Dynamic Modeling and Interactive Design of Origami Mechanisms

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***Abstract*—Origami-inspired robots leverage folding 2D surfaces to achieve complex 3D transformations with minimal actuation. However, accurately simulating folds, sheet properties, and the interactions of these mechanisms with other objects in their environments is challenging. In this paper, we introduce a design framework for origami mechanism simulation using MuJoCo's deformable body capabilities, accessible through an intuitive graphical user interface (GUI). We represent pre-folded origami sheets as a graph of interconnected deformable elements with user-specified constraints that define folds and actuation. MuJoCo's soft body simulation support allows us to reliably capture implicit compliance of deformable sheets as well as the dynamic interactions of the mechanisms with rigid objects and surfaces. This work enables efficient design analysis through an accessible tool for simulating origami mechanisms and mitigates physical prototyping iterations.**

I. Introduction & Related Works

Origami-based robotics is a promising paradigm for designing deployable, lightweight, and flexible robotic systems [1]. Unlike conventional robotic design, which follows a bottom-up approach by assembling independent components, origami robotics enables top-down fabrication of complex mechanisms from a single planar sheet [9] or combination of sheets of different materials [3]. Examples include an inch-worm inspired crawling robot [5], folded swarm robots [6], and robotic manipulators that utilize rigid tiling mechanisms [4].

There has been recent advances in computationally efficient origami simulations, particularly in algorithms defining the folding of origami sheets based on fold patterns [7]. In [1] Demaine et al. established rigorous geometric models for understanding foldability and motion in origami-based systems. Building on this, Ghassaei et al. [2] introduced a GPU-accelerated origami simulator that allows real-time interaction, while Sung et al. [8] developed a computational design tool that enables automated creation of compliant mechanisms from origami patterns. Although these methods emphasize speed and interactivity, they abstract away many of the physical dynamics needed for task-agnostic contact-rich simulations. To bridge this gap, we develop a simulation framework to incorporate physical constraints and compliance, enabling realistic modeling of actuated origami mechanisms. We use MuJoCo's deformable simulation capability to evaluate origami designs by varying material properties such as stiffness, damping, Young's modulus, and Poisson's ratio.

II. Methods

We represent origami mechanisms as a graph-based model where edges represent boundaries or folds along the sheet. We generate an origami blueprint of connected 2D faces from this graph. The user defines each face by selecting a point within the graph. The faces are computed as 2D regions encompassed by the smallest cycle around the selected point that includes at least one edge defined as a fold by the user. This results in all adjacent faces sharing at least one fold edge. We then obtain a deformable flex body in MuJoCo by running Delaunay triangulation on each face. The user can also select vertices in the graph and specify their degrees of freedom (DoFs) by assigning linear joints on desired axes. Actuators can then be added to these joints, enabling dynamic control. This enables the 2D sheet to have a desired degree of freedom dependent on the defined actuators and folds. The user can then reposition each vertex by changing its coordinates, allowing 3D structures to be formed from the 2D blueprint.

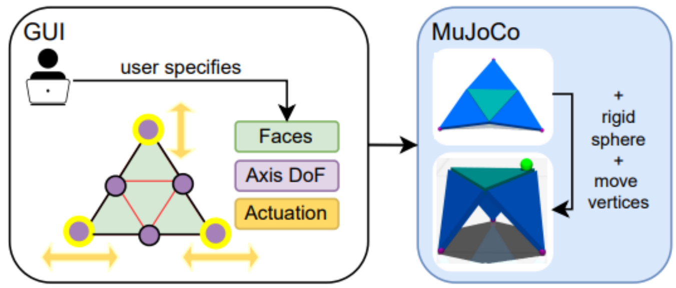

Fig. 1. Our algorithm converts input from the GUI (left) into MuJoCo XML format (MJCF) to simulate the specified components (right). The GUI accepts input as a 2D graph structure defining edges, vertices, their axis of motion, and actuation points (left: purple circles show moving vertices, yellow highlights linear actuators, black lines are boundary edges, and red lines are folds).

The flexible objects (or flexes) in MuJoCo are composed of stretchable geometric elements that connect vertices across different faces. These elements support collisions, contact forces, and deformations. They enable our origami mechanisms to interact with their environments while exhibiting realistic compliance and passive dynamics. For example, in Fig. 1, we have the origami mechanism consisting of four faces where three folds support and balance a rigid sphere object on the top face, by actuating the vertices in contact with the ground plane. The distributed forces across interconnected faces allows the simulation of global deformation behaviors driven by local actuation or contact. An example of such behavior could include one face folding/unfolding due to local actuation on a vertex of that face, resulting in adjacent faces deforming slightly as well.

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