

PROCEEDINGS

Physics-Enhanced Deep Learning for Multi-Objective Inverse Design of Micro-Nano Helical Structures with High Locomotion Flexibility and Load Capacity

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ABSTRACT

Micro-nano helical structures have demonstrated immense potential in targeted therapy and micromanipulation. However, conventional forward design methods struggle with high computational costs and the inherent trade-off between locomotion flexibility and load-bearing capacity. This study proposes a customized design methodology driven by a Physics-Enhanced Residual Neural Network (PERNN). By integrating resistive force theory as a physical feedforward constraint layer within the deep learning architecture, we establish an end-to-end mapping from target performance metrics to optimal geometric parameters. A multi-objective loss function is designed to balance locomotion speed (flexibility) and the limit load. To address the data scarcity in micro-scale fluid-structure interaction, we extract compound mechanical features such as the Slenderness Ratio and Geometric Anisotropy Factor. Experimental results and numerical simulations verify that the proposed inverse design framework can generate optimal structure parameters—including turns (N), diameter (D), and pitch (P)—in milliseconds, significantly reducing the design cycle. This methodology ensures physical consistency in low Reynolds number environments while achieving the Pareto optimal balance between load capacity and movement responsiveness.

KEYWORDS

Micro-nano robots; helical structure; inverse design; physics-informed neural network; multi-objective optimization

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