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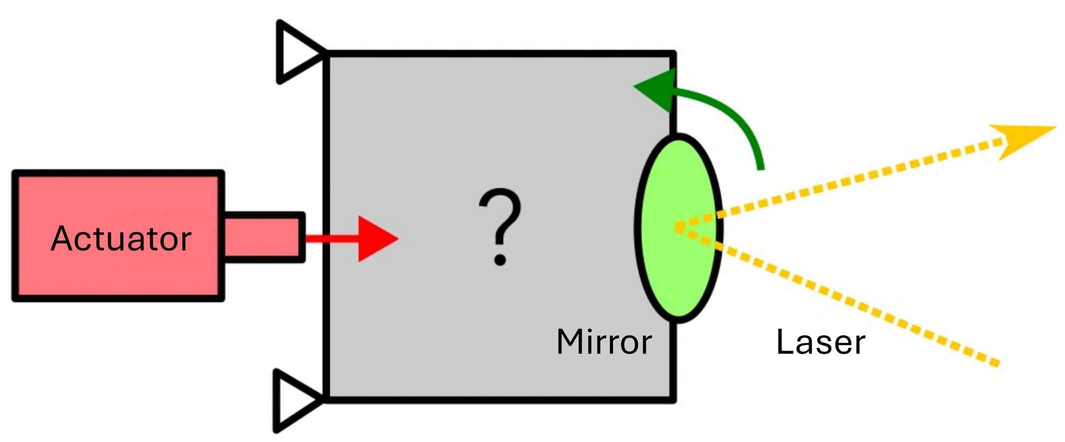
Design of Compliant Mechanisms via Truss and Frame Topology Optimization

Introduction

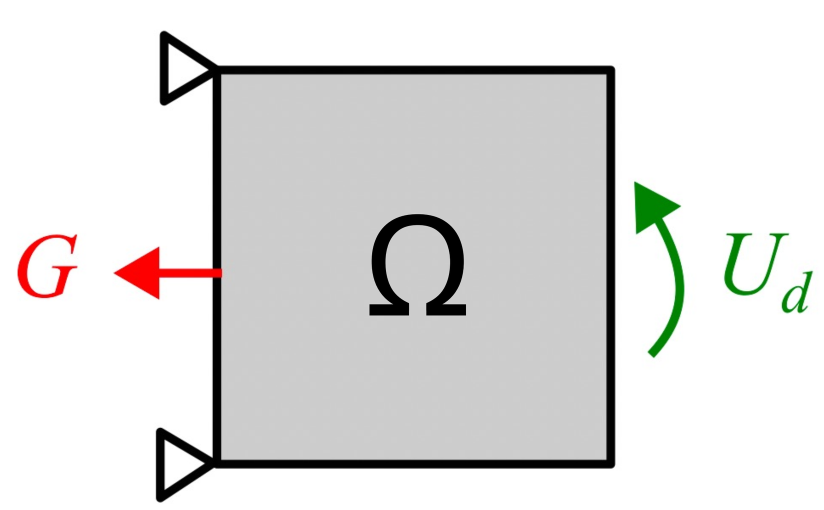
Compliant mechanisms achieve desired motions by elastic deformation. They are ideal for precision applications because they have little friction and require less assembly.



One example is a mechanism that precisely rotates a mirror using a linear actuator. This is often used in additive manufacturing or communication systems.

Problem Statement

$$\min_{x} \sum_{i \in D} (U_{d_i} - U_i)^2$$
$$\text{s.t. } \sigma_Y - (\sigma_{\mathrm{VM}})_i \geq 0 \quad \forall i \in \{1, 2, \ldots, n\}$$
$$G_i = U_i \quad \forall i \in P$$



Minimize the error of desired displacements under a displacement load, without yielding the material

Methods

Frame vs truss elements

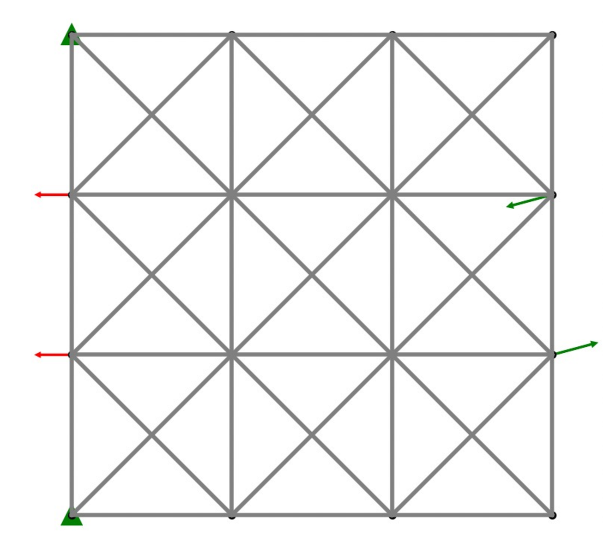
$$\begin{bmatrix} f_{x_1} \\ f_{y_1} \\ m_{z_1} \\ f_{x_2} \\ f_{y_2} \\ m_{z_2} \end{bmatrix} = \frac{wE}{L} \begin{bmatrix} t & 0 & 0 & -t & 0 & 0 \\ 0 & \frac{t^3}{L^2} & \frac{t^3}{2L} & 0 & -\frac{t^3}{L^2} & \frac{t^3}{2L} \\ 0 & \frac{t^3}{2L} & \frac{t^3}{3} & 0 & -\frac{t^3}{2L} & \frac{t^3}{6} \\ -t & 0 & 0 & t & 0 & 0 \\ 0 & -\frac{t^3}{L^2} & -\frac{t^3}{2L} & 0 & \frac{t^3}{L^2} & -\frac{t^3}{2L} \\ 0 & \frac{t^3}{2L} & \frac{t^3}{6} & 0 & -\frac{t^3}{2L} & \frac{t^3}{3} \end{bmatrix} \begin{bmatrix} u_{x_1} \\ u_{y_1} \\ u_{\theta_1} \\ u_{x_2} \\ u_{y_2} \\ u_{\theta_2} \end{bmatrix}$$

Frame elements account for moments and shear forces between elements. This describes the compliant behavior more accurately.

Setup

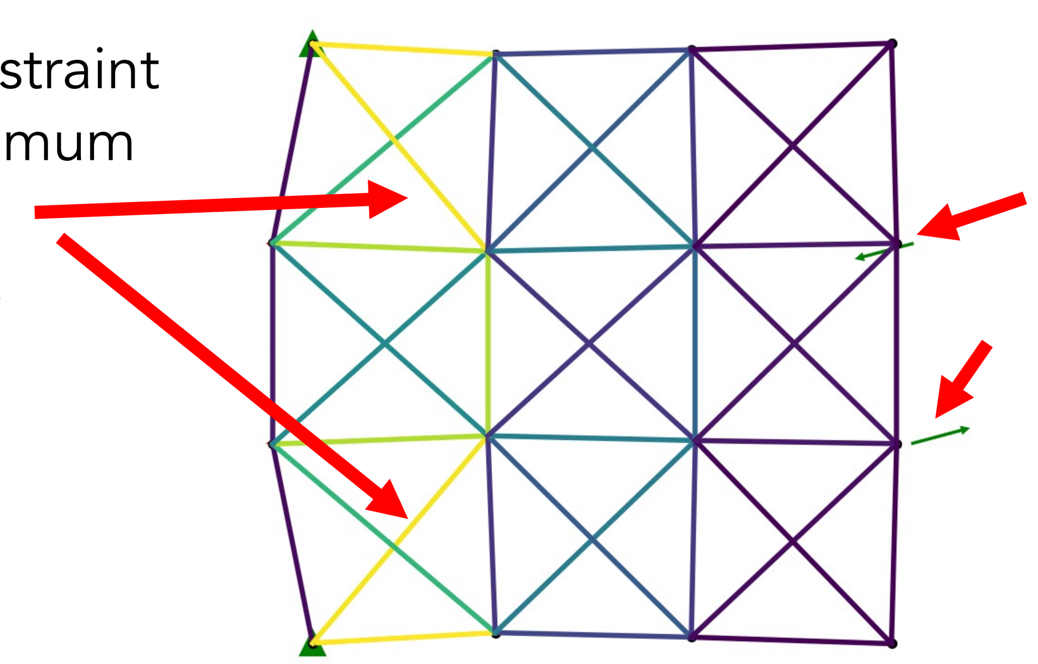
The truss is a 3x3 local ground structure with 42 elements. Two nodes are pinned, two have a prescribed displacement, and the rotation is described by two desired displacements.

The effective F is calculated based off the prescribed displacements.



Stress constraint

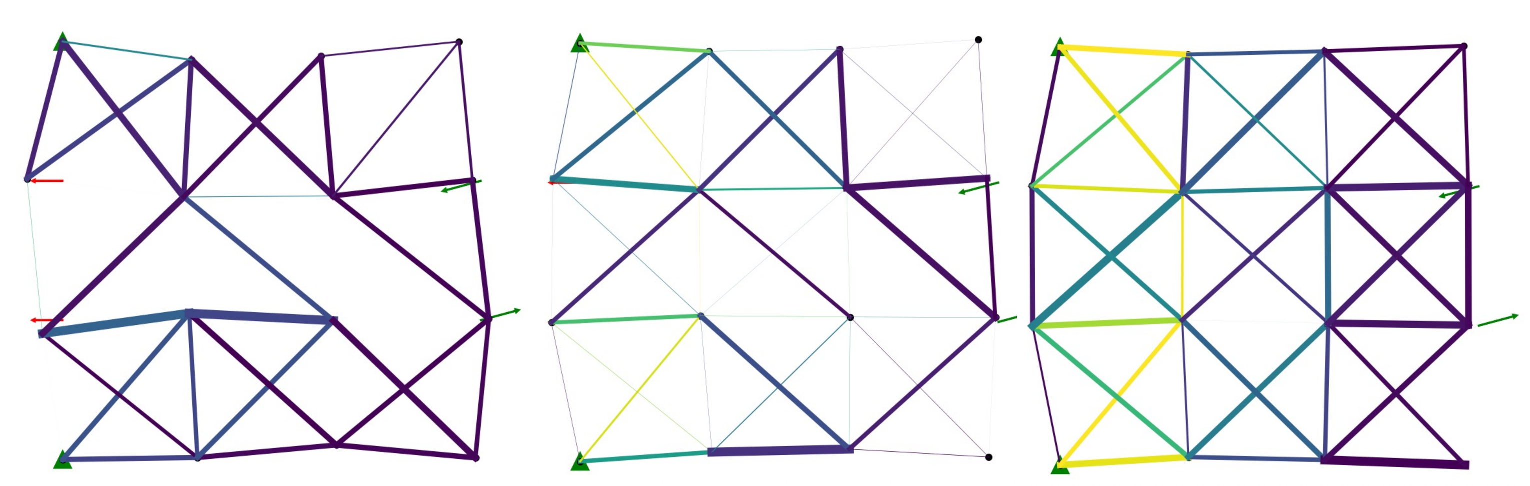
The stress constraint limits the maximum stress below material limits. No volume constraints.



Objective function

The objective function measures the squared error from the desired displacements

Initialization



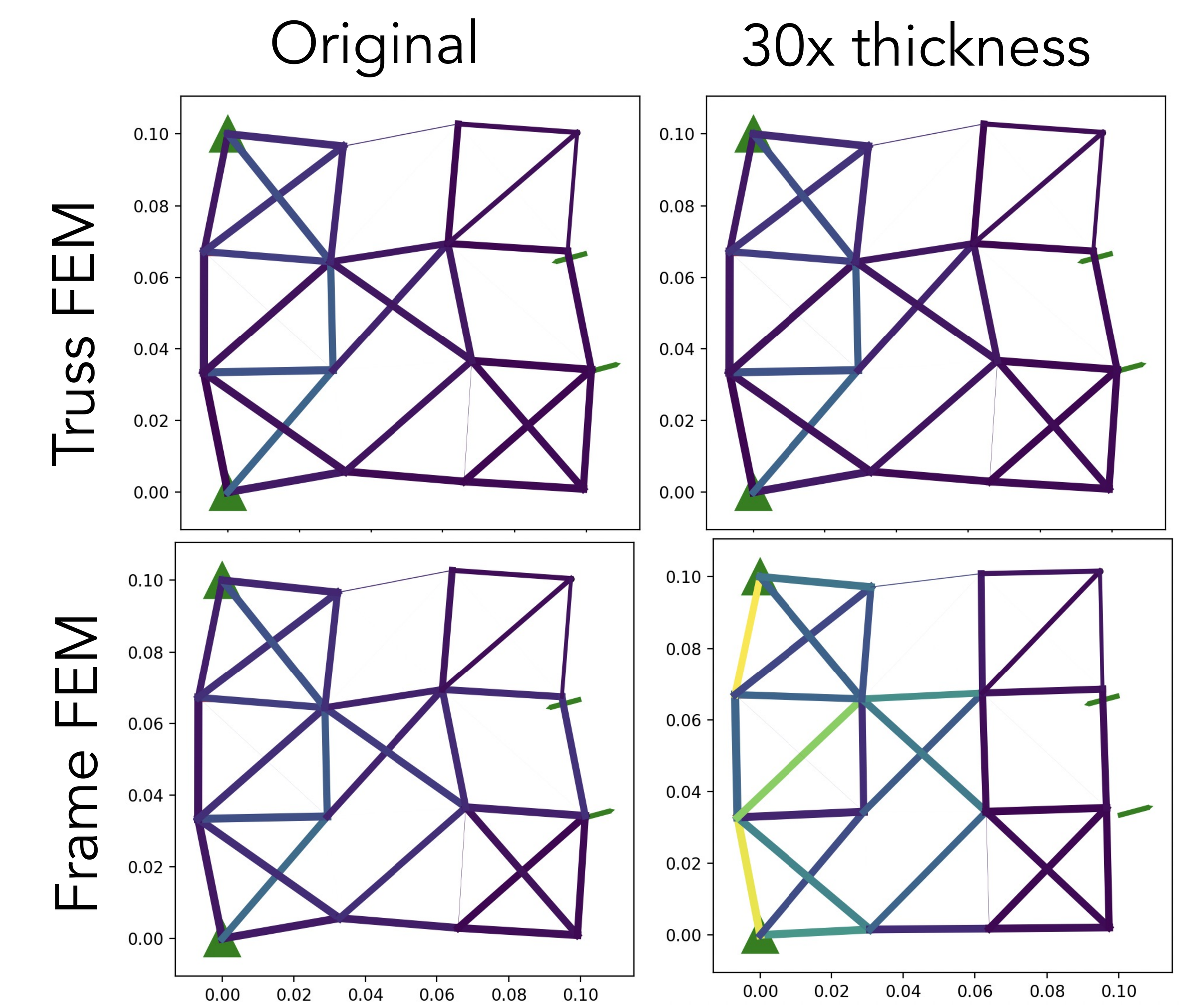
Initial thickness: 10^{-8} Initial thickness: 10^{-6} Initial thickness: 10^{-4}

Without a volume constraint, the solver is sensitive to the initial thickness. Smaller values tend to perform better.

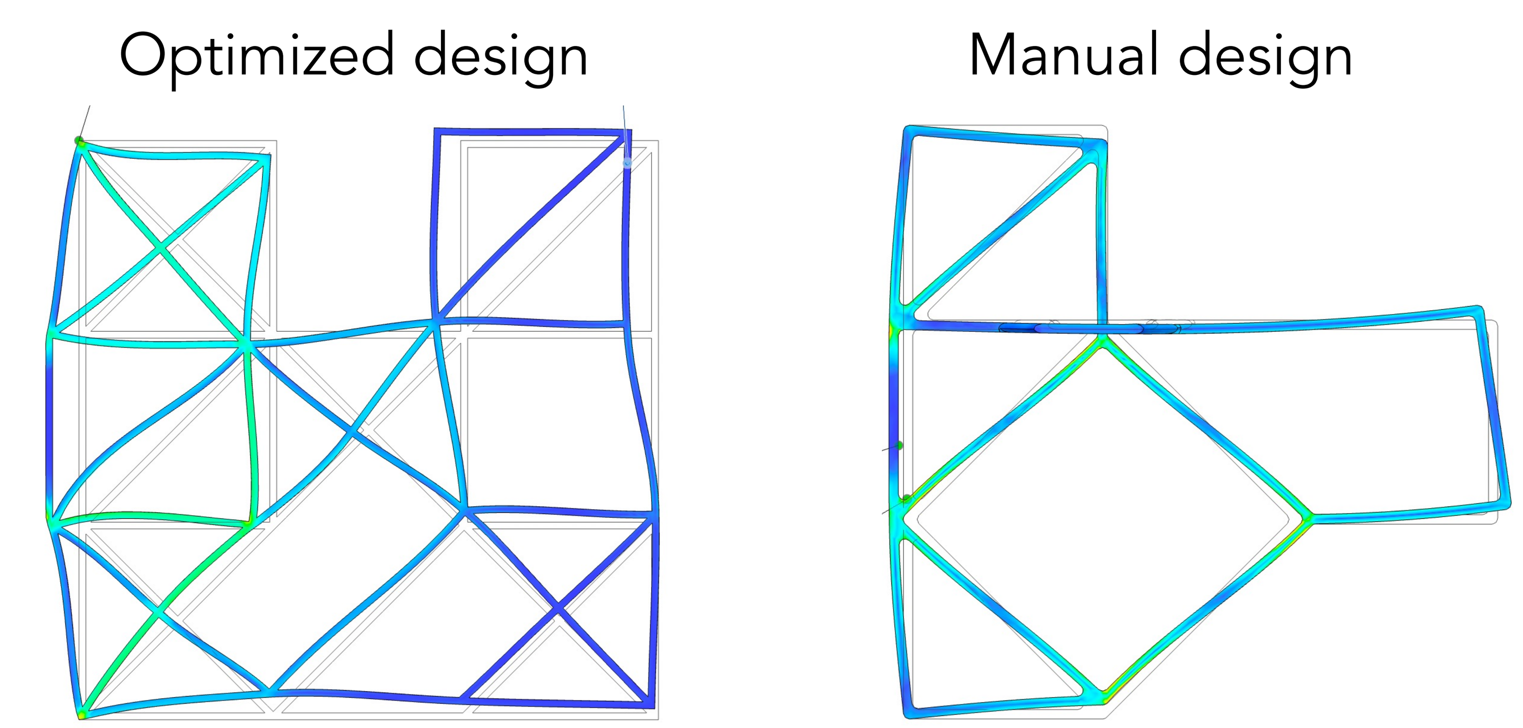
Results

The frame does not scale well with thickness. With thicker elements, bending effects dominate and are hard to optimize for.

Stress and thickness are plotted as normalized



Validation



Comparison of structures simulated in Fusion 360. The manual design has a non-local ground structure element. Both successfully rotate as intended.

Conclusions

- Truss/frame optimization needs less computation than continuum optimization
- Trusses are easier to optimize and are a reasonable approximation for thin frames.
- Initial conditions can greatly affect the results
- Some mechanisms are not possible with topology optimization