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Three-Dimensional Multiscale Design Using Neural Net Surrogate Models of Lattice Material Response

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Topology optimization is a methodology for assigning material or void to each point in a fixed design domain in a way that extremizes some objective function, such as the stiffness of a structure under given loads, subject to various imposed constraints, such as an upper bound on the mass of the structure. This generative design approach has been used to design both macro-structures, such as bridges, as well as lattice micro-structures, comparable to the familiar octet truss architecture. In both settings, the structural response is evaluated with the continuum finite element method, and a design sensitivity analysis provides the first-order derivatives of the objective and constraint functions to a gradient-based optimization algorithm, which iteratively updates the design to improve its performance.

Even with today's supercomputers, it is generally not feasible to design both the macrostructure and microstructure simultaneously on the same computational mesh; the necessary spatial resolution and domain size require too great a computational cost. Thus, multiscale topology optimization methods use some form of information mapping between the scales, enabling separate, smaller analyses at each scale. Homogenization is the most common mapping in the linear elastic regime we are interested in. Except in the case of certain specialized microstructures, e.g. ranked laminates, homogenization still requires solution of the elasticity PDE for several assumed test strains for each different microstructural design, and thus the overall design problem can still be quite costly, especially in three dimensions.

Our solution to reduce the overall computational cost of the multiscale topology optimization design problem is to generate neural net surrogate models of the homogenized microstructural response. Our particular interest is in open truss micro-architectures, which can be described in a very low-dimensional manner as a union of rods with given endpoint locations and cross-sectional diameters. Fixing the endpoint locations within a unit cell reduces the dimensionality further and guarantees a priori structural continuity from one unit cell to another. We translate the micro-architecture to a finite element mesh of the unit cell with a geometric projection approach. Adaptive mesh refinement of the mesh results in a very accurate translation as well as a very accurate calculation of the homogenized response. The off-line expense of creating the surrogate models is amortized over the solution of many design problems.

We generate a separate model for each of the 21 independent components of the homogenized elasticity tensor, as well as the volume fraction occupied by solid material (the balance is void space). These surrogate models are very fast to evaluate, enabling efficient design of the macrostructure while retaining accurate microstructural response, and additionally enable recovery of the full microstructure when the design is complete. We have generated surrogate models for a number of open truss micro-architectures, including the octet truss, ORC truss, and isotruss. We demonstrate our multiscale design capability via minimal-compliance designs on domains with millions of macro elements.

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