NUMERICAL TOOLS FOR TOPOLOGY OPTIMIZATION OF COMPUTATIONAL METAMATERIAL DESIGNS

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Motivation

- Millions of dollars are wasted every year in fuel consumption in the aerospace and automotive industry, this being directly related to the total weight of the vehicles. Consequently, the *reduction of their weight* becomes *crucial* in order to reduce both the *cost of materials* and the *cost of their operation*, while maintaining certain properties.

Economic savings / Reduction in material costs / Reduction in CO_2 emissions / Reduction in fuel consumption / Reduction in total weight

- *Optimal topologies* can be computed via **Topology optimization techniques**, which determine, from a mathematical standpoint, the *optimal position and shape of the corresponding voids* in a predefined design domain, without requiring the interaction of an engineer.

- **Topology Optimization** has become an active research field to seek *new, non-intuitive optimal designs* in a wide range of design problems governed by different physical problems: solid mechanics, thermal problems and acoustics, among others, requiring high computational resources.

- The aim of this work is the formulation and development of a **new topology optimization approach** which reduces the required computational cost, allowing to optimize complex industrial structures with manufacturability constraints in a reasonable amount of time.
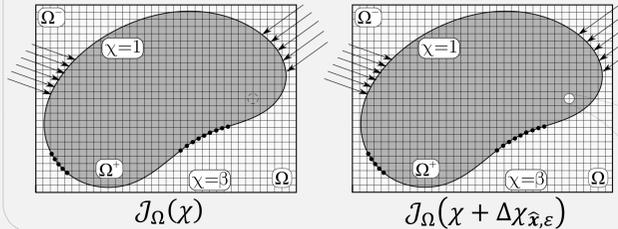

Formulation

The **topology optimization problem** is formulated as a *minimization of a cost functional* subjected to a *volume constraint* and governed by a state equation.

Initial design · Optimal design

Design domain
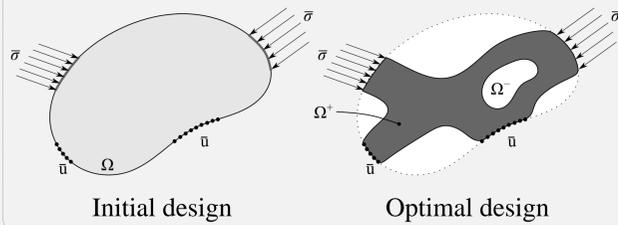
The **material domain**, Ω^+, is embedded in a fixed mesh and can be defined via the **characteristic function**, used as the *design variable*.

A new **Relaxed Topological Derivative** (RTD) evaluated as

$$\frac{\delta \mathcal{J}_\Omega(\chi)}{\delta \chi}(\hat{x}) = \lim_{\varepsilon \to 0} \frac{\mathcal{J}_\Omega(\chi + \Delta\chi_{\hat{x},\varepsilon}) - \mathcal{J}_\Omega(\chi)}{|\Omega_\varepsilon(\hat{x})|} = \frac{\partial j(\chi, x)}{\partial \chi} \Delta\chi(\hat{x})$$

$\mathcal{J}_\Omega(\chi)$ · $\mathcal{J}_\Omega(\chi + \Delta\chi_{\hat{x},\varepsilon})$

measures the change in *cost function* $\mathcal{J}(\chi)$ when a small area changes from one material (stiff) to another (void), being consistent with the *ersatz material approach*.

The **incremental-time-advancing scheme** provides the *Pareto Frontier of optimal solutions* with respect to the volume constraint, allowing the user to select the desired optimal design.
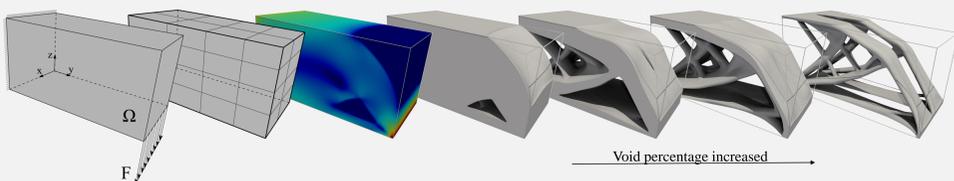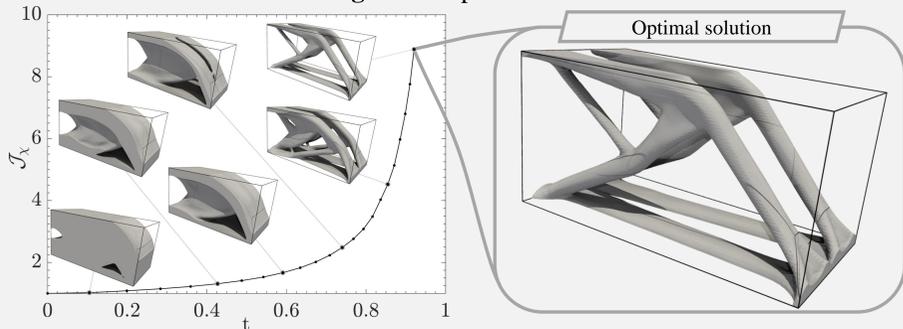
Cutting & Bisection Algorithm
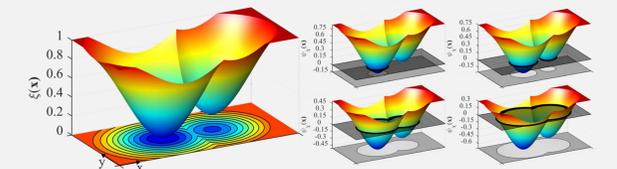
The **optimal topology** is obtained as the solution to a *closed-form optimality criteria*, fulfilling the target volume constraint via a *bisection algorithm*.
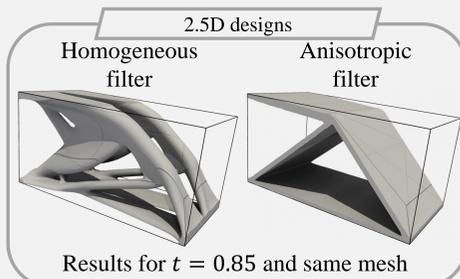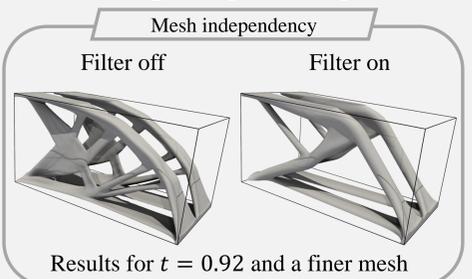
Structural problem

Topology optimization allows to find the optimal layout of a given structure that minimizes the *mean compliance* for a given *volume percentage*.


Void percentage increased

The **incremental-time-advancing scheme** provides the *Pareto Frontier*.

Optimal solution

Filter technique: *Laplacian regularization*

Mesh independency

Filter off · Filter on

Results for $t = 0.92$ and a finer mesh

2.5D designs

Homogeneous filter · Anisotropic filter

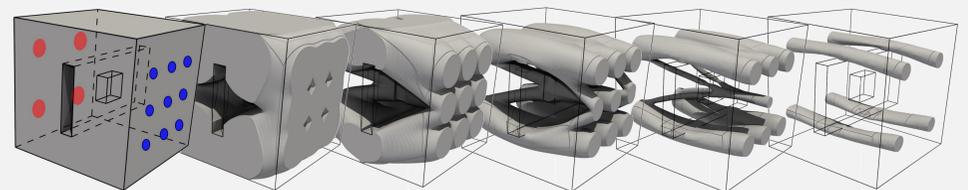Results for $t = 0.85$ and same mesh

Optimization of Compliant mechanisms: design of flexible structures to achieve a desired displacement at the *output port*.
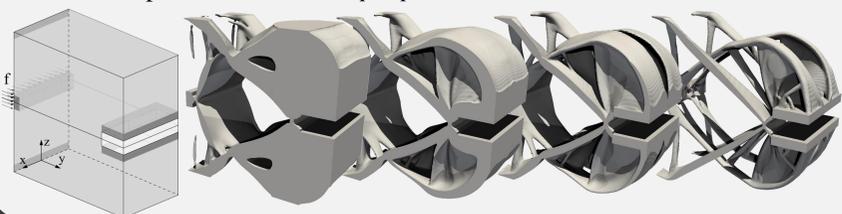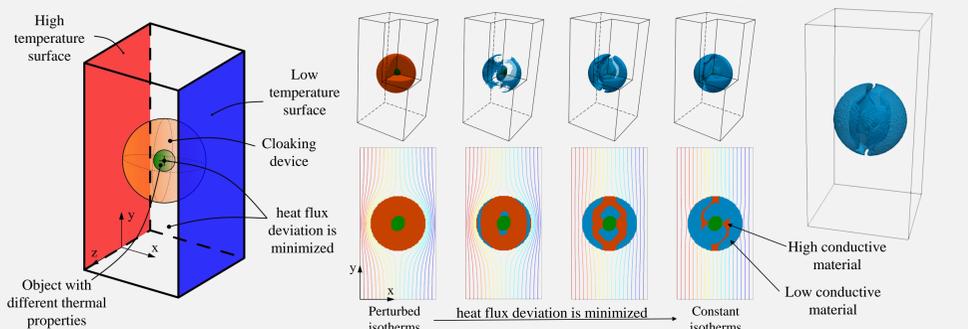

Thermal problem

**Heat conduction** is maximized in the structure for a given *volume percentage*.

Thermal cloaking: *Heat flux manipulation*
The object is cloaked from the exterior via manipulation of the heat flux by the cloaking device.

High temperature surface · Low temperature surface · Cloaking device · heat flux deviation is minimized · Object with different thermal properties · High conductive material · Low conductive material · Perturbed isotherms · heat flux deviation is minimized · Constant isotherms

Thermal cloaking: *Average and variance temperature minimization*
The thermal heat of a device is distributed by the cloaking device and dissipated through convection on the lateral surfaces to avoid being detected on the left surface.

Temperature average and variance are minimized · High temperature object · Cloaking device
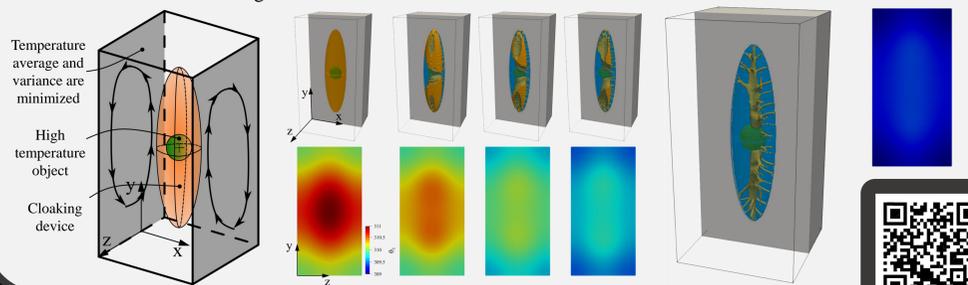
Conclusions

- The present method is up to **10 times faster** than the equivalent *Level-set method*, when using an *incremental-time-advancing scheme*.

- **Smooth black-and-white designs** with *minimum filament size control* are obtained, improving manufacturability compared to other approaches.