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Student Project Proposal

Design Space Exploration of Unstructured Umbrella Meshes

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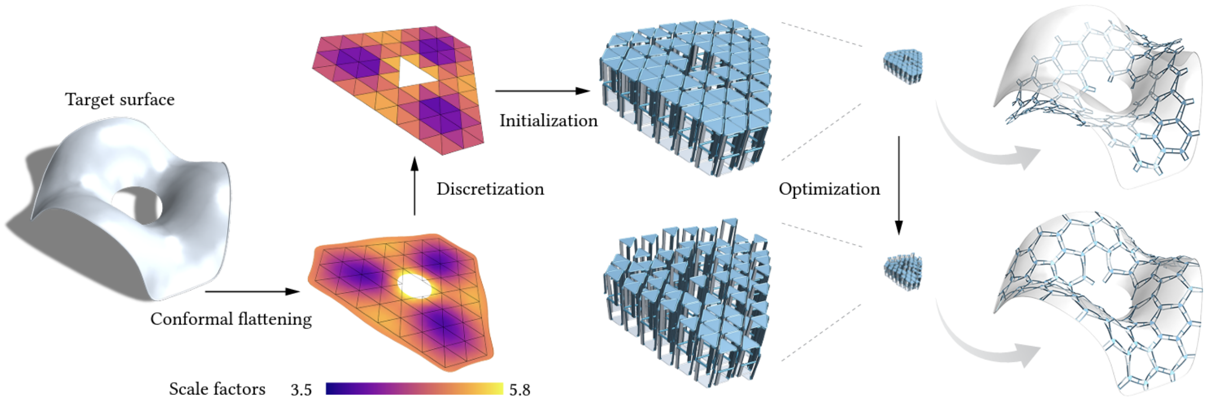

Figure 1: The current computational pipeline involves using a regular equilateral tiling to discretize the conformal map, and thereafter initialize isotropic umbrellas.

Background

Umbrella meshes are a new type of elastic mechanisms that deploy into doubly-curved surface like structures[1]. Umbrella meshes consist of elastic beams, rigid plates, and hinge joints that can be directly printed or assembled in a zero-energy fabrication state. During deployment, as the elastic beams of varying heights rotate from vertical to horizontal configurations, the entire structure transforms from a compact block into a target curved surface.

Umbrella meshes are composed of a triangular tessellation of umbrella unit cells as illustrated in Figure. 2. Each unit cell is connected to three adjacent umbrellas via single-axis rotational joints. Notice that each unit cell expands isotropically, which is the defining property of a conformal map. For each cell, we can determine this expansion factor using kinematics (refer to Section 3.2 in [1]). The connection to conformal maps gives insights into how the heights of an umbrella mesh control the intrinsic curvature of the deployed surface. Specifically, our kinematic analysis combined with the Yamabe equation from conformal geometry, directly relates the Gaussian curvature to the height distribution. Figure. 1 illustrates the current computational pipeline.

Description

In this project, we want to explore the idea of relaxing the constraint of having the umbrella arms at an angle of 120°to each other in a unit cell. The idea is to model unstructured meshes instead of just regular equilateral tilings to explore the design space of umbrella meshes. This entails two main problem directions: 1. Formulating the design optimization with the additional degrees of freedom being the angles between the arms in each unit cell, 2. Coming up with a good initialization strategy for the optimization

When we deal with unstructured meshes, it is not obvious to come up with an initialization strategy. For example, if we choose each plate to be centered at the centroid of a triangle, the

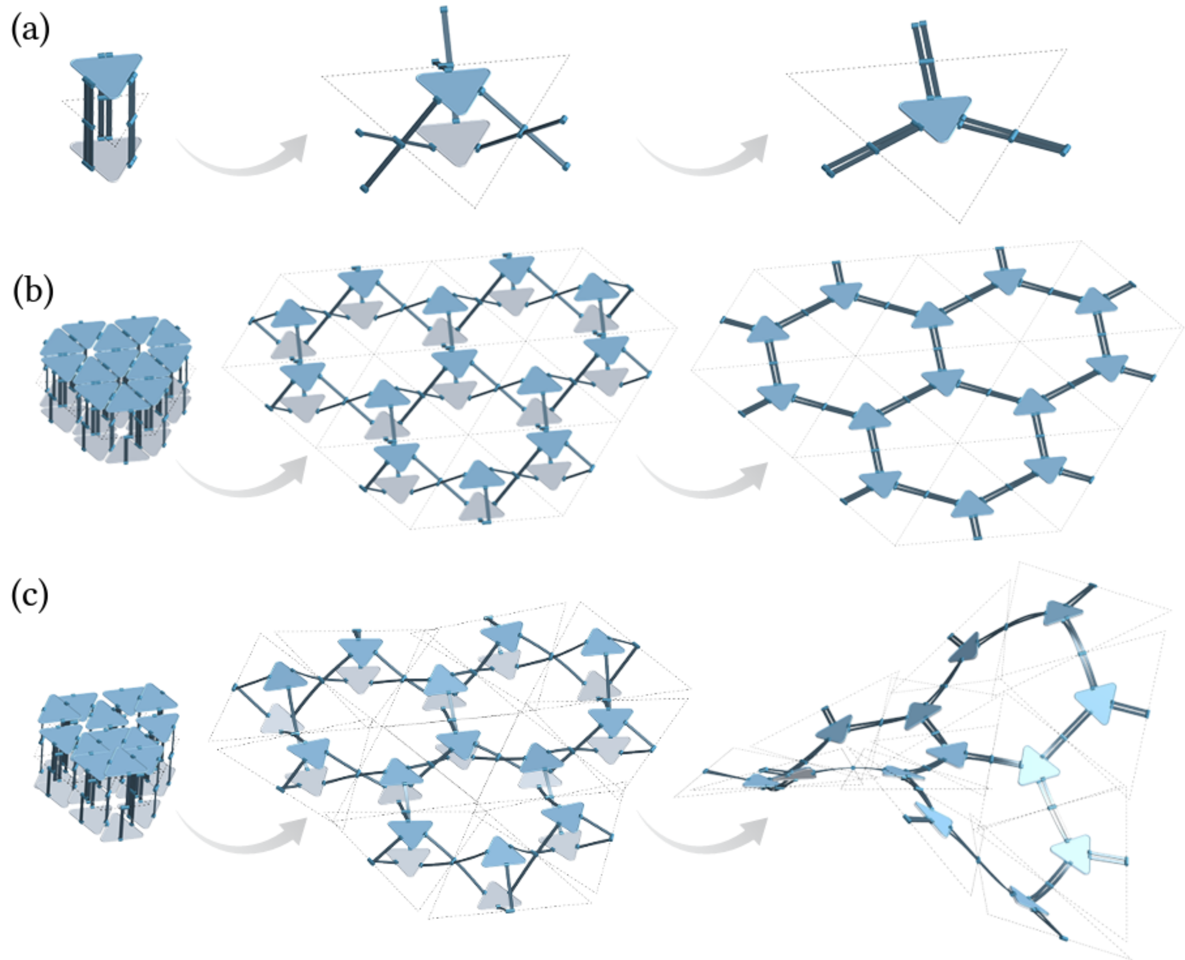

Figure 2: A single umbrella mechanism is deployed by pushing the two triangular plates towards each other, inducing a rotation of the vertical scissor beams into the plane (a). The triangular area footprint, sketched with dashed lines, increases during deployment. Regular tessellations of identical umbrella cells expand in plane (b). Spatially varying umbrella heights lead to incompatible deployed area footprints, and the structure buckles into a curved shape (c). Note that the angle between a pair arms in a unit cell is 120°

connecting arms might have a lot of torsion depending on the underlying mesh. One interesting idea to explore regarding this is to use Circle Packing meshes [2]. We can find a CP-mesh that is close to our target mesh to find a torsion-free initialization. This would also possibly entail new design choices for the umbrella plate shape. Further ideas involve optimizing the cross-sections of the arms to minimize the subsequent torsion, and exploring anisotrpically expanding umbrella meshes by relaxing the top and bottom plates' coplanarity constraint or by using rectangular plates with quad meshes.

Prerequisites

Good coding skills in Python and C++ are essential. You will need to get familiar with a lot of existing code and the project can also be designed to be more engineering focused. Expertise of linear algebra, calculus and differential geometry is very helpful.

Remarks

The scope of the project can be adapted for semester projects at the master level or for a master thesis project.

References

[1] Yingying Ren, Uday Kusupati, Julian Panetta, Florin Isvoranu, Davide Pellis, Tian Chen, and Mark Pauly. Umbrella meshes: Elastic mechanisms for freeform shape deployment. *ACM Trans. Graph.*, 41(4), jul 2022.

[2] Alexander Schiftner, Mathias Höbinger, Johannes Wallner, and Helmut Pottmann. Packing circles and spheres on surfaces. *ACM Trans. Graph.*, 28(5):1–8, dec 2009.