex: JWST, Hubble



Coronagraphs
Ex: WFIRST CGI



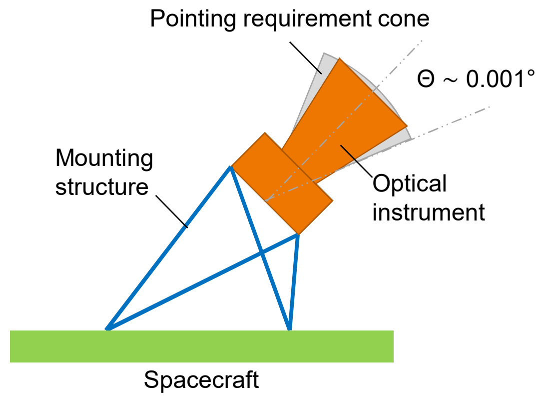
Magnetometers
Ex: Juno, Europa Clipper



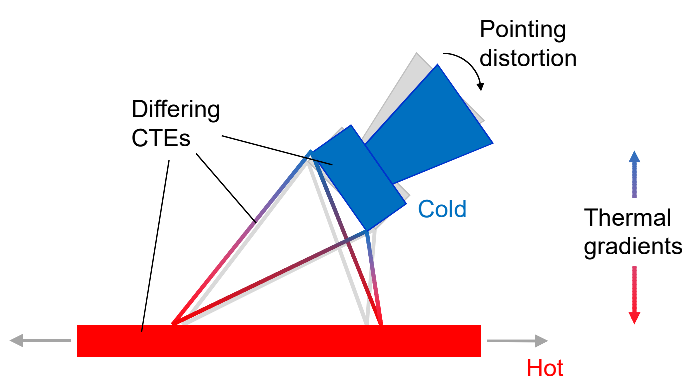
Star trackers
Ex: Nearly all missions

Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov

To function properly, optical instruments have tight pointing requirements



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



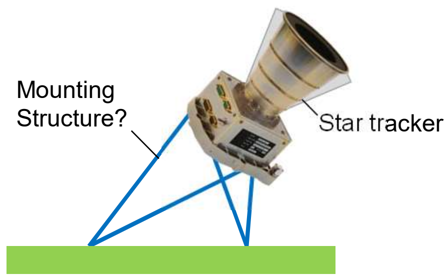
*CTE: Coefficient of Thermal Expansion

Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov

Came across a star tracker system that is struggling to meet tight pointing requirements

Can Topology Optimization (TO) design this bracket?
Pointing requirement as a constraint in TO

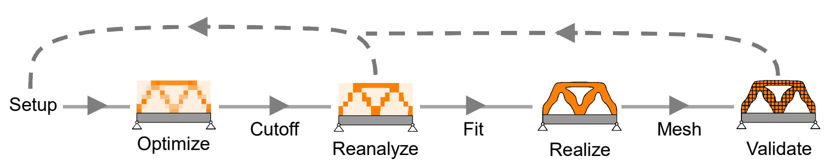
Can the structure be additively manufactured?
Manufacture complex design quickly and at low cost



For this coupled thermoelastic problem,

SIMP-based TO struggles to produce a *realized* design

that meets *all* design requirements

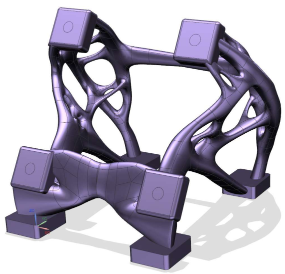


Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov

Jet Propulsion Laboratory
California Institute of Technology

Designing optical instruments for space applications

Multiphysics topology optimization



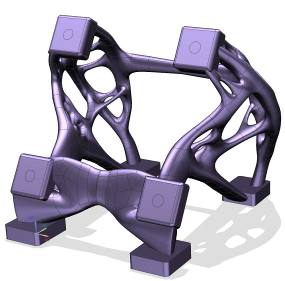
TO in the context of JPL
Institutional relevance

Design problem
Requirements/formulation

Intricacies of TO
Solving a real world problem

Designing optical instruments for space applications

Multiphysics topology optimization



TO in the context of JPL
Institutional relevance

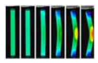
Design problem
Requirements/formulation

Intricacies of TO
Solving a real world problem

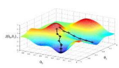
Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov

A little bit about me…

From upstate NY
Saratoga Springs – horse racing town

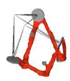


PhD in experimental and theoretical mechanics
Studied shape memory alloys at the University of Michigan



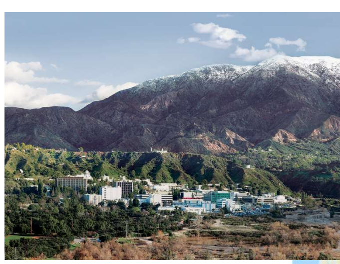
Doing optimization for about a decade
Roommate from college is a mathematician in the field

At JPL for 4 years
Worked as a structural analyst and hardware engineer

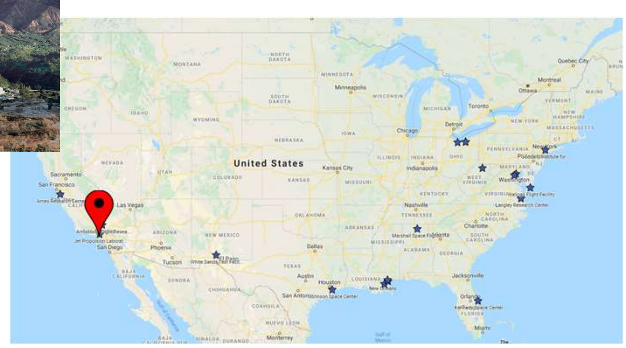


Spearheading use of topology optimization at JPL
Working on this topic since arriving at JPL

JPL is a NASA-based Federally Funded Research and Development Center (FFRDC)



Approximately 6,000 employees
Engineers, scientists, manufacturing, …

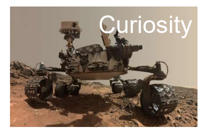


Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov

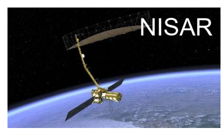
JPL specializes in robotic space and Earth science missions

Interplanetary

Mars rovers



Earth science

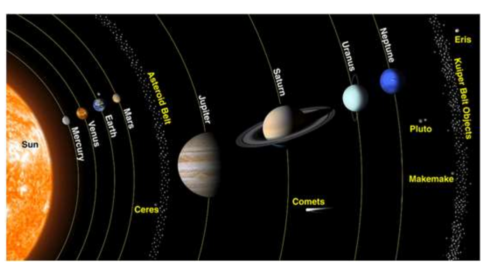


TO is well suited for the design problems commonly faced at JPL

Interplanetary missions are highly driven by mass
Ex: ~40 kg propellant needed to get 1 kg to Jupiter

Each spacecraft is uniquely designed
Continually solving new problems

Low manufacturing quantity
Viable to make high complexity parts



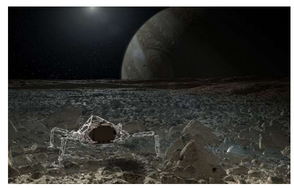
Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov

JPL has been actively attempting to infuse TO into flight projects for four years

Primarily use OptiStruct (Inspire and HyperMesh)
Based on software comparison and benchmark testing

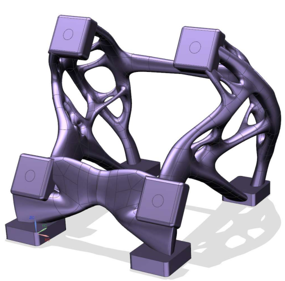
Recently completed Project Gamma development
Collaboration with AutoDesk to design a lander concept

Investigating noncommercial code for “hard” problems
Government (Sandia’s Plato) and university collaboration



Designing optical instruments for space applications

Multiphysics topology optimization



TO in the context of JPL
Institutional relevance

Design problem
Requirements/formulation

Intricacies of TO
Solving a real world problem

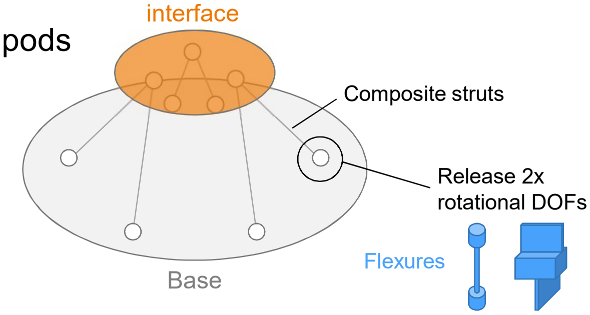
Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov

Optical mounts are typically made of low CTE materials that perfectly constrain the instrument

Perfect constraint → No elastic strain

Low CTE materials → Minimize gradient effects

Ex: 3x bipods



Why use TO when a methodology already exists for this design problem?

Flexures only simulate desired DOF release
Only minimize over constraint

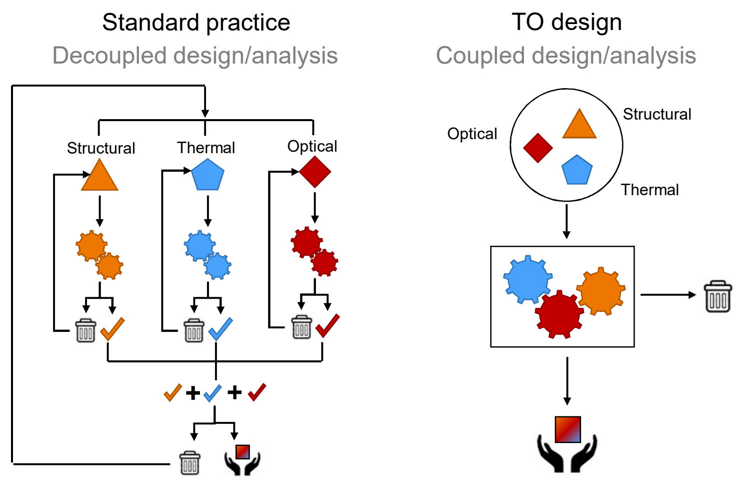
Flexures require precision machining
Tend to be fatigue sensitive

Composites are high cost and long lead time
Require bonding and additional analysis/testing

May not be possible to achieve kinematic mount
Predefined interfaces, limited space, etc.

Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov

Why use TO when a methodology already exists for this design problem?



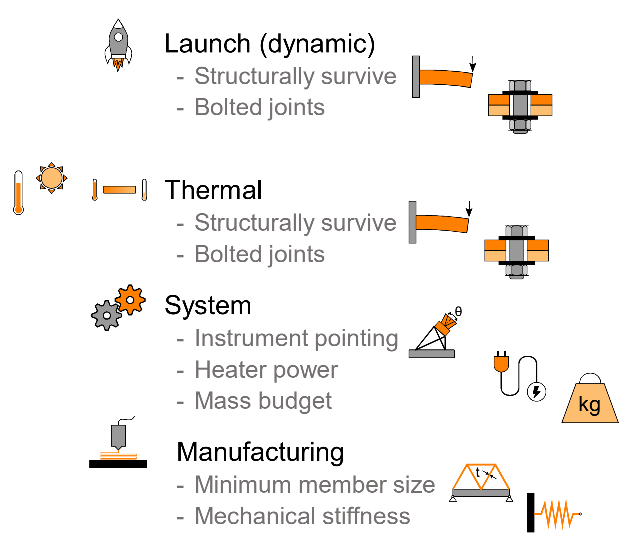
Instrument design is governed by launch, thermal, system, and manufacturing requirements

Launch (dynamic)
- Structurally survive
- Bolted joints

Thermal
- Structurally survive
- Bolted joints

System
- Instrument pointing
- Heater power
- Mass budget

Manufacturing
- Minimum member size
- Mechanical stiffness



Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov

Modeling and optimization limitations require the problem to be slightly reframed

Launch (static)
- Structurally survive
- Bolted joints
- Fundamental frequency

Thermal
- Structurally survive
- Bolted joints

System
- Instrument pointing
- Heater power
- Mass budget

Manufacturing
- Minimum member size
- Mechanical stiffness
- Discrete/connected solution

Check after optimization

kg

There are three primary choices for the objective function

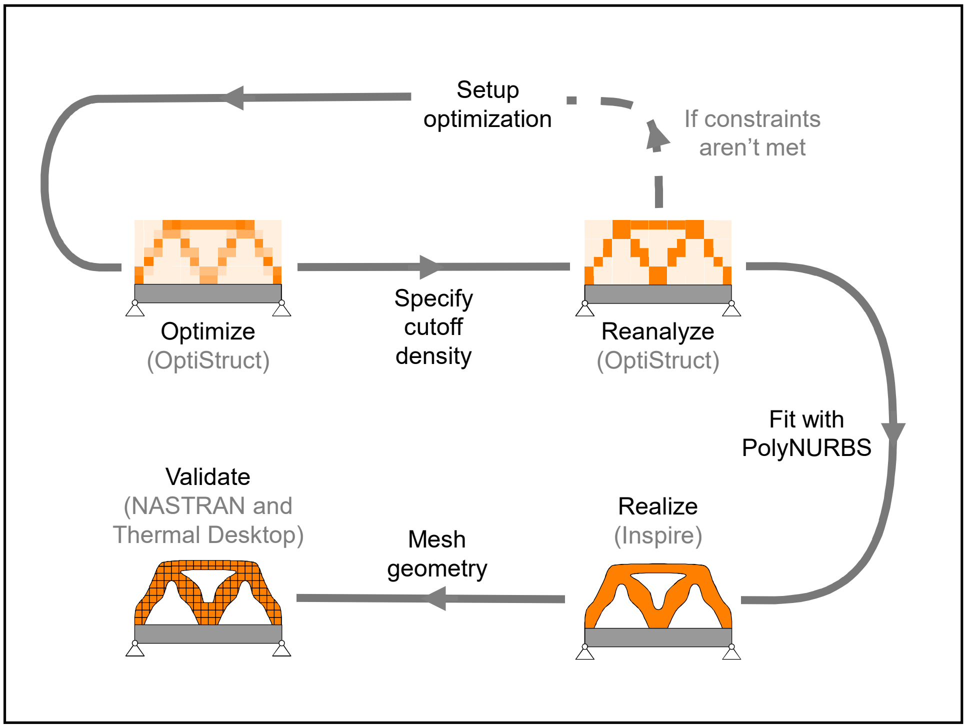
Maximize stiffness
Most common formulation, but often least relevant

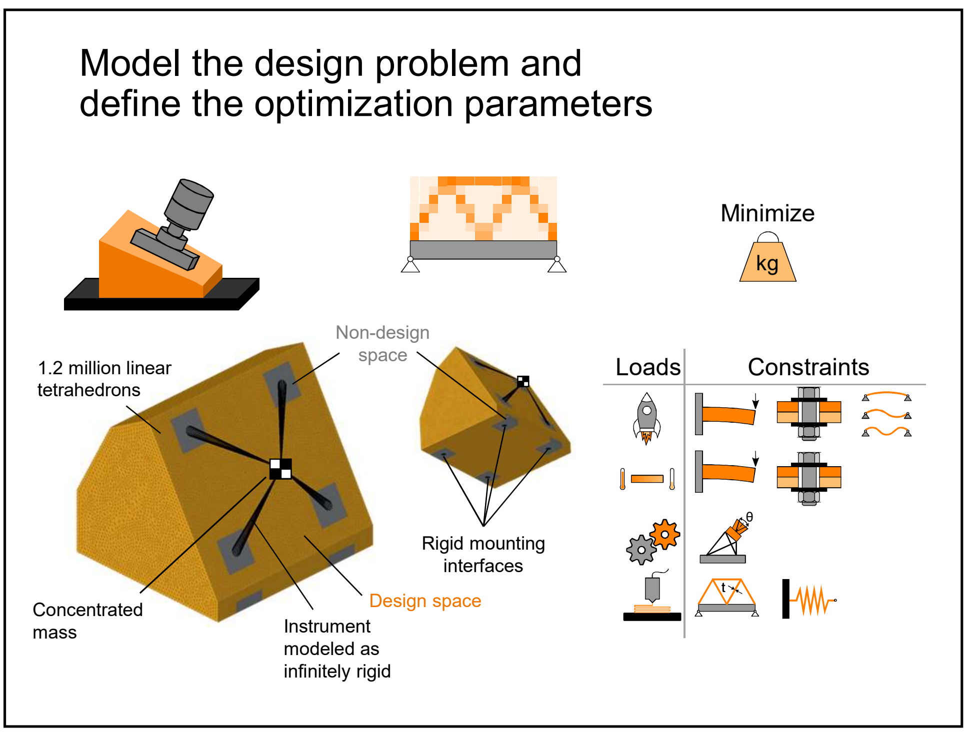
Minimize mass
Most relevant for deep space missions

kg

Maximize instrument performance
How important is the scientific mission?

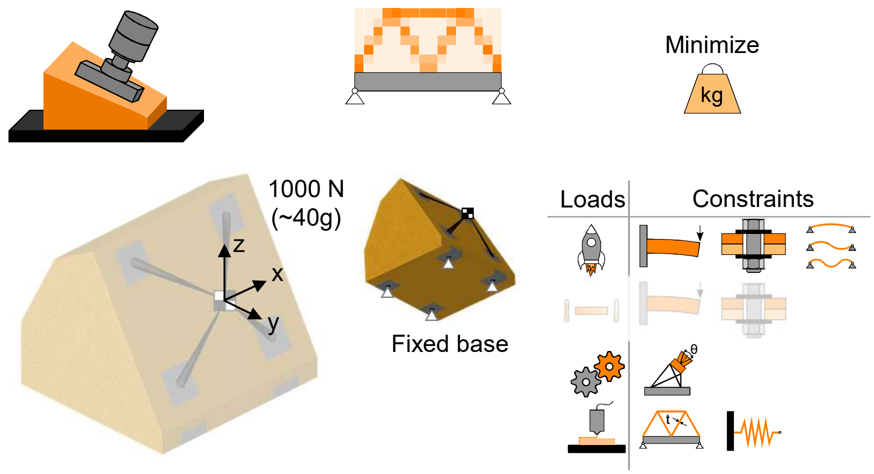
Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov



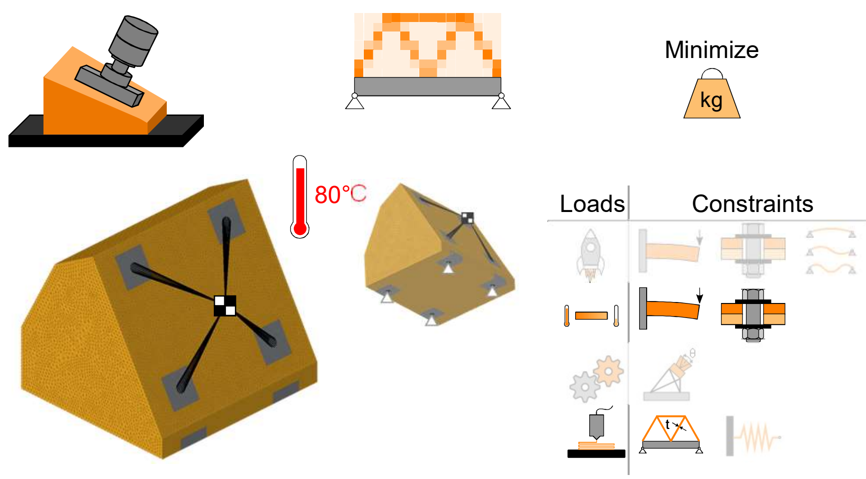


Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov

Impose three launch cases:
static load in three orthogonal directions

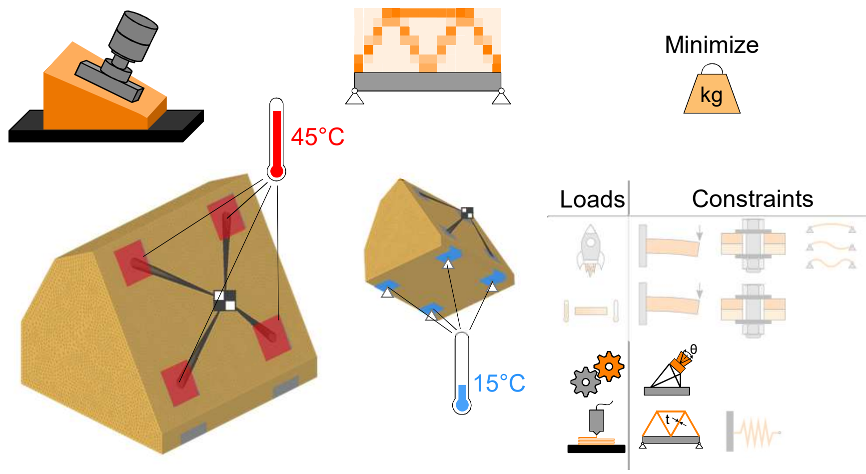


Impose a worst-case thermal load case:
Bulk steady state (SS) thermal soak

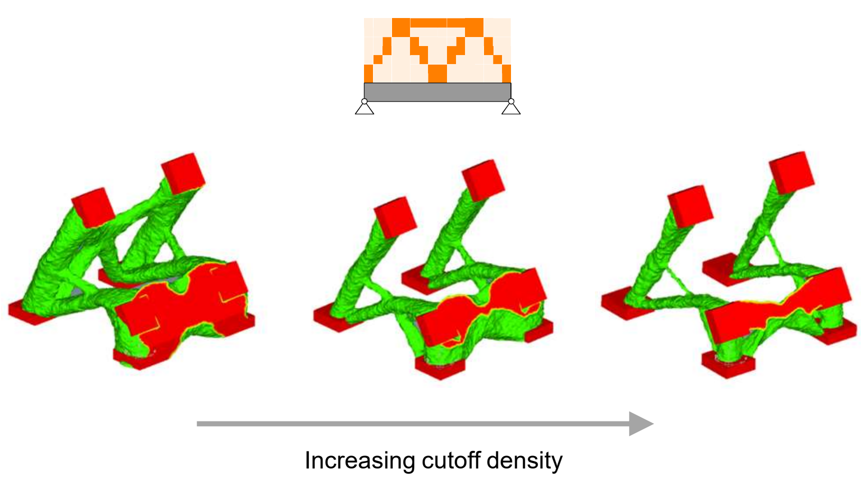


Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov

Impose an operational thermal load case:
SS heat conduction → elastic deformation

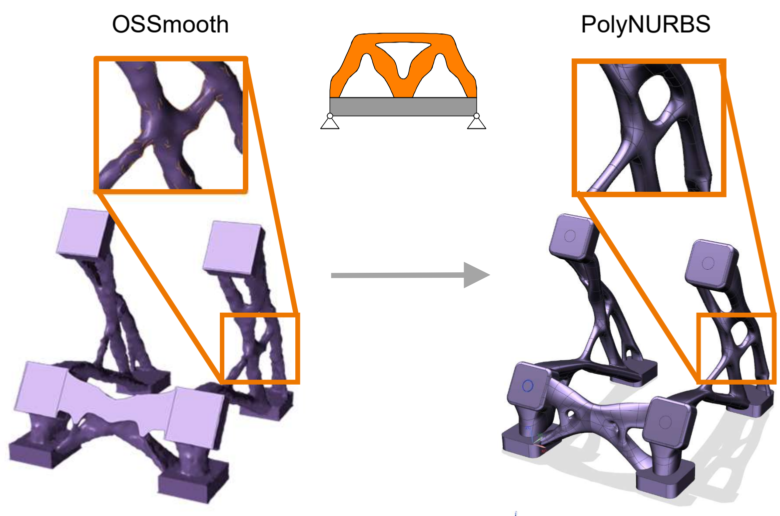


Specify cutoff density and reanalyze to verify
that constraints are still satisfied

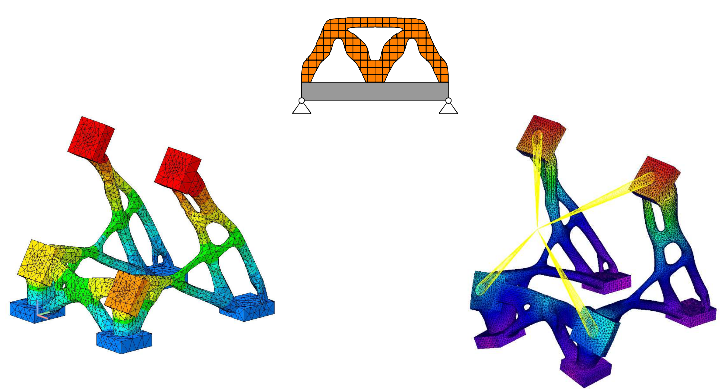


Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov

Export geometry with OSSmooth and fit with PolyNURB surfaces in Inspire



Validate realized design using standard JPL flight analysis practices



Thermal Analysis
(Thermal Desktop)

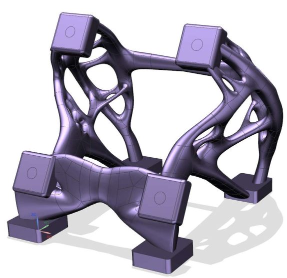
Structural Analysis
(NASTRAN)

Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov

Jet Propulsion Laboratory
California Institute of Technology

Designing optical instruments for space applications

Multiphysics topology optimization



TO in the context of JPL
Institutional relevance

Design problem
Requirements/formulation

Intricacies of TO
Solving a real world problem

In general, the penalty *continuation method* did not produce discrete/connected results

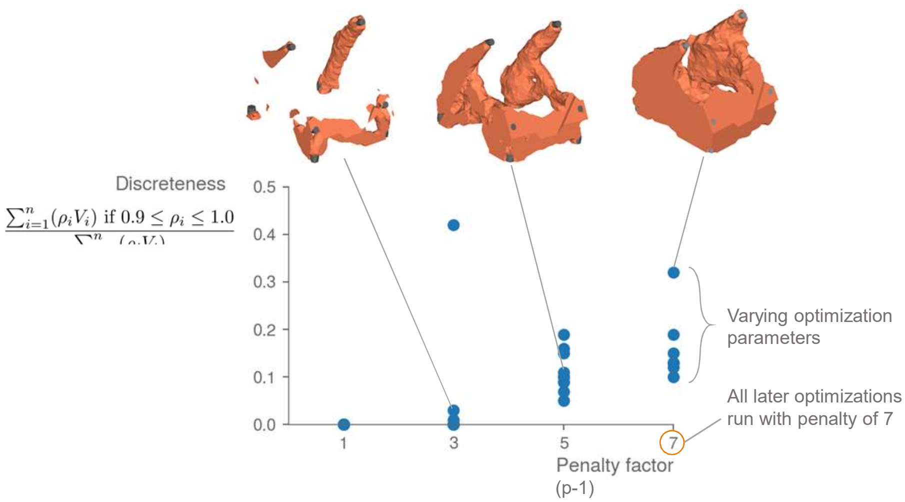
$$E^* = \rho^{p+1} E$$

Density range	Step 1 (p = 1)	Step 2 (p = 2)	Step 3 (p = 3)
0.0-0.1	9.1 %	9.1 %	9.1 %
0.1-0.2	90.8 %	90.8 %	90.8 %
0.2-0.3	0.0 %	0.0 %	0.0 %
0.3-0.4	0.0 %	0.0 %	0.0 %
0.4-0.5	0.0 %	0.0 %	0.0 %
0.5-0.6	0.0 %	0.0 %	0.0 %
0.6-0.7	0.0 %	0.0 %	0.0 %
0.7-0.8	0.0 %	0.0 %	0.0 %
0.8-0.9	0.0 %	0.0 %	0.0 %
0.9-1.0	0.0 %	0.0 %	0.0 %

*Note: results questionable due to limited knowledge of solver formulation
*Note: results are for a slightly different optimization formulation

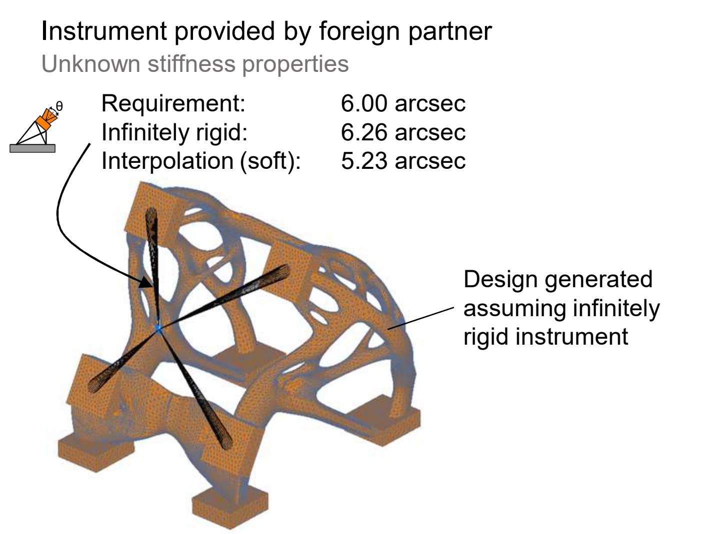
Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov

A penalty factor of 7 consistently resulted in discrete and connected solutions



*Note: results are for a slightly different optimization formulation

It can be challenging to bound interface uncertainties in multiphysics optimizations



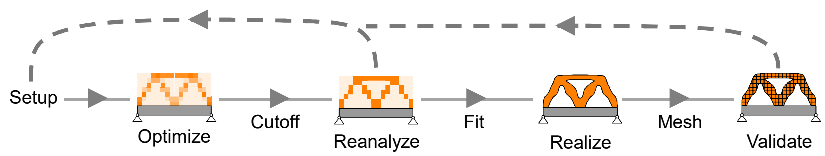
Ryan Watkins
Materials Development And Manufacturing Technology
Ryan.t.Watkins@jpl.nasa.gov

A successful optimization run does not necessarily result in a “real” viable design

“Gray” solutions behave different than real structures
Optimizer is fundamentally solving a different problem

Realizing a design is user dependent
Defining cutoff density and smoothing the results

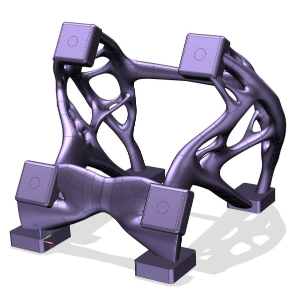
Multiphysics problem is non-intuitive
This is less of an issue for purely structural problems



	Optimize	Reanalyze	Validate
Case 1	5.94 arcsec	15.33 arcsec	6.26 arcsec
Case 2	0.42 arcsec	51.52 arcsec	N/A

Designing optical instruments for space applications

Multiphysics topology optimization



TO in the context of JPL
Institutional relevance

Design problem
Requirements/formulation

Intricacies of TO
Solving a real world problem

Ultimately, TO was able to come up with a design that nearly met requirements

- Optimized a multiphysics design problem
  - Thermal and mechanical load cases
- SIMP struggled to generate a fully compliant design
  - Issues realizing a design from density formulation
- Driving requirement was instrument pointing
  - Current design violates requirement by 5%
- Complete free shape optimization in future work
  - Hone TO solution to be compliant with requirements

Designing optical instruments for space applications

Multiphysics topology optimization

Ryan Watkins
Ryan.T.Watkins@jpl.nasa.gov

November, 19th 2019

Jet Propulsion Laboratory
California Institute of Technology