Convolution Hierarchical Deep Learning Neural Network (C-HiDeNN)-AI: From Topological Optimization to Additive Manufactured Materials

Walter P. Murphy Professor, Northwestern University, w-liu@northwestern.edu
Co-Founder of HIDENN-AI, LLC, wingkamliu@gmail.com

In recent years, the integration of deep learning-based universal approximation and traditional numerical methods has led to the development of a new computational science theory, called **Hi**erarchical **De**ep-learning **N**eural **N**etwork (HiDeNN). An AI system has been created to leverage these capabilities, achieving unprecedented speed and accuracy compared to conventional numerical methods for solving problems with limited physics and extensive computational requirements. The HiDeNN-AI system offers multi-resolution analysis with automatic adaptivity refinement and built-in **C**onvolutional interpolants for higher-order accuracy. A new mathematical theory, C-HiDeNN-TD which is carefully design with controlling parameters: s-patch size, a-dilation, p-order of polynomial and g-any other interpretable parameters, has been proposed under the HiDeNN-AI framework by combining Tensor Decomposition (TD) with Convolution-HiDeNN, allowing for faster and more accurate solutions to large-scale problems.

Here, we demonstrate the newly developed capabilities of C-HiDeNN-TD by solving a large-scale topological optimization problem, which involves concurrent design and optimization of N-meso-scale lattice structures and M-microscale materials systems. The concurrent design optimization theory (C-HiDeNN-TD-TO) at multiple scales ensures lightweight construction and desired performance, which can be manufactured through 3D printing.

Additionally, the HiDeNN-AI framework is showcased by developing a digital twin of additive manufacturing materials systems. This approach utilizes multi-fidelity and multimodal data from both experiments and physics-based process simulations to construct a surrogate model for real-time prediction and online process control and monitoring. The HiDeNN-AI system is capable of accounting for uncertainties in the experimental process and unresolved physics in the simulations, making it a powerful tool for predicting the performance of additive manufacturing materials.

References

Zhang, L., Cheng L., Li, H., Gao, J., Yu, C., Domel, R., Yang, Y., Tang, S., & Liu, W.K., (2021) Hierarchical deep-learning neural networks: finite elements and beyond. Computational Mechanics, 67, 207-230.

Saha, S., Gan, Z., Cheng, L., Gao, J., Kafka, O. L., Xie, X., Li, H., Tajdari, M., Kim, H. A., & Liu, W. K. (2021). Hierarchical Deep Learning Neural Network (HiDeNN): An artificial intelligence (AI) framework for computational science and engineering. Computer Methods in Applied Mechanics and Engineering, 373, 113452.

Xie, X., Bennett, J., Saha, S., Lu, Y., Cao, J., Liu, W. K., & Gan, Z. (2021). Mechanistic data-driven prediction of as-built mechanical properties in metal additive manufacturing. npj Computational Materials, 7(1), 86.

Gan, Z., Kafka, O. L., Parab, N., Zhao, C., Fang, L., Heinonen, O., ... & Liu, W. K. (2021). Universal scaling laws of keyhole stability and porosity in 3D printing of metals. Nature communications, 12(1), 2379.

Xie, X., Samaei, A., Guo, J., Liu, W. K., & Gan, Z. (2022). Data-driven discovery of dimensionless numbers and governing laws from scarce measurements. Nature Communications, 13(1), 7562.

Li, H., Knapik, S., Li, Y., Guo, J., Mojumder, S., Lu, Y., Apley, D., & Liu, W. K. (2023). Convolution Hierarchical Deep-learning Neural Network Tensor Decomposition (C-HiDeNN-TD) for high resolution topology optimization. Computational Mechanics, issue on Machine Learning Theories, Modeling, and Applications to Computational Materials Science, Additive Manufacturing, Mechanics of Materials, Design and Optimization.

Lu, Y., Li, H., Zhang, L., Park, C., Mojumder, S., Knapik, S., Sang, Z., Tang, S., Apley, D., Wagner, G. & Liu, W. K. (2023). Convolution Hierarchical Deep-learning Neural Networks (C-HiDeNN): Finite Elements, Isogeometric Analysis, Tensor Decomposition, and Beyond. Computational Mechanics, issue on Machine Learning Theories, Modeling, and Applications to Computational Materials Science, Additive Manufacturing, Mechanics of Materials, Design and Optimization.

Park, C., Lu, Y., Saha, S., Xue, T., Guo J., Mojumder, S., Apley, D., Wagner, G., & Liu, W. K. (2023) Convolution Hierarchical Deep-learning Neural Network (C-HiDeNN) with Graphics Processing Unit (GPU) Acceleration. Computational Mechanics, issue on Machine Learning Theories, Modeling, and Applications to Computational Materials Science, Additive Manufacturing, Mechanics of Materials, Design and Optimization.

Liu Y, Park C, Lu Y, Mojumder S, Liu WK, Qian D. (2023) HiDeNN-FEM: A seamless machine learning approach to nonlinear finite element analysis. Computational Mechanics, issue on Machine Learning Theories, Modeling, and Applications to Computational Materials Science, Additive Manufacturing, Mechanics of Materials, Design and Optimization.