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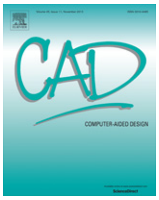

Interactive design exploration for constrained meshes

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HIGHLIGHTS

- A general optimization framework for deforming meshes under constraints.
- Soft constraints and hard constraints are handled in a unified way.
- An efficient parallel solver suitable for interactive applications.
- A system for exploring the feasible shapes of constrained meshes in real time.

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ABSTRACT

In architectural design, surface shapes are commonly subject to geometric constraints imposed by material, fabrication or assembly. Rationalization algorithms can convert a freeform design into a form feasible for production, but often require design modifications that might not comply with the design intent. In addition, they only offer limited support for exploring alternative feasible shapes, due to the high complexity of the optimization algorithm.

We address these shortcomings and present a computational framework for interactive shape exploration of discrete geometric structures in the context of freeform architectural design. Our method is formulated as a mesh optimization subject to shape constraints. Our formulation can enforce soft constraints and hard constraints at the same time, and handles equality constraints and inequality constraints in a unified way. We propose a novel numerical solver that splits the optimization into a sequence of simple subproblems that can be solved efficiently and accurately.

Based on this algorithm, we develop a system that allows the user to explore designs satisfying geometric constraints. Our system offers full control over the exploration process, by providing direct access to the specification of the design space. At the same time, the complexity of the underlying optimization is hidden from the user, who communicates with the system through intuitive interfaces.

1. Introduction

Digital tools have become ubiquitous in the architectural design process. For freeform architecture in particular, proper mathematical models, efficient geometry processing algorithms, and interactive shape editing software are essential for effective design. These tools provide great flexibility in creating complex architectural designs, but offer limited support for incorporating constraints imposed by material, fabrication, or assembly. One example is building with planar quadrilateral panels, which are popular for cost-effective realization of freeform structures with glass panels. In such a construction, the distance between the two diagonals of a panel needs to be smaller than a certain threshold to avoid large internal bending stress [1,2]. These constraints are difficult to control manually and typically require a separate rationalization process that maps the design to physical production. Rationalization needs to negotiate between physical constraints and design intent, often triggering several iterations to enable real-world fabrication of the digital design. This time-consuming process can lead to suboptimal designs or a significant increase in overall cost.

In this paper, we propose a new approach to geometric form finding and design that takes the constraints into account. Given a set of soft constraints and hard constraints, our approach enables the user to explore the space of shapes that satisfy the hard constraints exactly, and the soft constraints as much as possible. By integrating constraints into the design process, our approach yields designs that can be more effectively rationalized with respect to

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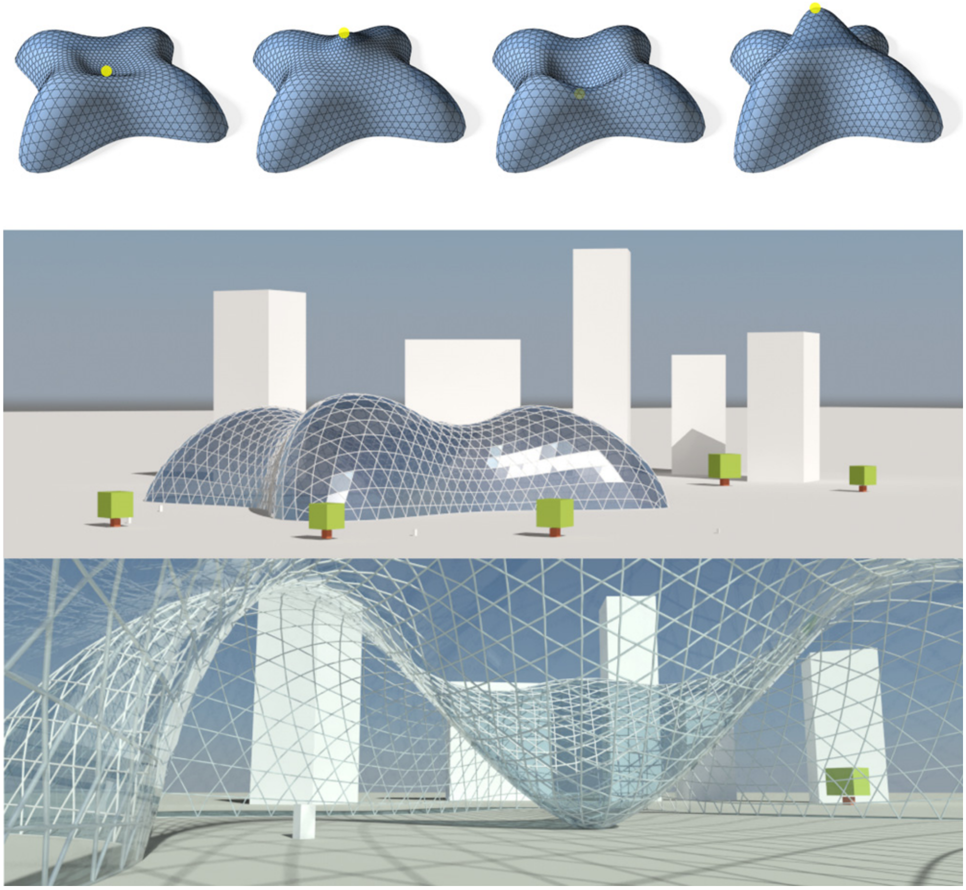

Fig. 1. Handle-based constrained deformation of the Lilium tower, under hard constraints of planar faces (for all faces with more than three vertices) as well as soft constraints of regular polygonal faces (for all faces). Top: different feasible shapes during the exploration, with all boundary vertices and a set of interior vertices in the middle selected as handles. The interior vertex handles are moved during the exploration (shown in yellow). Middle and bottom: architectural design based on one of the feasible shapes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a given construction approach, thus avoiding unnecessary design iterations or suboptimal design solutions.

In our system, a typical design session proceeds as follows (Fig. 1): first, an initial specification of constraints is provided by the designer. Starting from some initial shape, the user can then freely navigate feasible shapes by directly interacting with the current design. Our optimization algorithm computes a new design that stays within the constraint space, thus satisfying the geometric requirements imposed by the design rationale. This new design provides realtime visual feedback according to the user input, enabling effective exploration of design alternatives. The user can also alter the shape space by introducing new constraints, or by modifying or removing existing constraints. The design is automatically updated to remain in the new shape space. Such flexibility allows the user to test different rationalization options easily.

1.1. *Related work*

Computational methods for architectural design have become increasingly popular in recent years [3,4]. With a focus on physical production, various rationalization algorithms have been proposed for many geometric goals such as: planar mesh optimization [5–11], multi-layer structures [12], single-curved panels [13], straight panels [14,15], double-curved panels [16,17], ruled panels [18,19], circle and sphere packings [20], circular arc structures [21], point-folding structures [22] and functional webs [23]. These methods typically take a given freeform surface as input and compute a surface decomposition that relates to a physical layout of panels. Usually such rationalization methods allow some deviation from the input reference surface to improve the quality of the paneling. They do not, however, support interactive exploration of the design alternatives.

Integrating rationalization methods into existing shape editing tools is typically not a viable option, since these algorithms often require minutes or sometimes hours to compute a solution, thus preventing an interactive shape exploration process. Therefore, research efforts have focused on alternative approaches.

Geometric shape spaces have recently become popular as a tool for design exploration. One common interpretation of a shape space is a restriction of the space of all free parameters of a design. For example, Kilian et al. [24] represented a triangle mesh as a point in a high-dimensional space that treats each vertex coordinate as a free variable. They defined suitable Riemannian metrics on this space to restrict the embedding of the mesh to nearly isometric deformations of a given input surface. This allows exploring the manifold of shapes that approximately preserve lengths.

The method by Yang et al. [2] introduced a shape exploration tool for constrained meshes. They compute a local approximant of a high-dimensional constrained shape manifold, which the user can navigate efficiently. Based on this work, Zhao et al. [25] developed a guided exploration tool for the local approximant by automatically sampling new shapes. For these approaches, the generated shapes only satisfy the constraints approximately, and the constraint violation may exceed the tolerance for large deformations. Thus it is usually necessary to project the new mesh onto the constrained shape manifold to obtain feasible results.

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