
Conquering Generalization Challenges-A Problem-Independent Machine Learning (PIML) Approach for AI enhanced Computational Mechanics

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Abstract

Artificial Intelligence (AI) for computational mechanics is one of the current research focuses in the field of solid mechanics. The field of computational mechanics involves complex physical phenomena and diverse engineering scenarios. Traditional end-to-end AI models often perform well on specific datasets but exhibit significant loss of generalization ability when facing new boundary conditions, material properties, or geometries. To address this challenge, a problem-independent machine learning (PIML) enhanced large-scale structural analysis and topology optimization framework is developed. The main idea is to focus on the origin of finite element analysis method-the shape function. This is achieved by using machine learning to establish an implicit mapping between the material distribution within coarse mesh elements and corresponding numerical Green's functions. The proposed PIML algorithm is truly independent of specific analysis and topology optimization problems. This is because the numerical shape functions of coarse mesh elements are uniquely determined by the material distribution inside, and do not depend on the external loads, boundary conditions, or shapes of design domain. Numerical examples demonstrate that this algorithm can achieve a two-order-of-magnitude improvement in optimization efficiency for million-scale three-dimensional topology optimization problems compared to mainstream commercial topology optimization software, under the same computational resources. In a 6750-core parallel environment, a 3D topology optimization problem with 10 billion degrees of freedom requires only 42 seconds per iteration. In the future, it is possible to develop a universal CAE software framework based on this technology by integrating AI with traditional numerical methods, enabling more efficient and intelligent engineering simulation and design.

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