topoptlab: An Open and Modular Framework for Benchmarking and Research in Topology Optimization

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Software

- Review
- Repository
- Archive

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Summary

Topology optimization (TO) is becoming increasingly popular across physics, engineering, and materials science, as it provides a systematic way to discover efficient designs. Given a set of bounded design variables $x_{\text{min}} \leq x_e \leq x_{\text{max}}$ and a cost or objective function $C(x)$, subject to a discretized physical problem $K(x)u = f$ as well as a set of m equality and n inequality constraints, the general TO problem can be formulated as

$$\begin{aligned} &\min_{x} \; C(x) \\ &\text{subject to:} \\ &\quad K(x)u = f, \\ &\quad g_i(x) = 0, \quad i = 1, \dots, m, \\ &\quad h_j(x) \leq 0, \quad j = 1, \dots, n, \\ &\quad x_{\text{min}} \leq x_e \leq x_{\text{max}}, \quad \forall e \in \text{elements}. \end{aligned}$$

The common TO choice of design representation is a density-based material interpolation scheme, where the abstract design variables x_e become relative element-wise densities which scale the physical properties A of each element via simple relationships as in the popular modified SIMP approach (Sigmund, 2007):

$$A(x_e) = A_{min} + (A_0 - A_{min}) x_e^k \text{ with } 0 \leq x_e \leq 1$$

where k is a penalization factor ensuring densities close to 0 or 1, A_0 is the property of the full material and A_{min} is a small value to prevent singularities in the physical problem. The final design then emerges from the optimal density distribution.

Topoptlab is a modular and transparent framework for research and benchmarking in topology optimization with a focus on clarity, reproducibility, and accessibility as a tool for both research and advanced education.

Statement of need

In TO, it has become longstanding practice to demonstrate new methods with short Matlab scripts (Andreassen et al., 2011; Ferrari & Sigmund, 2020; Sigmund, 2001; Wang et al., 2021). While these codes have played an important role in the spread and development of ideas, they also come with notable limitations: First, Matlab requires a commercial license, and is only partially compatible with its free alternative Octave. Second, extension and combination of state-of-the-art methods demands combining multiple monolithic scripts, some of which are outdated or mutually incompatible. Third, while modern finite element frameworks such as **FEniCS** (Alnæs et al., 2014; Baratta et al., 2023; Scroggs, Dokken, et al., 2022; Scroggs, Baratta, et al., 2022), **deal.II** (Arndt et al., 2021), and **ElmerFEM** (Malinen & Råback, 2013) provide powerful high-performance environments, their abstraction layers tend to complicate access to low-level implementation details which is necessary for research in TO. Examples of standard TO tasks with the need to access low-level data structures are the update of the element stiffness matrices $K_e(x)$ based on the design variables x, calculation of the sensitivity of the element matrices with respect to the design variables $\frac{\partial K_e}{\partial x}$, and access to the global stiffness matrix for solving the adjoint problem to derive the gradients. Also, common use cases in TO allow shortcuts such as regular meshes as ideally the geometry emerges during the optimization process or partial negligence of close to empty elements as preconditioning.

Topoptlab was developed to address these challenges by providing a stable and extensible environment tailored to the needs of the TO community. It serves as a library for writing complete problems from scratch in spirit of the already conventional Matlab scripts, and offers a high-level driver routine (`topology_optimization`) in which users can exchange components (filter, objective function, etc.) by passing custom callables or objects as arguments. It may also serve as a reference implementation which can be used as test case for existing HPC codes that want to incorporate TO in their software. An example demonstrating the topology_optimization routine, as well as links to from-scratch implementations, are available in the `README.md` while tutorials, derivations and explanations of the background of TO are in the documentation. A more extensive list of examples can be found in the `examples` section of the repository.

Topoptlab offers the components needed for TO such as different material interpolation schemes (SIMP, RAMP, and bound-based interpolation), filters for regularization (Bruns & Tortorelli, 2001; Sigmund, 1997), projections (Guest et al., 2004; Sigmund, 2007; Xu et al., 2010) and manufacturability (Langelaar, 2017), and finite element implementations for different physical problems (linear elasticity, heat conduction, etc.) with both standard numerical integration and analytically integrated elements generated through *Symfem* (Scroggs, 2021). Constrained optimization is supported through the Method of Moving Asymptotes (MMA) (Svanberg, 1987), the Globally Convergent Method of Moving Asymptotes (GCMMA) (Svanberg, 2002) as implemented in Deetman (2025), as well as the Optimality Criteria (Andreassen et al., 2011; Bendsoe & Sigmund, 2003), while the solution of the system of equations is done via routines offered by *scipy* (Virtanen et al., 2020), *cvxopt* (Andersen et al., 2020), and also custom implementations of preconditioners like algebraic multigrid or block-preconditioners. Finally, *Topoptlab* offers a number of introductory articles with comments on implementation and contains monolithic scripts that serve as teaching tools as well as an archive for Python translations of important Matlab teaching codes (e.g., Andreassen et al., 2011; Andreassen & Andreasen, 2014).

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