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Optimization-based Design for Manufacturing: Using Plato to Incorporate Manufacturability Objectives into the Design Process

CONTRIBUTORS

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PRESENTED BY

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Motivation

Additive manufacturing process outcomes, e.g., residual stress and part distortion, vary with part design and support structure.

Design courtesy of Clinton Holtey using Plato. Displacement predictions by Kyle Johnson. Red = 0.1 mm.

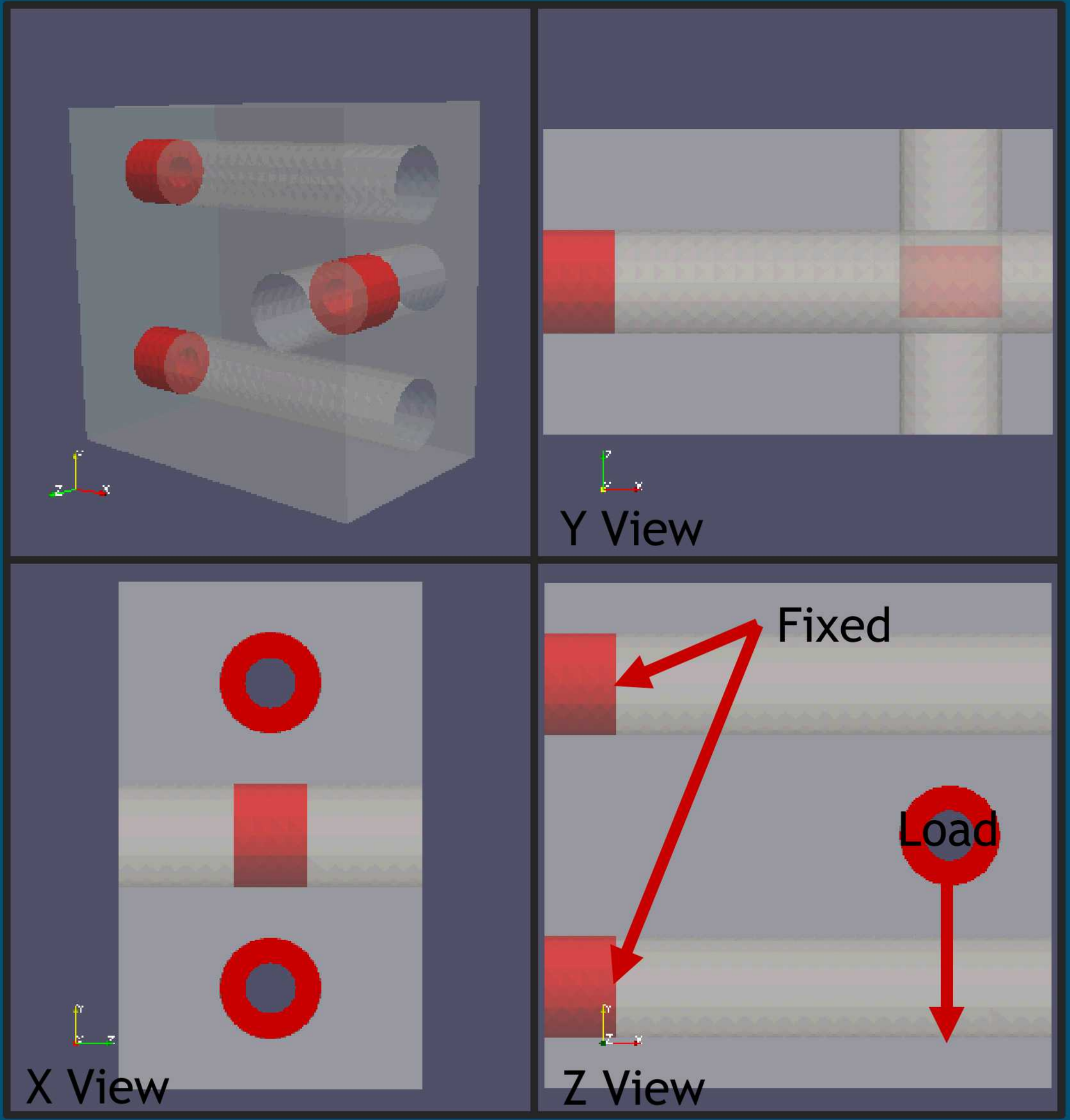
Objective: Create software for generating designs and support structure that are optimized for performance *and manufacturability.*

Approach: Incorporate fast process simulations into the optimization loop to introduce manufacturability objectives.

- Plato Engine – parallelism
- Plato Analyze – fast PDE enforcement

* B. Jared et al., Additive Manufacturing: Toward holistic design, Scripta Materialia. 135 (2017)

Topology Optimization with “Process Objectives”



Objectives:

Mechanical stiffness
+
Manufacturability

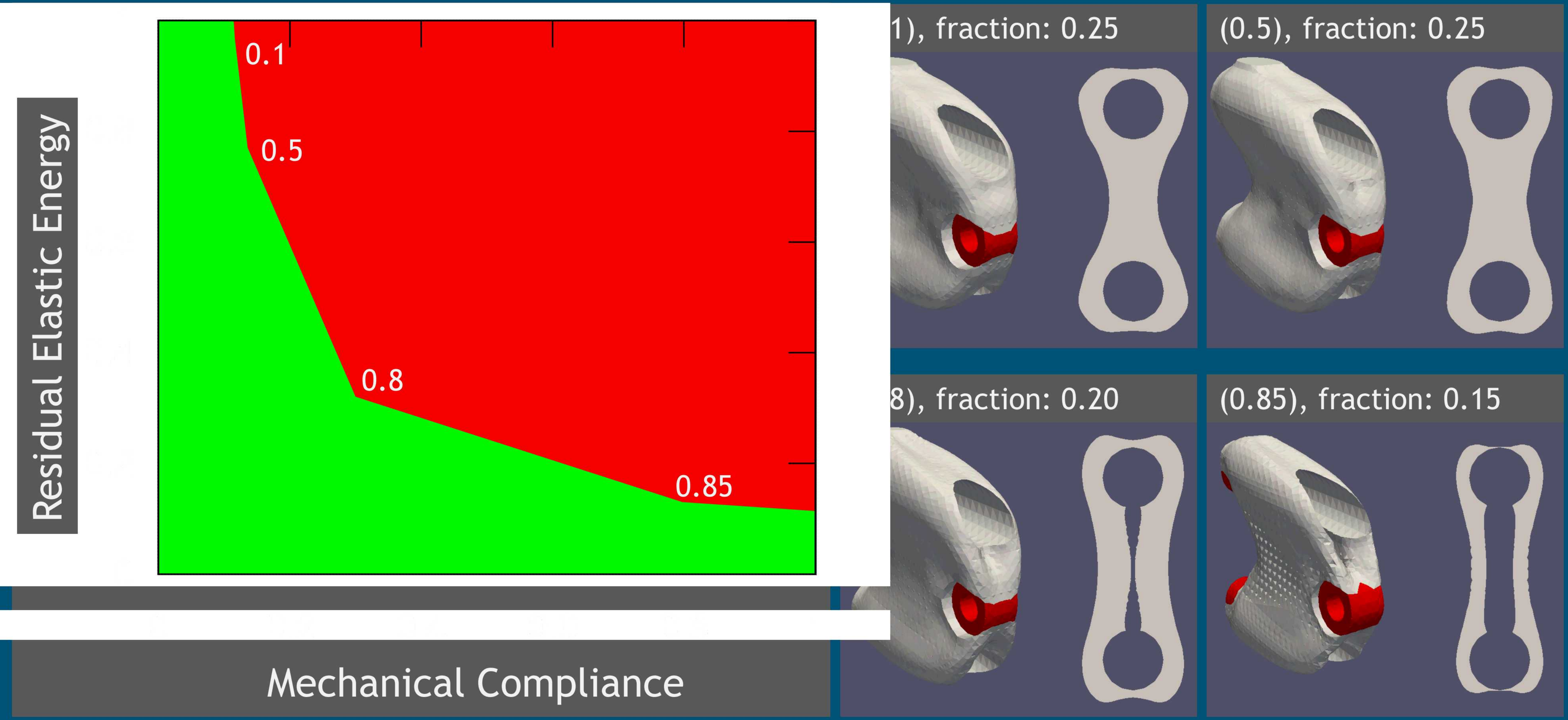
PDE Constraints:

Mechanical equilibrium w/ Load
+
Mechanical equilibrium w/ IS

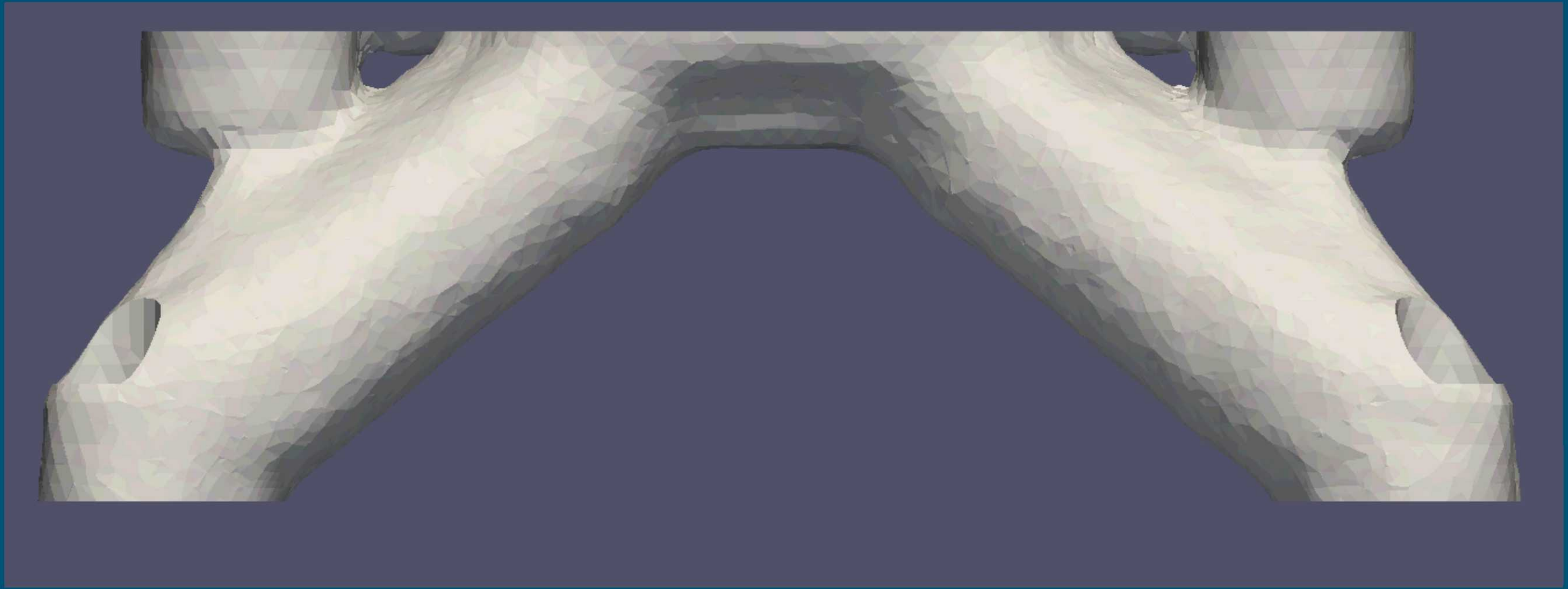
Inequality Constraint:

Design volume

Topology Optimization with "Manufacturability Objectives"



Approach: Fast Process Simulation



Simulation Process

- For each “super layer”
  - Deposition
  - Time dependent thermomechanical equilibration
- Remove from baseplate
- Compute mechanical equilibrium and process outcomes (metrics)

Balance Equations

$$\rho C_p \dot{T} - \nabla \cdot q - \dot{q}_v = 0$$
$$\nabla \cdot \sigma + b = 0$$

Material Response

$$\sigma = C\, \varepsilon^e$$
$$q = k \nabla T$$
$$\varepsilon^e = \nabla_s u - \alpha\left(T - T_{ref}\right) - \varepsilon^p(c)$$

Solution Variables

$$u \equiv u(x,t) \in R^{n_d}$$
$$T \equiv T(x,t) \in R$$
$$c \equiv c(x,t) \in R^{n_s}$$

Approach: Fast Process Simulation

Advantages:

- Improved accuracy relative to Inherent Strain Method. Important for residual stresses.
- Quantities of interest are available at intermediate stages. Control distortion *during the print*.
- Support structure is produced with the design, so it can inform constraints and objectives.

Disadvantages:

- Higher computational cost relative to Inherent Strain Method.

Progress:

- (100%) Time dependent heat equation
- (100%) Stabilized thermomechanics
- (100%) J2 Plasticity
- (90%) Path-dependent adjoint
- (50%) Differentiable support structure

Initial capability to be available mid FY20

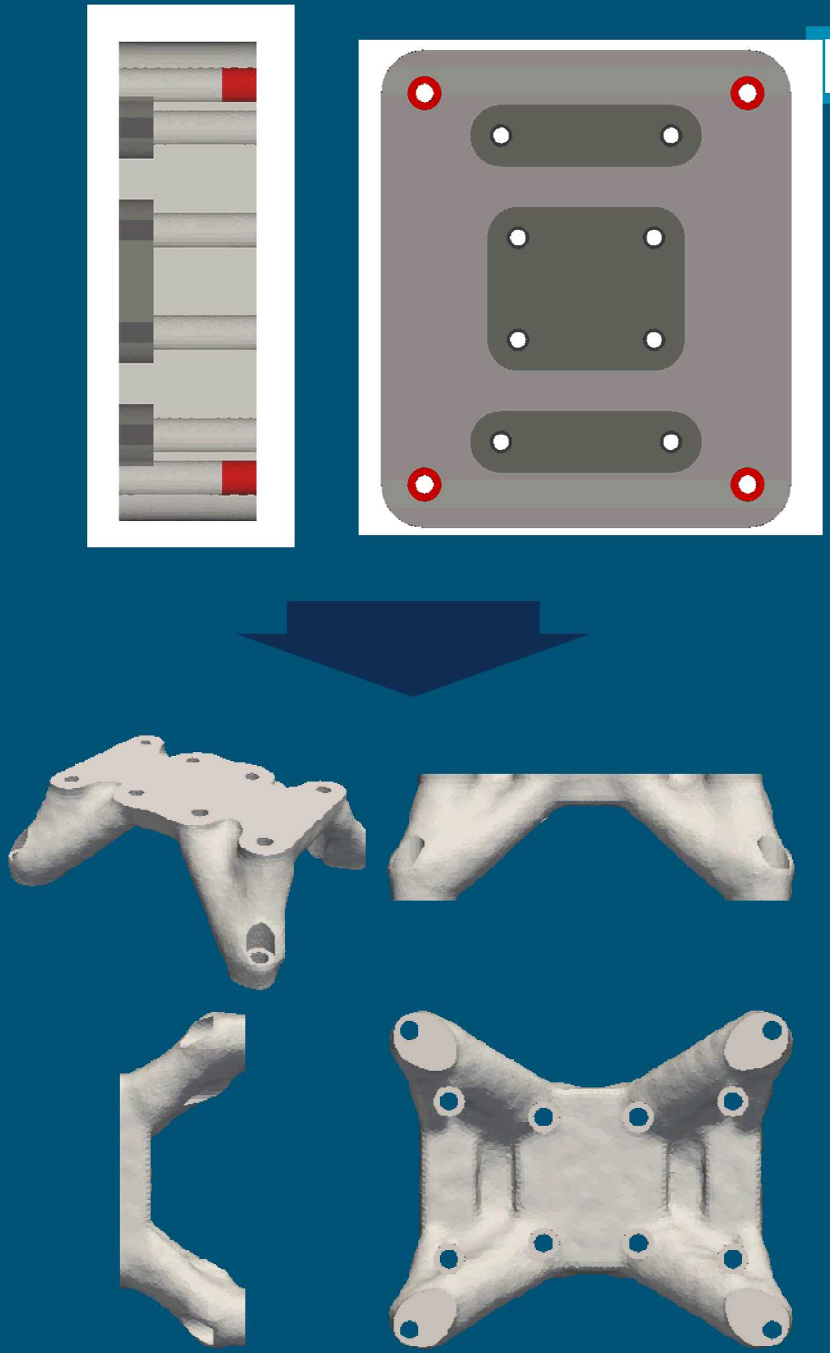
Plato Analyze

Code Design:

- Uses hardware abstraction so compiles readily on GPU and CPU
- Uses Automatic Differentiation and Adjoint Variable Method so gradients are automagic
- Physics, objectives, and constraints are templated, so new additions are straightforward

Physics:

- Thermal / electrostatics
- Elastostatics
- Coupled thermomechanics, electromechanics
- Time dependent heat equation, thermomechanics
- Nearly incompressible mechanics, thermomechanics
- Coming soon: elastoplasticity, thermoelastoplasticity

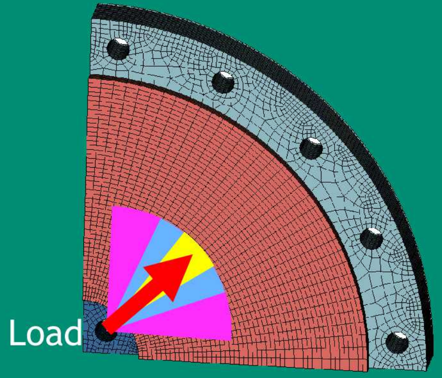


Available at github.com/platoengine/platoanalyze

Plato training session in early 2020.
Contact Plato3D-help@sandia.gov for more info.

Design under Uncertainty

Load Uncertainty + Material Uncertainty = Huge Computational Cost

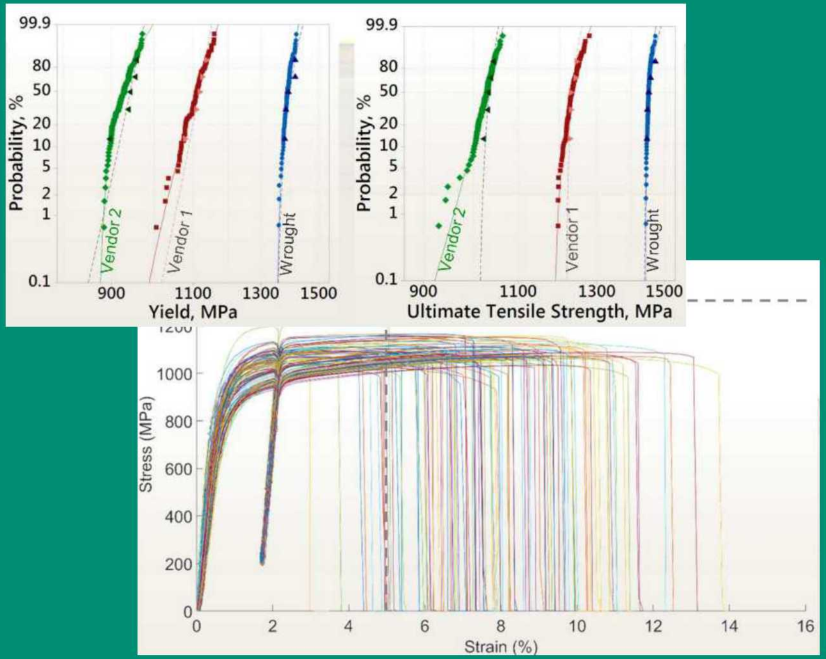


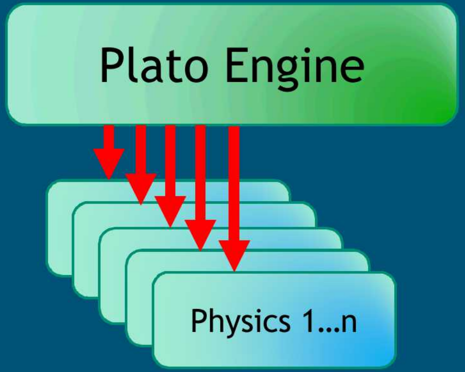
Certain

22.5º range

45º range

90º range





Plato Engine

Physics 1…n

summit

OAK RIDGE
National Laboratory

Shape Optimization with Plato Analyze and ESP

For shape optimization, we need derivatives with respect to the parameters, p:

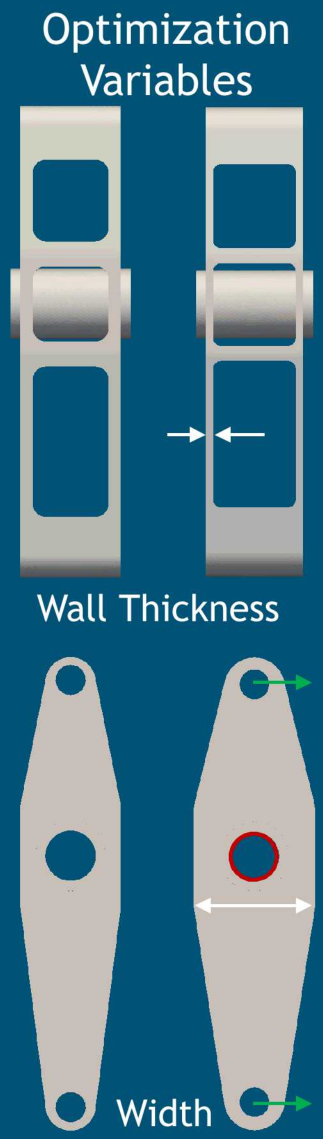
Provided by Plato Analyze

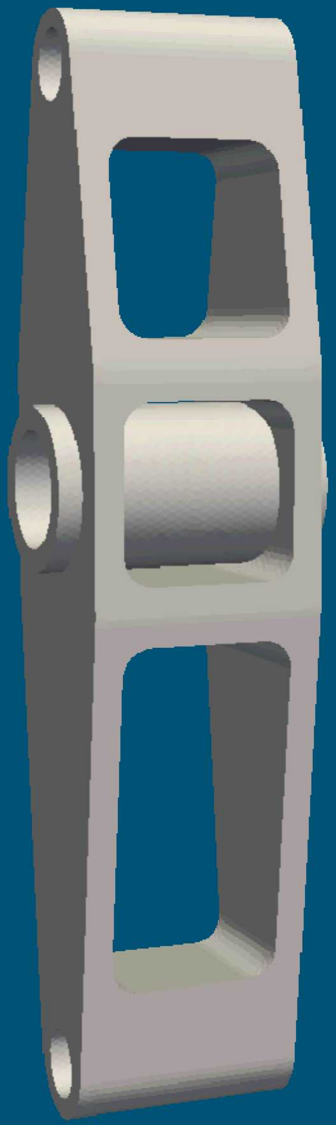
$$\frac{df}{dp} = \frac{df}{dX}\frac{dX}{dp}$$

Provided by ESP

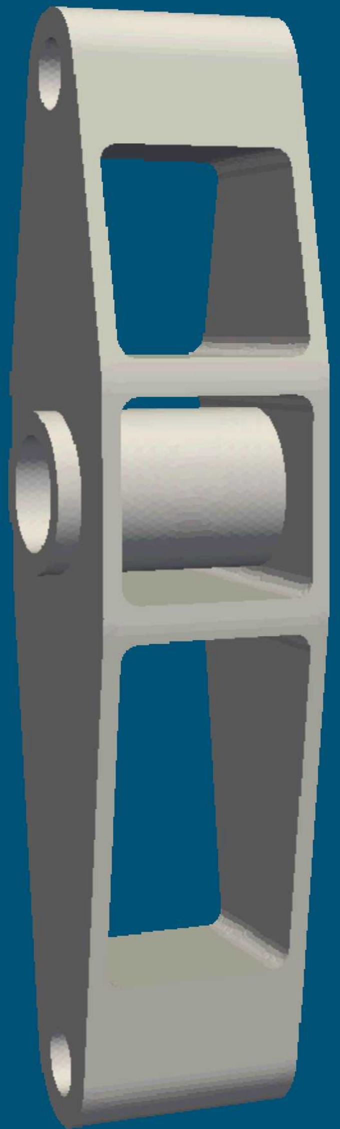
Derivatives with respect to design parameters require parameterized models

Compliance Minimization with Volume Constraint

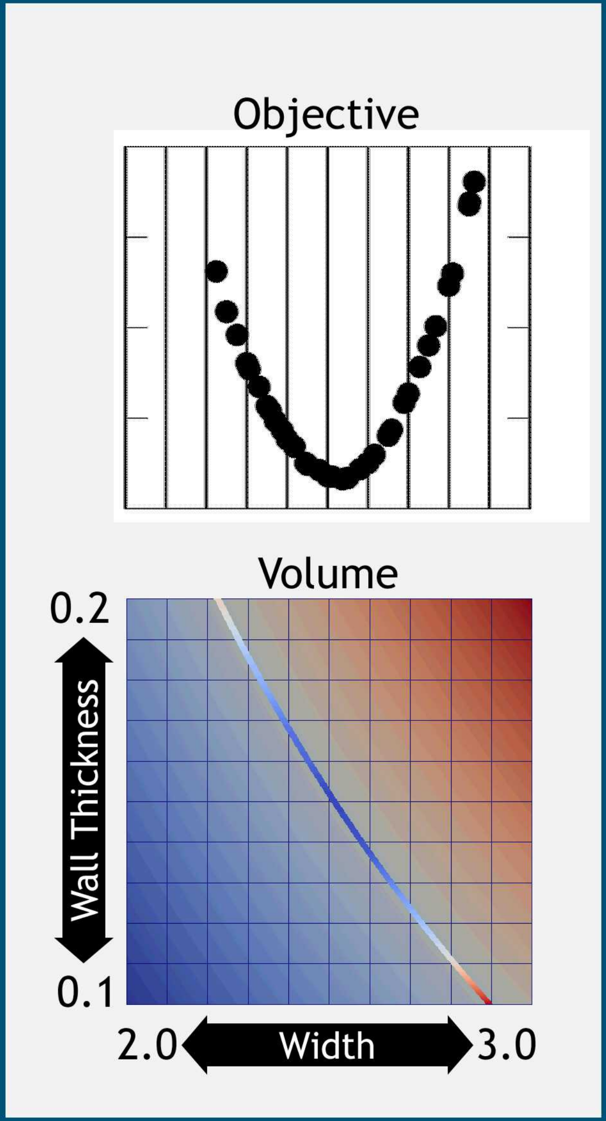


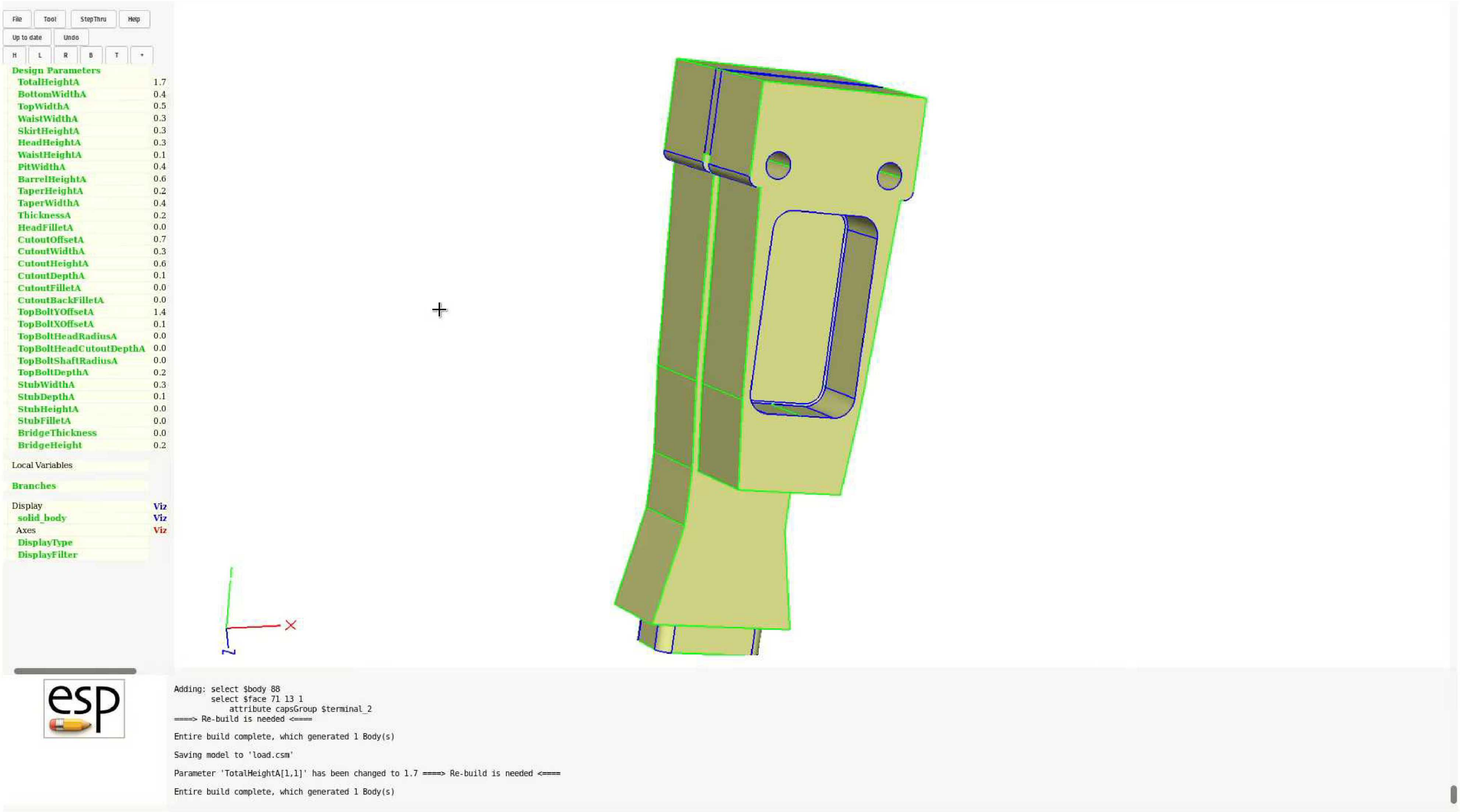


Initial Guess



Optimized

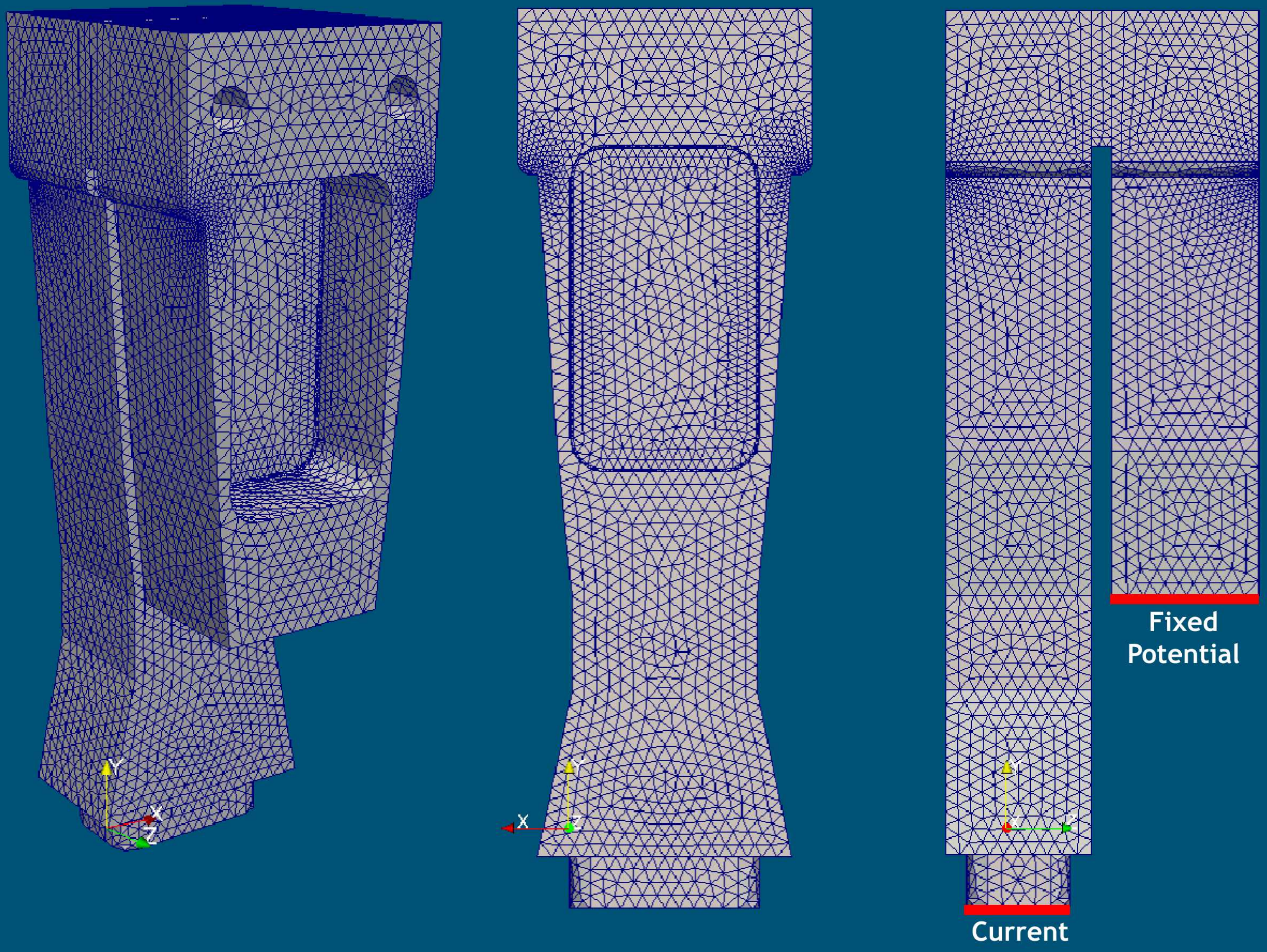


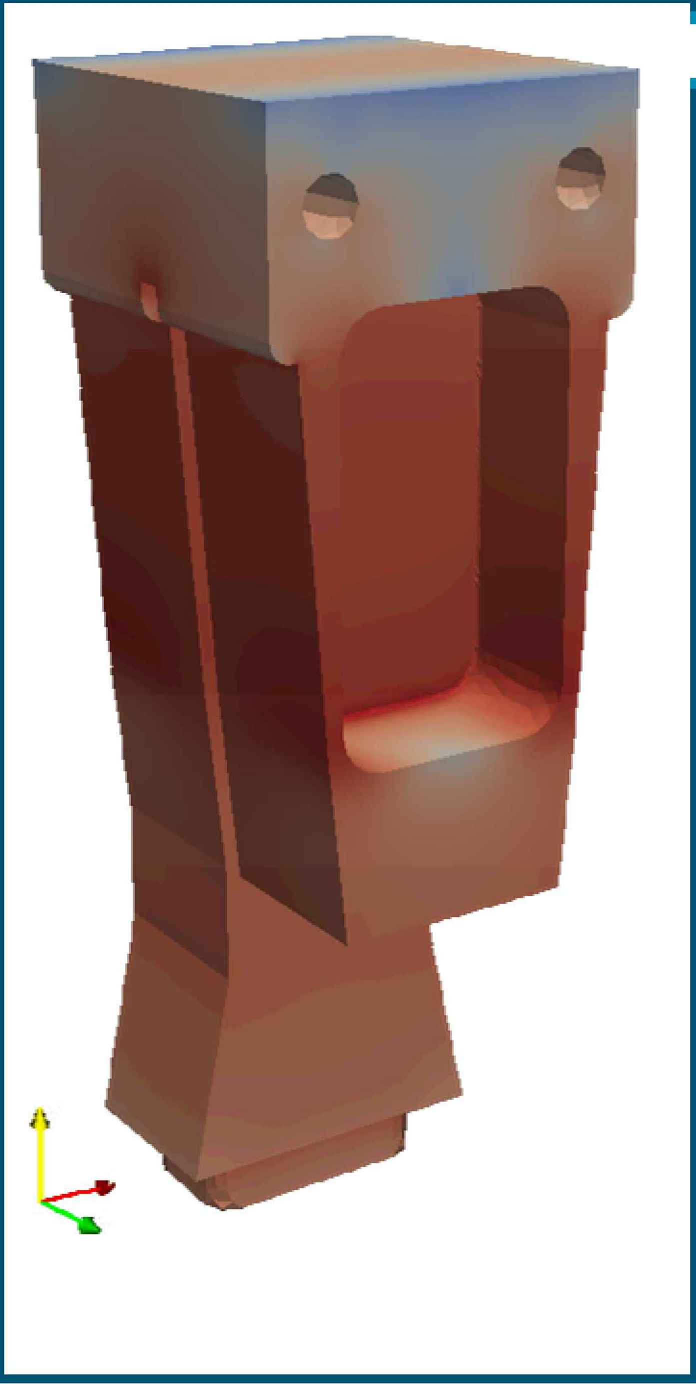


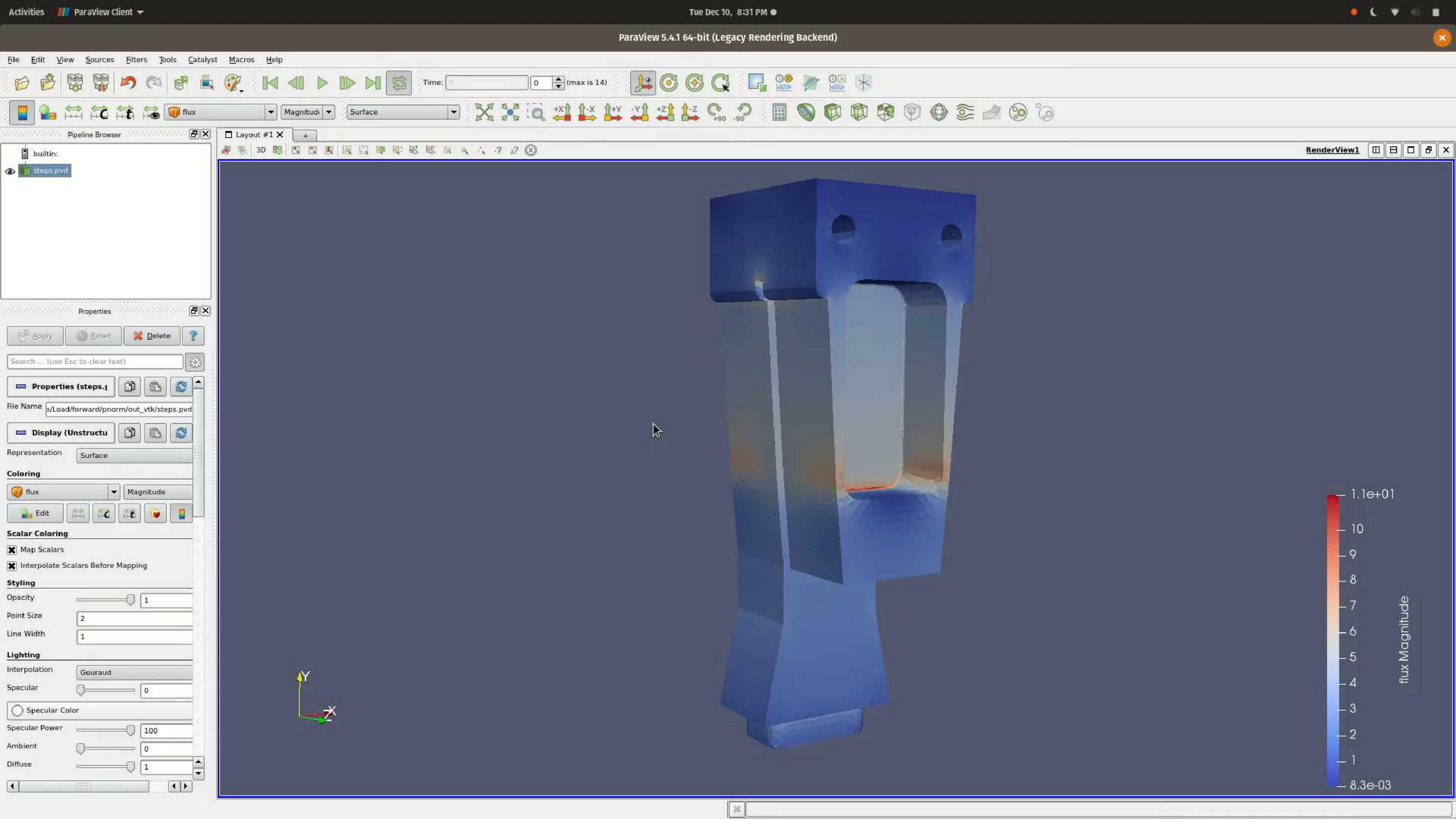
Design Parameters	
TotalHeightA	1.7
BottomWidthA	0.4
TopWidthA	0.5
WaistWidthA	0.3
SkirtHeightA	0.3
HeadHeightA	0.3
WaistHeightA	0.1
PitWidthA	0.4
BarrelHeightA	0.6
TaperHeightA	0.2
TaperWidthA	0.4
ThicknessA	0.2
HeadFilletA	0.0
CutoutOffsetA	0.7
CutoutWidthA	0.3
CutoutHeightA	0.6
CutoutDepthA	0.1
CutoutFilletA	0.0
CutoutBackFilletA	0.0
TopBoltYOffsetA	1.4
TopBoltXOffsetA	0.1
TopBoltHeadRadiusA	0.0
TopBoltHeadCutoutDepthA	0.0
TopBoltShaftRadiusA	0.0
TopBoltDepthA	0.2
StubWidthA	0.3
StubDepthA	0.1
StubHeightA	0.0
StubFilletA	0.0
BridgeThickness	0.0
BridgeHeight	0.2
Local Variables	
Branches	
Display	Viz
solid_body	Viz
Axes	Viz
DisplayType	
DisplayFilter	

```
Adding: select $body 88
        select $face 71 13 1
            attribute capsGroup $terminal_2
====> Re-build is needed <====

Entire build complete, which generated 1 Body(s)

Saving model to 'load.csm'

Parameter 'TotalHeightA[1,1]' has been changed to 1.7 ====> Re-build is needed <====

Entire build complete, which generated 1 Body(s)
```

Electrostatic Load Case







File Name: /Load/forward/pnorm/out_vtk/steps.pvd

Representation: Surface

Coloring: flux, Magnitude

☒ Map Scalars

☒ Interpolate Scalars Before Mapping

Opacity: 1

Point Size: 2

Line Width: 1

Interpolation: Gouraud

Specular: 0

Specular Power: 100

Ambient: 0

Diffuse: 1

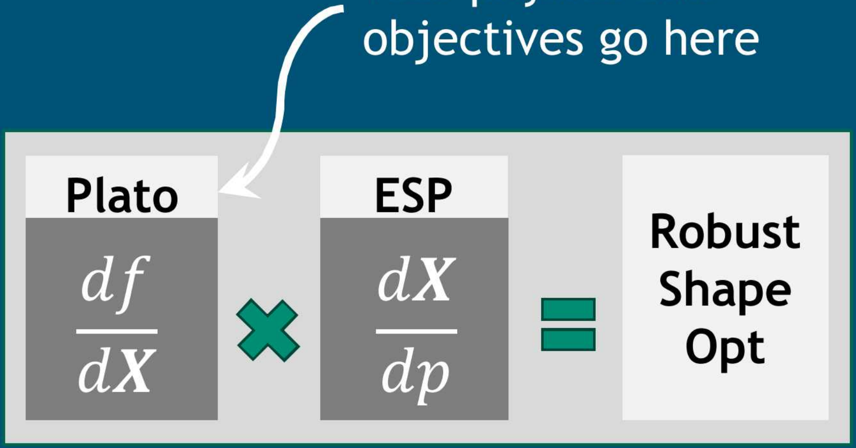
Time: 0

Shape Optimization with Plato/ESP

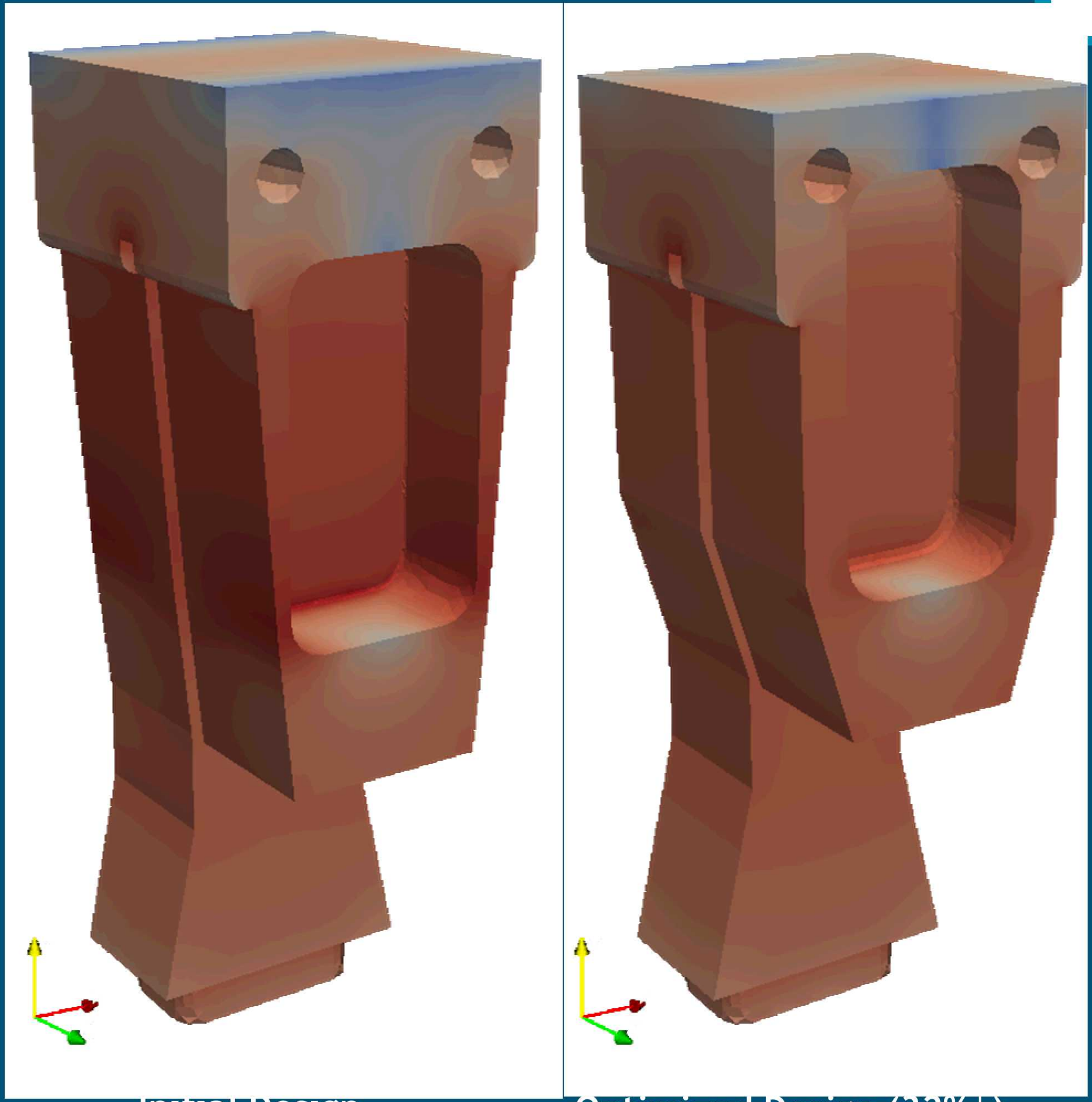
Progress:
- ESP functionality implemented in Plato Engine
- Beta Plato/ESP capability available for early adopters.

Next Steps:
- Testing and hardening of Plato/ESP
- Shape optimization + topology optimization

Your physics and objectives go here



Plato $\frac{df}{d\mathbf{X}}$ × **ESP** $\frac{d\mathbf{X}}{dp}$ = **Robust Shape Opt**



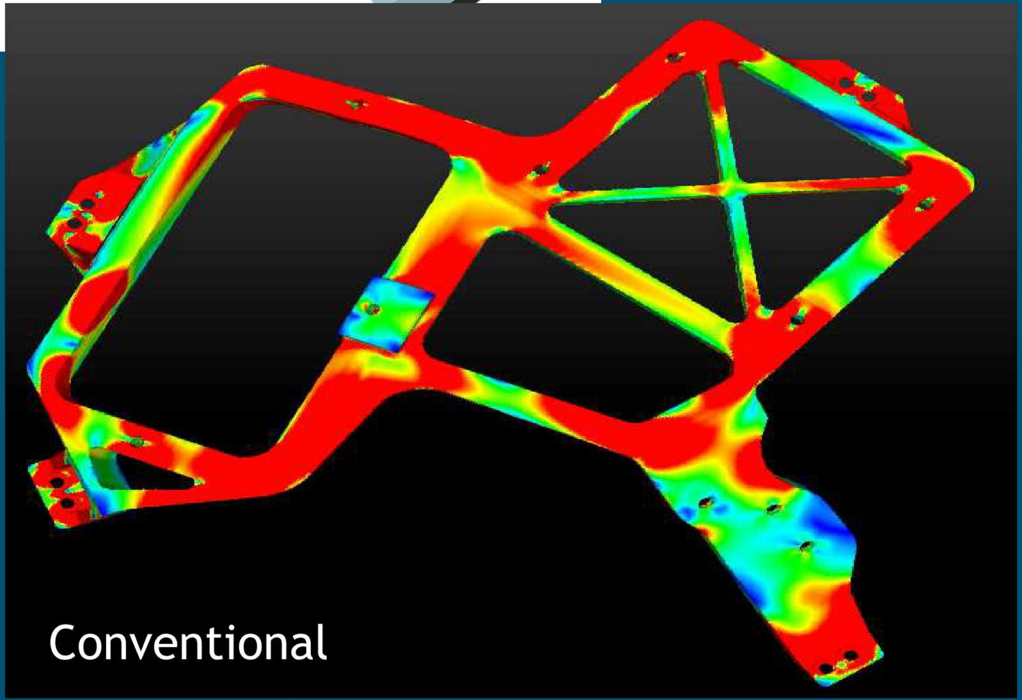
Initial Design

Optimized Design (32%↓)

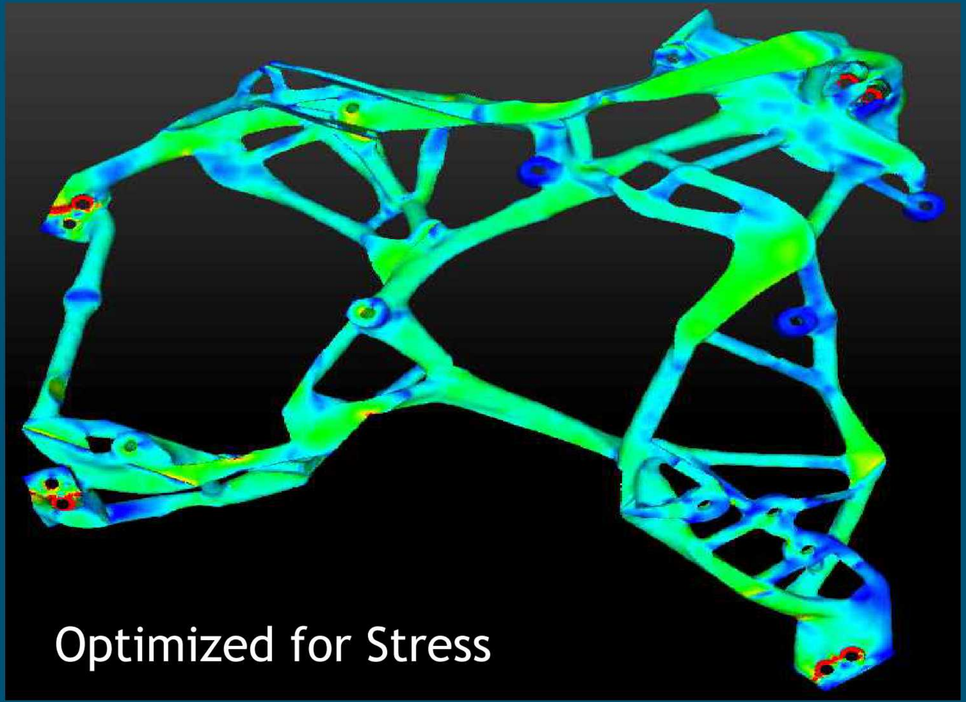
Local Constraints

New PLATO capability for locally constraining quantities of interest (like stress) during optimization

(stress plot showing stress hot spots as red)



Conventional



Optimized for Stress

Summary

Approach: compose objectives that reflect details of the print process so designs can be computed that i) exhibit superior printability, and ii) meet essential performance requirements.

Progress:

- Stabilized two-field formulation
- Implemented forward and adjoint problems
- Comparison with finite difference shows good agreement
- Initial performance is encouraging
- Local state residual implemented and thoroughly unit tested

Current effort:

- Integrate stabilized two-field residual and local state residual for non-linear transient thermomechanics
- Experiments: hole drilling w/ digital image correlation
- Implement layer hatching for super-layer deposition
- Differentiable support structure

source: github.com/platoengine

Contact Plato3D-help@sandia.gov