Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/NA11.20260038
Published: June 9, 2026

A High-Performance Simulation Framework for Accelerating the Design of Origami-Inspired Structures

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Abstract

Origami-inspired structures are increasingly critical for developing lightweight, deployable components in autonomous robotics and aerospace engineering. However, simulating their non-linear mechanical behavior and complex folding patterns remains a major computational bottleneck. This research presents a high-performance simulation framework built on JAX, designed to accelerate the design and optimization of three fundamental origami geometries: Miura-ori, Yoshimura, and Kresling. By leveraging JAX's just-in-time (JIT) compilation and automatic differentiation, we developed a physics-informed model that incorporates kinematic constraints with spring and bending energies. To further enhance efficiency, we trained a supervised graph neural network (GNN) on simulated deformation data to serve as a fast surrogate model. Results indicate that the JAX-based framework achieves over 100x speedups compared to traditional NumPy-based baselines, enabling real-time simulation of large-scale patterns. Statistical validation confirms that the GNN surrogate accurately predicts complex deformations in milliseconds with minimal loss. This work provides a scalable foundation for the automated design and control of deployable robotic systems, where rapid iteration and differentiable physics are essential for performance optimization. By bridging the gap between high-fidelity physics and real-time execution, this framework facilitates the discovery of next-generation autonomous structures with mathematically guaranteed structural integrity.

Keywords
Origami Simulation, JAX, Differentiable Physics, Robot Kinematics, Deployable Systems.

Biographies
Leon Le is a student researcher at The Harker School with a primary focus on Operations Research, Physics-Informed Machine Learning, and Systems Optimization. He has been recognized for his contributions to computational engineering, serving as a 1st Place Winner at the Stem4All Silicon Valley Regional Competition and a State Finalist at the California State Science & Engineering Fair. His research interests include the development of high-performance simulation frameworks for deployable structures and the application of mathematical optimization to Large Language Model infrastructure. Beyond his technical research, Leon is the Public Forum Debate Captain for the Harker Varsity Team and a Junior Youth Board Member for OrigamiUSA, where he leads national youth engagement initiatives. He is dedicated to advancing sustainable and mathematically-guaranteed efficiency in complex AI and engineering systems through the integration of formal Operations Research methodologies and advanced computational modeling.