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Agile structural analysis for fabrication-aware shape editing

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ABSTRACT

This paper presents an agile simulation-aided shape editing system for personal fabrication applications. The finite element structural analysis and geometric design are seamlessly integrated within our system to provide users interactive structure analysis feedback during mesh editing. Observing the fact that most editing operations are actually local, a domain decomposition framework is employed to provide unified interface for shape editing, FEM system updating and shape optimization. We parameterize entries of the stiffness matrix as polynomial-like functions of geometry editing parameters thus the underlying FEM system can be rapidly synchronized once edits are made. A local update scheme is devised to re-use the untouched parts of the FEM system thus a lot repetitive calculations are avoided. Our system can also perform shape optimizations to reduce high stresses in model while preserving the appearance of the model as much as possible. Experiments show our system provides users a smooth editing experience and accurate feedback.

1. Introduction

The fast developing of rapid prototyping technologies, such as 3D printing, enables convenient manufacturing of real objects from complex 3D digital models. As a prominent example, 3D printing has been extensively adopted in various areas such as architecture construction, industrial design and medical industries. The 3D printing technology converts an input digital model into layers, manufactures each layer and glues them together to shape a real object with various types of technologies, such as selective inhibition sintering (SIS), stereolithography (SLA) and fused deposition modeling (FDM) (Dutta et al., 2000). People can handily fabricate their own designs with emerging low-cost 3D printers and open-source softwares (Reprap, 2010; Vidimče et al., 2013).

To provide novice users feasible controls over the physical properties of the designed objects, many computational design tools have been developed in computer graphics community, i.e. devising objects with desirable structural stability (Stava et al., 2012; Zhou et al., 2013), deformation behaviors (Bickel et al., 2010; Chen et al., 2013) or kinetic constraints (Coros et al., 2013; Zhu et al., 2012). The finite element method (FEM) is widely adopted in such tools for accurate structural analysis, but it becomes time-consuming when the input digital models are complex. This can downgrade the system usability, especially in cases that users need to iterate the editing–simulating process. Moreover, most existing methods or commercial CAD/CAE packages only combine design and FEM simulation at the interface layer and users have to do the shape design and

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FEM simulation in separate stages. A recent contribution aims to update FEM simulation data structures during geometry editing (Umetani et al., 2011b). However, it only focuses on the design problems of moderate-size 2D models using linear elements. Fast design and simulation integrated system for large-scale 3D models using high order elements remains a technical challenge under investigation.

In this paper, we present a fabrication-aware shape editing system which can provide structure analysis feedback interactively for large 3D models. The main feature of our system is the seamless integration of FEM simulation and shape editing operations at domain level via the domain decomposition method, a well-known technique in FEM simulation for solving large scale matrix systems (Farhat and Roux, 1991). In our case, such integration enables to assemble the stiffness matrix of the FEM system locally at each domain. Furthermore, the entries of the stiffness matrix can be parameterized as closed-form expressions of the parameters of editing operations at domain-level, such as scaling and rotating. Thus, the FEM system updating speed is largely improved. The editing interface of our system is mainly a skeleton-driven editing interface where domains are connected to form kinematic chains. Scaling operations are also supported at each domain to support stress-relief operations (Stava et al., 2012). We also develop a domain-based optimizer that can optimize the domain geometry parameters to reduce the maximal stress value to a required threshold while preserving model shape. The parameterized entries allow us to compute the derivatives of stiffness matrix with respect to editing parameters easily in the optimization. The optimization algorithm can release the user efforts to manually adjust shapes to improve the structural stability.

The distinctive features of our system are:

- Observing that users often perform editing operations locally, such as posing, scaling and thickening parts of a mesh, we propose to adopt the non-overlapping domain decomposition as a unified interface for geometry editing, FEM system updating and shape optimization. Therefore, when only a part of the mesh is modified, our system can locally re-assemble the sub-matrices of FEM system belonging to the affected domains while leaving the rest parts untouched. Compared to re-assembling the whole system, a lot unnecessary calculations can be avoided. Our shape optimizer can also take advantage of domain decomposition to decrease the number of optimization variables for fast convergence.
- We derive closed-form formulas to parameterize each entry of the stiffness matrix as a polynomial-alike function of the domain scaling factors. With coefficients pre-computed, when a domain is scaled our system could update each entry of its stiffness matrix through 3 multiplications plus 2 additions. Compared to assembling stiffness matrices directly from vertex coordinates, our parametrization method is 2–3× faster.
- We propose a domain-based shape optimization algorithm that can perform local optimizations to reduce high stresses while preserving the model shape. Observing that the shapes of the mesh parts far away from high stresses are almost not changed during optimizations, our system only chooses the domains close to high stresses as optimizing variables. A constraint list is also dynamically maintained to reduce the cost of constraints enforcement. With the described optimization algorithm, our system can obtain the optimized results within 1–2 minutes.

We have tested our system with a variety of 3D models and the results show that our system provides users agile feedbacks. The accuracy of our system is also verified through two physical experiments on 3D print-out objects.

2. Related work

3D printing: Since 3D printing technology provides users the opportunities to interact with the designed 3D object in real world, it receives a significant amount of research interests in the computer graphics community. In recent years, many techniques are invented to facilitate the printing process, such as adding scaffoldings as support structures (Dumas et al., 2014), decomposing a printable model to separate parts (Hu et al., 2014; Luo et al., 2012), hollowing printable models (Lu et al., 2014) and using skin-frame structures as internal supports (Wang et al., 2013). Research efforts have also been devoted to design algorithms to let the printed 3D objects possess desirable physical properties, such as deformation (Bickel et al., 2010; Skouras et al., 2013), articulation (Bächer et al., 2012; Calì et al., 2012), mechanical motion (Bächer et al., 2014; Ceylan et al., 2013; Coros et al., 2013; Zhu et al., 2012) and appearance (Chen et al., 2013, 2014; Dong et al., 2010; Lan et al., 2013; Prévost et al., 2013). 3D printing technology has been adopted in many works as a convenient method of fabrication, for example, in face cloning (Bickel et al., 2012), self-supporting structures (Deuss et al., 2014) and appearance-mimicking surfaces (Schüller et al., 2014).

Our work is most related to the structural stability analysis of the 3D printable design. Stress relief operations, such as hollowing and thickening, are adopted in Stava et al. (2012) to improve the structural stability of the 3D objects, once areas with high stress are detected. A fast method to analyze worst load distribution that will cause high stress in printed object is developed in Zhou et al. (2013). These two algorithms can be viewed as a post-processing of the 3D design. In contrast, given the material properties which will be used in 3D printing, our goal is to develop an interactive structural analysis algorithm to let the user predict the stress distribution during designing. The structural analysis algorithm can also efficiently handle various external load constraints.

Fabrication-aware design: Fabrication-aware design focuses on developing geometric design algorithms that facilitate fabrication. For instance, in architecture geometry, Liu et al. (2006, 2011) developed algorithms to design planar quad mesh for freeform architectural surface to reduce the fabrication cost. To facilitate the 3D shape fabrication, algorithms have been designed to convert the 3D shape into planar slices (Hildebrand et al., 2012; McCrae et al., 2011). Given a 3D furniture model,