Data-driven Design Of Heterogeneous Metamaterial System

Northwestern University

Northwestern McCORMICK SCHOOL OF ENGINEERING

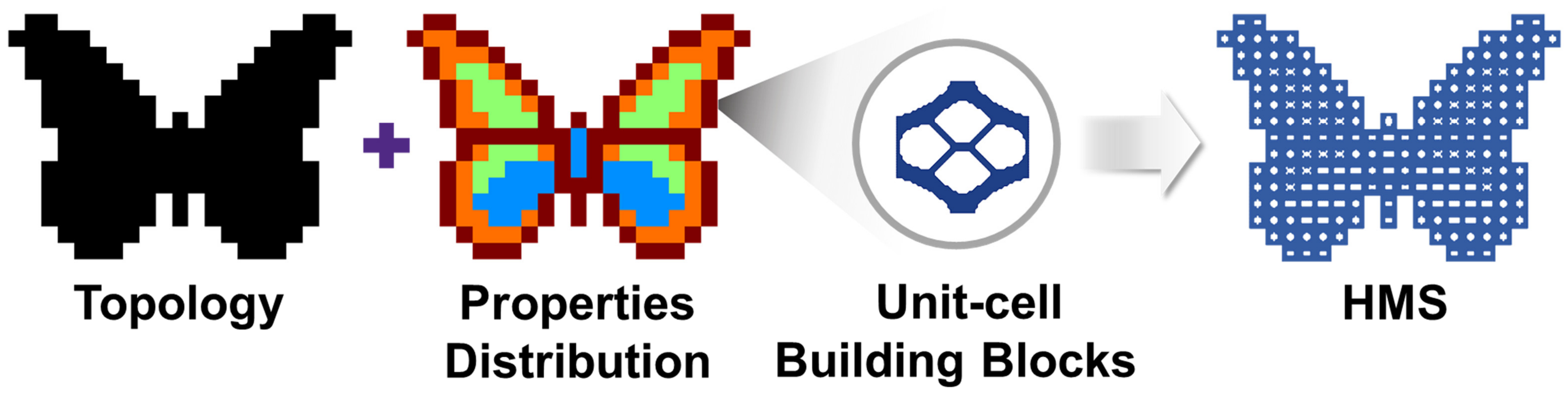
Liwei Wang[1,2], Wei (Wayne) Chen[2], Wei Chen[2*]

1. Department of Mechanical Engineering, Northwestern University
2. School of Mechanical Engineering, Shanghai Jiao Tong University

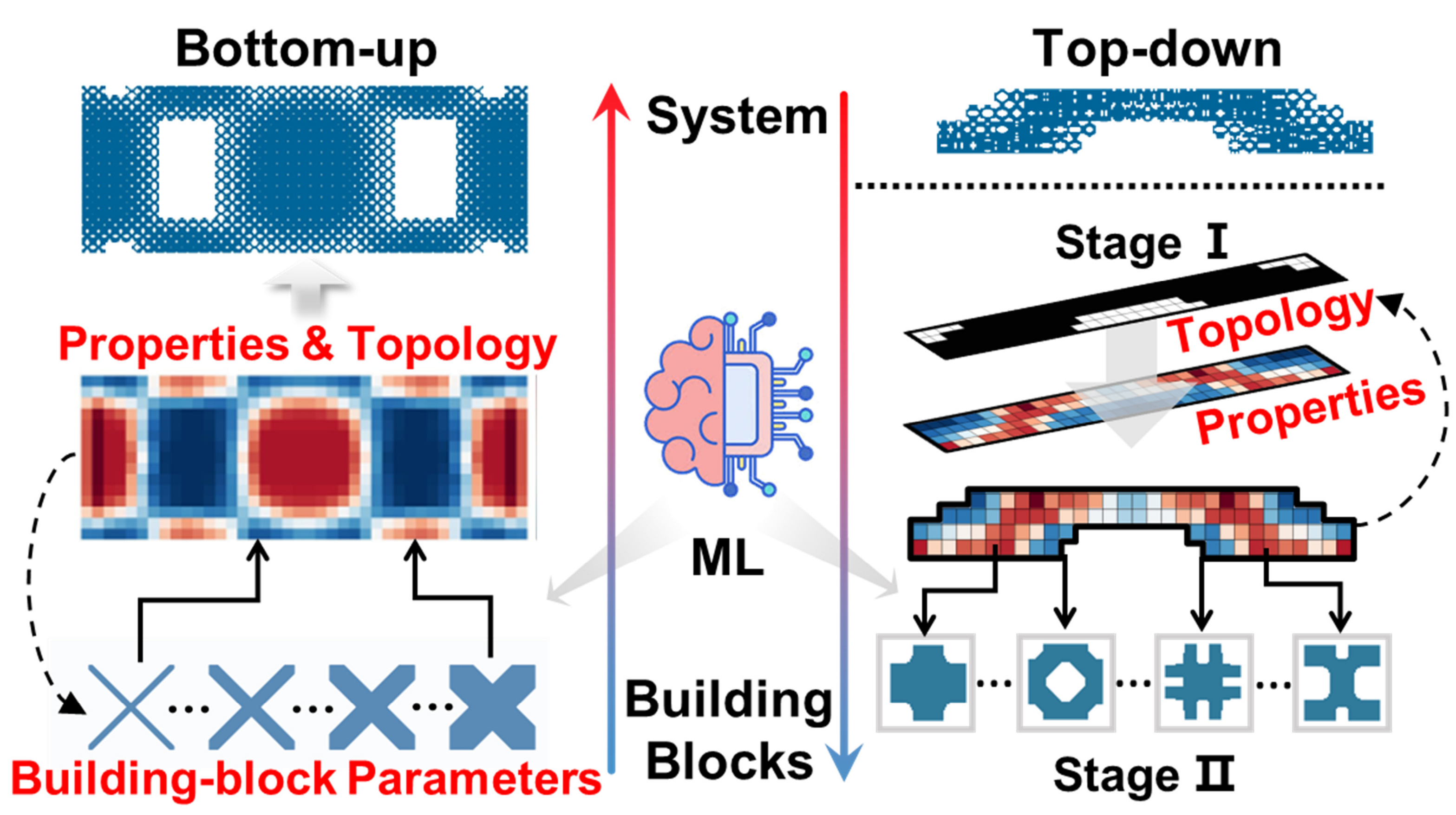
E-mail : weichen@northwestern.edu

Introduction

Heterogenous metamaterial system (HMS) assembles aperiodic unit-cells together to achieve spatially-varying properties, which are desirable and critical for complex engineering functions.



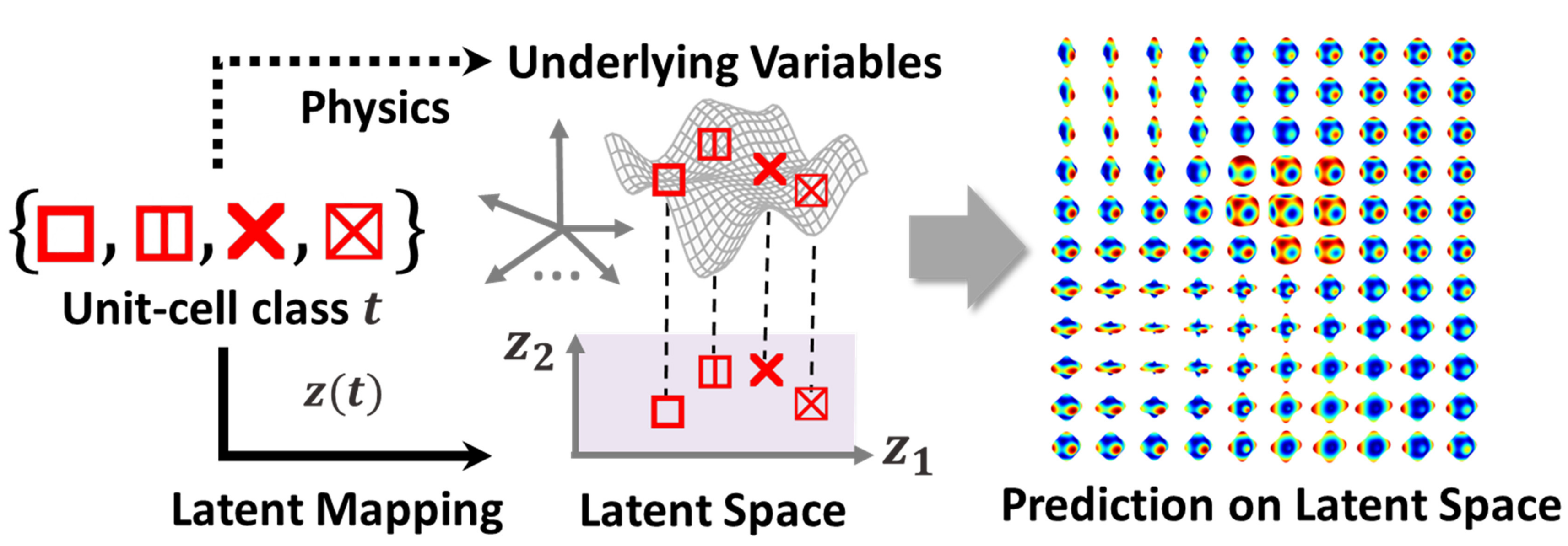
Motivation: HMS design turns out to be an intricate process that suffers from the infinite-dimensional topological design space, mixed-variable optimization, the complex cross-scale mapping, and an exhaustive computational cost.



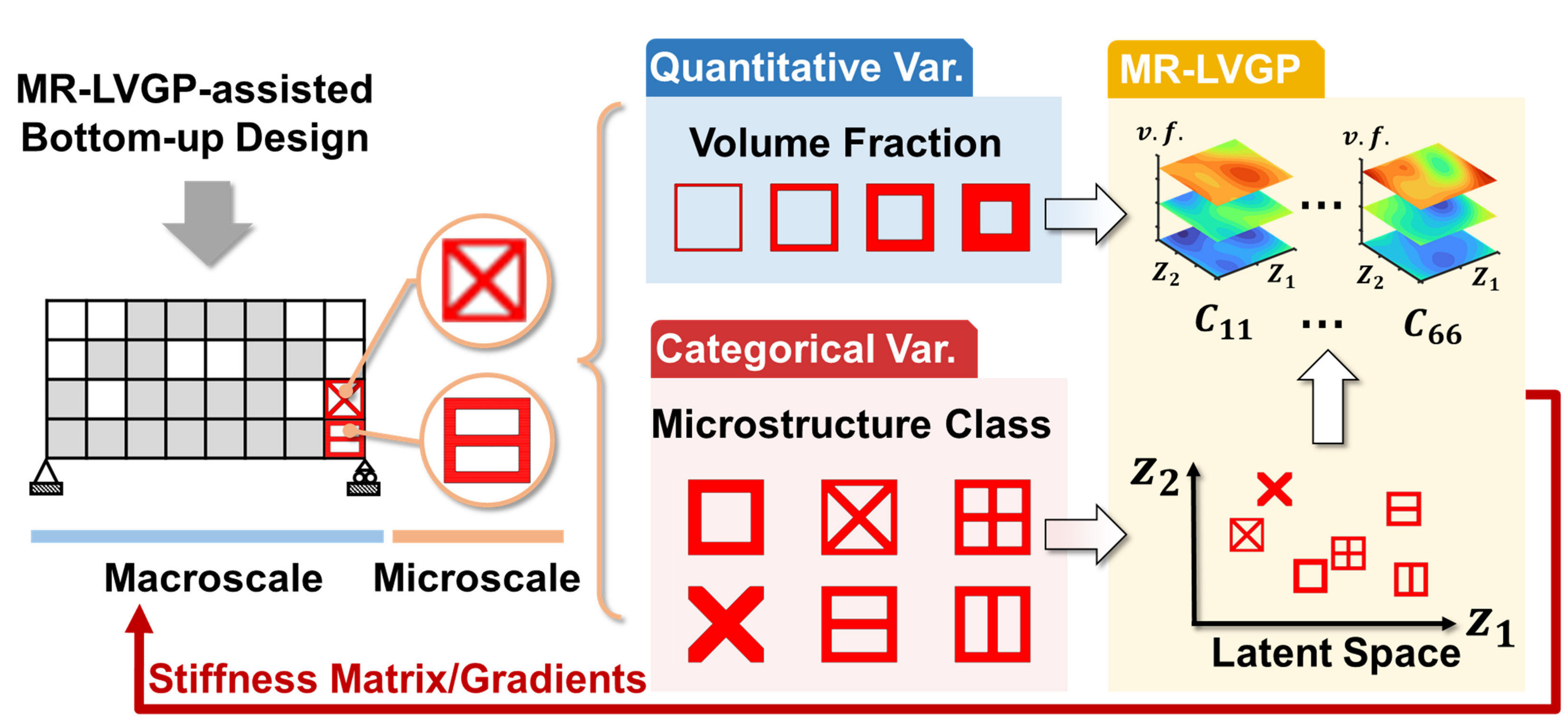
Contribution: We develop two data-driven design frameworks, i.e., bottom-up and top-down frameworks, that exploit latent-variable machine learning models to facilitate and expedite the design of HMS.

Bottom-up Framework

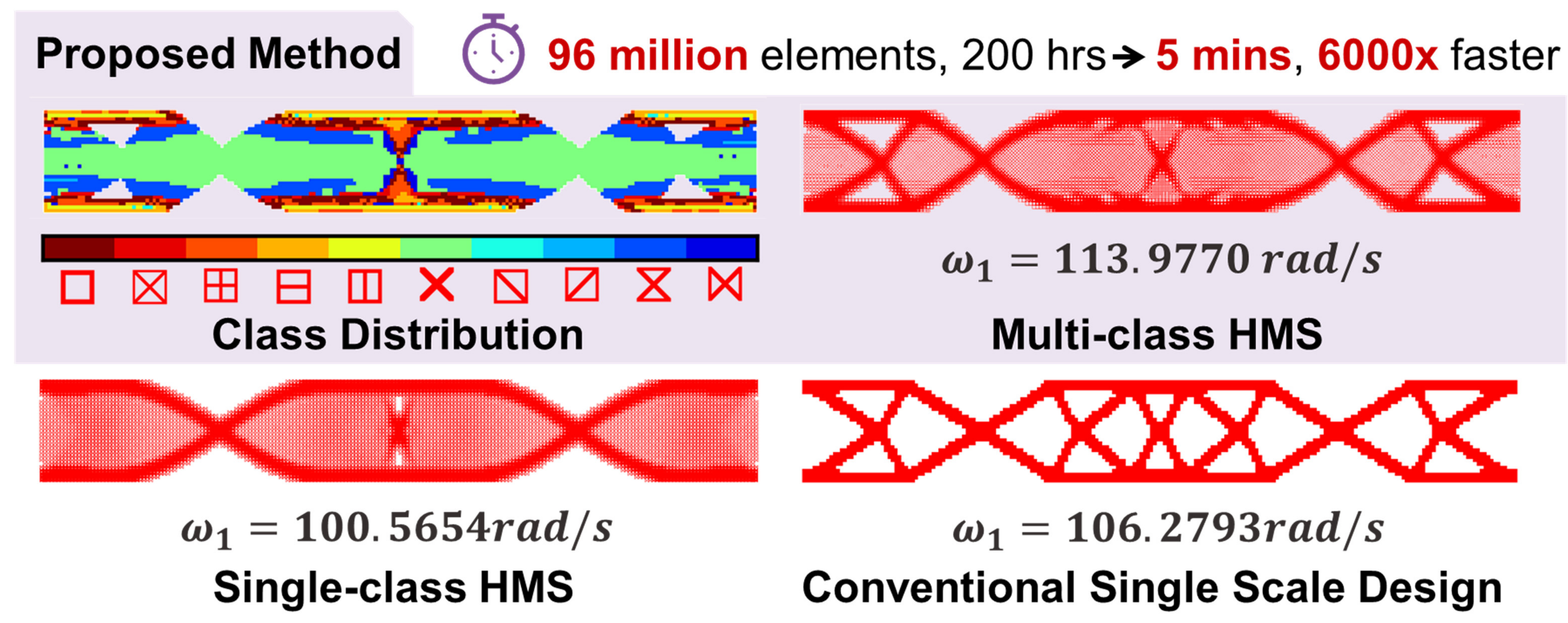
1. **Multi-response Gaussian Process (MR-LVGP)** to map different classes into a continuous latent space, inducing a distance metric to capture their correlation.



2. With MR-LVGP models to provide effective stiffness and gradients, **data-driven topology optimization** is proposed to enable concurrent exploration of unit-cell classes and the associated geometric parameters.

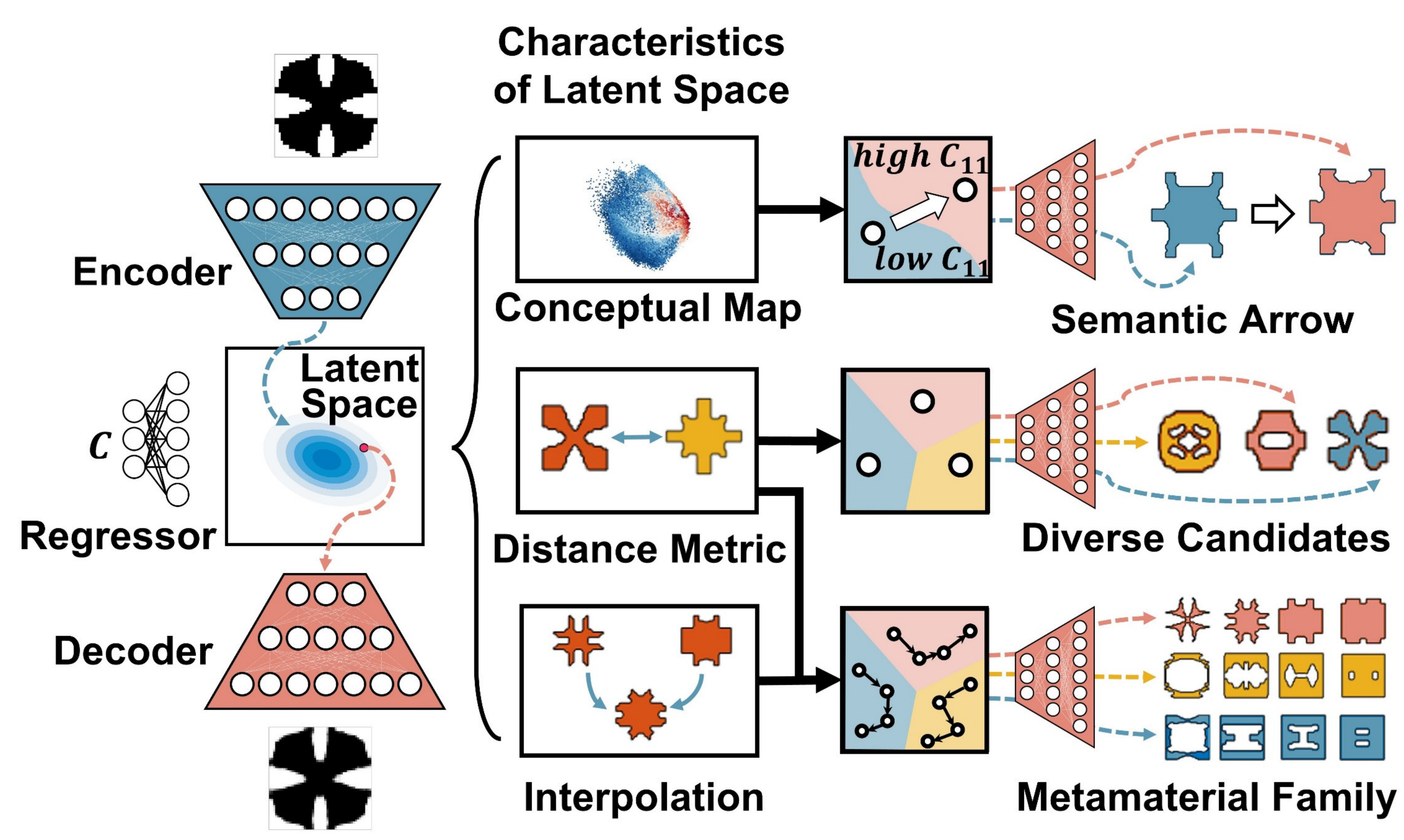


3. The method is **applied to both static and dynamic cases**, such as maximizing the natural frequencies. It generates multiclass HMS that outperforms both single-class and single-scale designs, increasing the efficiency by over 6000 times.

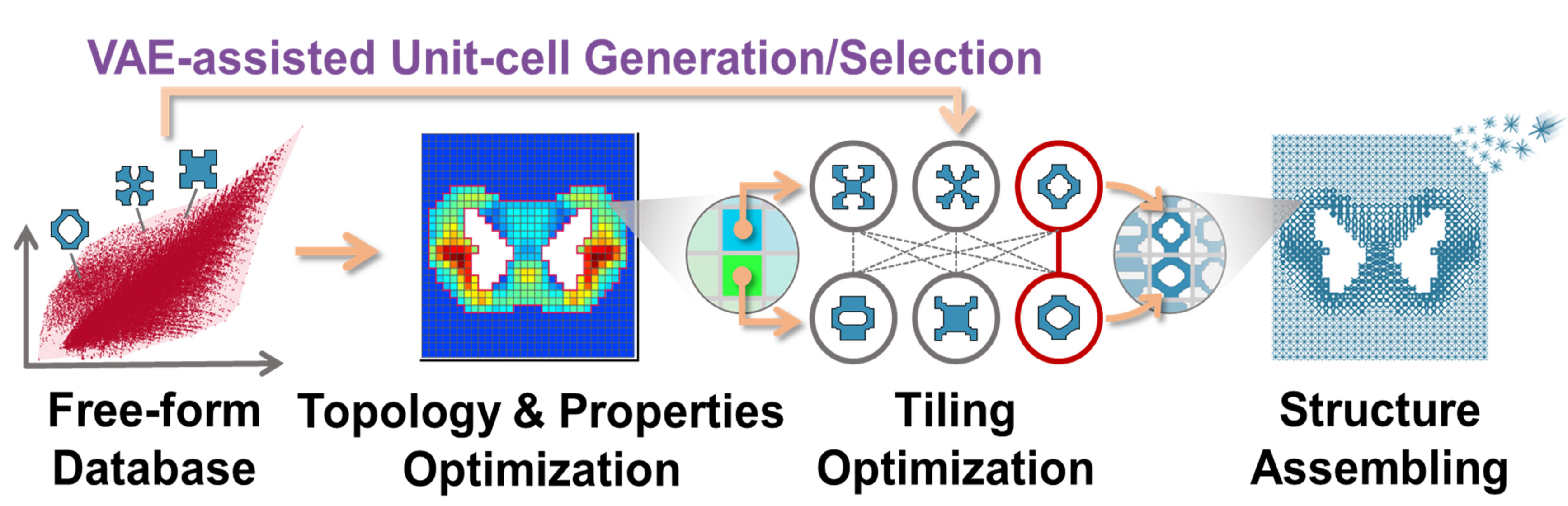


Top-down Framework

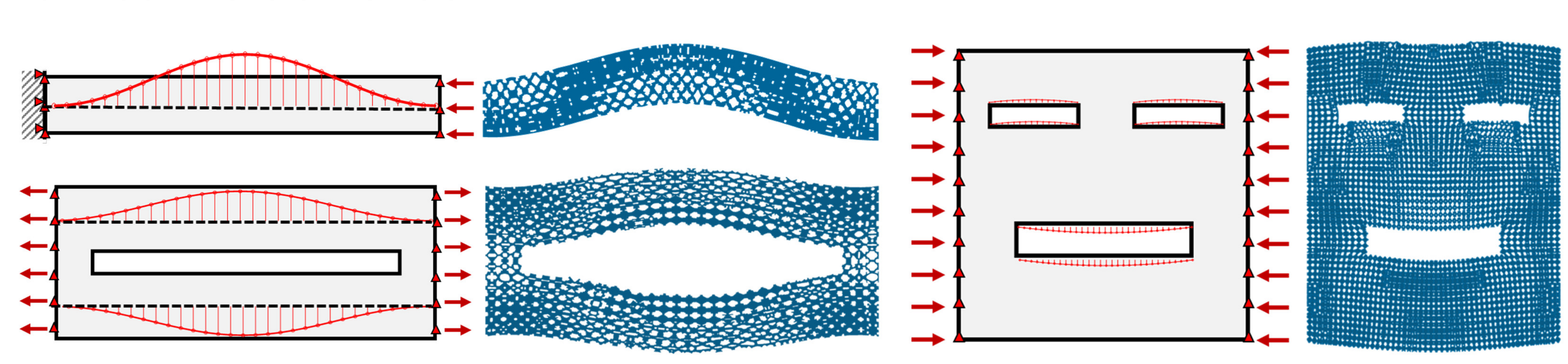
1. **Variational autoencoder (VAE)** combined with a regressor to map unit cells into a low-dimensional latent space. The latent space encodes rich mechanical information and serves as a control panel for metamaterial design.



2. **An integrated top-down framework** is proposed for efficient aperiodic HMS design. It begins with a concurrent optimization of topology and properties distribution, followed by a tiling optimization to assemble unit cells in a compatible way.



3. It is applied to design HMS with target displacement profiles. Although with millions of finite elements, HMS designs can be obtained within hours with compatible tiling, which was previously difficult to achieved.



Conclusions

Our research illustrated the benefits of data-driven approaches in quickly responding to new design scenarios and resolving the computational challenge associated with multiscale designs of functional structures. The proposed methods could be generalized to accommodate other applications that require heterogeneous property distribution, such as soft robots and implant design.

1. Mechanical cloak via data-driven aperiodic metamaterial design, *Proceedings of the national academy of sciences of the USA*,, 119(13), p. e2122185119.
2. Deep generative modeling for mechanistic-based learning and design of metamaterial systems, *Computer Methods in Applied Mechanics and Engineering*, 372, p.113377.
3. Data-driven topology optimization with multiclass microstructures using latent variable Gaussian process, *Journal of Mechanical Design*, 143(3) :031708
4. Data-driven multiscale design of cellular composites with multiclass microstructures for natural frequency maximization, Composite Structures, 280, p.114949.