Modular-Topology Optimization: Towards Performant and Reusable Designs

Martin Doškář*†[1], Marek Tyburec[2], Michael Somr[2], Martin Kruzik[3], and Jan Zeman[1]

[1]Czech Technical University in Prague (CTU) – Zikova 1903/4, 166 36 Prague 6, Czech Republic
[2]Czech Technical University in Prague – Czech Republic
[3]Institute of Information Theory and Automation of the Czech Academy of Sciences – Czech Republic

Abstract

Modularity has long been a fundamental design paradigm in civil and mechanical engineering. However, optimization algorithms for modular structures have only recently begun to emerge. This lag is partly due to the fact that single-scale optimisation of both modules and their layouts requires addressing two main questions simultaneously: (1) what should the topology of individual modules look like, and (2) how should these modules be arranged in the final design? Especially the second question poses a challenge due to its combinatorial nature.
We address these challenges with a modular-topology optimization framework designed to produce structures and mechanisms that balance high performance with sustainability and reusability. In prior work on truss-like modular structures (1), we utilized the convex formulation of truss topology optimization for module design and meta-heuristics for module arrangement, resulting in a bi-level staggered scheme. However, extending this approach to continuum-like modules presents two key obstacles: (i) the lack of an efficient convex formulation, making module arrangement comparison non-deterministic, and (ii) the high computational cost of fine continuum finite-element representations.

To overcome these limitations, we propose a sequential optimization strategy (2). Our method begins with free material optimization, which determines the optimal distribution of material stiffness across the design domain while suppressing numerical artifacts like checkerboarding. The optimized stiffness tensors pertinent to positions of future modules are then segmented into distinct regions using a deterministic clustering algorithm, which defines the layout of modular components. Finally, the topology of each module is optimized using a standard density-based topology optimization strategy with variable linking scheme employed to achieve desired mechanical properties while using the initial free material optimization results as a starting point.

To ensure the modules can be manufactured and assembled effectively as a single piece, we incorporate additional constraints to (i) maintain connectivity and (ii) account for potential fabrication inaccuracies using a three-field projection technique (3). We showcase the full design process of modules capable of being assembled into two distinct compliant mechanisms: an inverter and a gripper, including an experimental validation. Our results represent the beginning of a broader exploration into modular-topology optimization, with significant

*Speaker
†Corresponding author: Martin.Doskar@cvut.cz

opportunities for further refinement and application in complex engineering systems.

Acknowledgement

This research has been supported by the European Union under the project ROBOPROX (reg. no. CZ.02.01.01/00/22 008/0004590).

References:

(1) Tyburec, M., Zeman, J., Doškář, M., Kružík, M., & Lepš, M. (2021). Modular-topology optimization with Wang tilings: An application to truss structures. *Structural and Multidisciplinary Optimization*, *63*(3), 1099–1117. https://doi.org/10.1007/s00158-020-02744-8

(2) Tyburec, M., Doškář, M., Zeman, J., & Kružík, M. (2022). Modular-topology optimization of structures and mechanisms with free material design and clustering. *Computer Methods in Applied Mechanics and Engineering*, *395*, 114977. https://doi.org/10.1016/j.cma.2022.114977

(3) Tyburec, M., Doškář, M., Somr, M., Kružík, M., & Zeman, J. (2025). Modular-topology optimization for additive manufacturing of reusable mechanisms. *Computers & Structures*, *307*, 107630. https://doi.org/10.1016/j.compstruc.2024.107630