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Interactive design and simulation of tubular supporting structure

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ABSTRACT

This paper presents a system for design and simulation of supporting tube structure. We model each freeform tube component as a swept surface, and employ boundary control and skeletal control to manipulate its cross-sections and its embedding respectively. With the parametrization of the swept surface, a quadrilateral mesh consisting of nine-node general shell elements is automatically generated and the stress distribution of the structure is simulated using the finite element method. In order to accelerate the complex finite element simulation, we adopt a two-level subspace simulation strategy, which constructs a secondary complementary subspace to improve the subspace simulation accuracy. Together with the domain decomposition method, our system is able to provide interactive feedback for parametric freeform tube editing. Experiments show that our system is able to predict the structural character of the tube structure efficiently and accurately.

1. Introduction

Tubes serve as a type of important supporting structure and are commonly used in people's everyday life (Fig. 1). Traditionally, such supporting structures are often hollow to conserve the manufacture cost and self-weight. They mostly consist of regular cylinders, which are more budget-friendly for mass production with traditional manufacturing techniques. On the other hand, the rapid development of prototype technology (e.g. 3D printing) makes personalized and customized tube fabrication using generalized cylinders conveniently possible, which greatly expands the designing space of supporting tubes.

Although most existing computer-aided design (CAD) softwares (e.g. AutoCAD) well support the geometric design of such tubular structures. Users still need to manipulate many geometric degrees of freedom (DOFs) to model freeform tubes. Interpolatory and tangential controls at the boundary cross-sections are two widely-adopted mechanisms to control the shape of the tube. However, profile control [1] or solving higher-order differential equations [2] is still necessary to prevent shape distortion, which is often tedious or time-consuming. On the other hand, existing CAD packages merely focus on the aspect of shape editing while the structural properties of the 3D model remain unknown to novice users. Following the trend of design-simulation integration, current commercial produces start to enable user to analyze their design using finite element method. Unfortunately, an accurate simulation of the structural characteristic of a customized tubular structure is expensive because generalized shell element with high-order shape functions is usually required to avoid shear-locking artifact [3] and a simulator often possesses a large number DOFs that is prohibitive to regular desktop computers, not to mention performing interactive structural analysis of the 3D model being edited.

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Fig. 1. Two furniture designs using supporting tubes.

As a response to the aforementioned challenges, we present a system for interactive design and simulation of supporting tubular structures. Tube components can be intuitively edited using *boundary* and *skeletal* controls and a complex tube system can be handily created by assembling tube components at their open interfaces. The underlying simulation is carried out using general quadratic nine-node quadrilateral element. A constraint subspace is constructed at each component, which serves as the primary subspace for the follow-up structural analysis. On the top of the constraint subspace, we build a load-dependent secondary subspace named residual subspace, which is able to precisely capture the detailed intra-component deflection due to the regional external loads without resorting to expensive full-space simulation. As a result, our system is able to provide interactive yet accurate structural analysis along with the editing operation of the tube.

Contribution In general, the contribution of our work can be briefly summarized as follows:

- This paper presents a system integrating parametric shape editing and finite element method based structural analysis into a unified environment for the design and simulation of freeform tubular supporting structures.
- We provide user an intuitive shape design mechanism with lower geometric DOFs by using the boundary and skeletal controls to manipulate the geometry of each tube component.
- A new simulation strategy is proposed based on the fact that the supporting tube is often of light self-weight comparing to its external loads. We use a two-level subspace simulation that is able to accurately capture the deflection induced by external loads while still keep the simulator compact.

2. Related work

Swept surface is often used to model general cylinders [4] by transforming cross-section curves along a smooth rotation field on a swept trajectory. Topics such as how to design smooth rotation field on a given trajectory [5,6], how to interpolate cross-section curves [7,8] and how to support profile editing [9,10] are all well studied in the literature. However, it is tedious to manipulate lots of control vertices of swept surfaces represented by standard tensor product spline surfaces. Recently, You et al. [1] suggest modeling swept surfaces by solving ordinary differential equations (ODE). They showed that interpolatory and tangential boundary controls are available by using fourth-order ODE, which leads to lower DOFs in controlling the shape of swept surfaces. They also derived analytical solutions to six-order partial differential equations and gave extra curvature control to swept surfaces [11]. The similar idea is also exploited in shape modeling using meshed surfaces. In [2,12], the authors showed that generalized cylinders can be obtained by solving harmonic and higher-order harmonic equations. In our system, the geometric design of freeform supporting tubes is motivated by these existing studies.

Thin shell element is a natural choice for the tubular structure, which has a high width-thickness ratio. Such degeneracy motivates researchers, especially in graphics community, to seek for alternative energy models to capture the deformation of thin shell in a more efficient and intuitive manner such as spline/NURBS [13–15], hinge-based bending [16–19], or meshless method [20–22], rather than resorting to classic strain theory [23]. Zhang et al. [24] proposed to use 1D orientated rod element with incremental strain theory to model the thin shell structure, which could be considered as an extended version of mass-spring system. While compelling results have been reported, these methods only produce physically plausible animations while we are looking for an accurate simulation that directly serves for potential follow-up fabrication (e.g. via 3D printing).

Design-simulation integration has received increased attention recently and fabrication-purposed design system becomes an active research topic. Simulation based optimization has been widely applied to make sure the fabricated object possesses the desired structural robustness [25–27], kinematic constraints [28,29], and deformable behavior [30–32]. There are also many contributions trying to unify the simulation and the design processing. Umetani et al. [33] present a garment designing system that allows an interactive editing between 2D patterns and 3D simulated draped forms. Cirak et al. [34] propose to use subdivision surface for the design-simulation integration for thin-shell objects.

Simulation acceleration stands out a grand technical challenge for the integration of design simulation because an accurate finite element method (FEM) [3] simulation is often expensive while timely-coupled design-simulation environment is always favored. To accelerate the FEM simulation of thin shell, Seth et al. [35] employ a multi-resolution framework. In regular FEM simulation of 3D solid volume, subspace modal reduction is a widely used technique [36–38] and it can also be applied to accelerate thin-shell simulation [39].

Our method well complements exiting contributions by developing a design-simulation framework based on domain decomposition [40] and finite element tearing and interconnect (FETI) method [41], as we notice that tubular structures are often component-wise and the geometric symmetry commonly exists. The geometry of each tube component is dealt with using boundary and skeletal controls. The structural behavior is simulated using quadratic nine-node quadrilateral mesh automatically generated via the surface parametrization, which will assign five DOFs for each free node. To accelerate the simulation, we construct