Computer-Aided Design 65 (2015) 1–10

Contents lists available at ScienceDirect

Computer-Aided Design

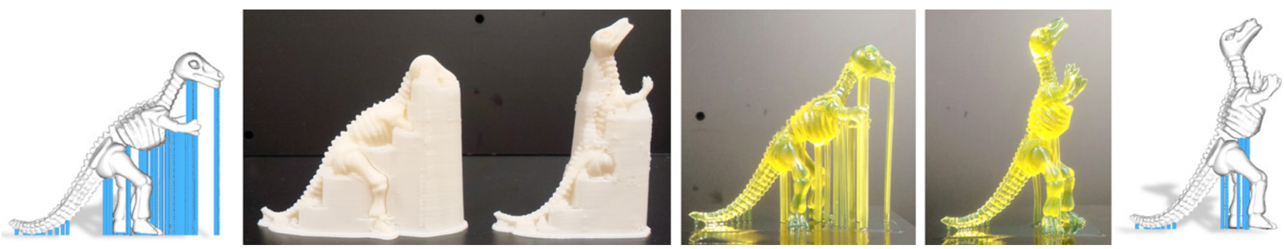
journal homepage: www.elsevier.com/locate/cad

Support slimming for single material based additive manufacturing☆

Kailun Hu, Shuo Jin, Charlie C.L. Wang *

Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, PR China

GRAPHICAL ABSTRACT



HIGHLIGHTS

- Optimize the shape of a designed model into a 'self-supported' state for AM.
- Global shape of a model is preserved by minimizing the energy of rigidity.
- A closed-form solution for minimal rotation to drive the optimization.
- Tackle the shape optimization problem for reducing supporting structures.

ARTICLE INFO

Article history:
Received 5 August 2014
Accepted 7 March 2015

Keywords:
Geometric algorithm
Shape optimization
Design tool
Additive manufacturing

ABSTRACT

In layer-based additive manufacturing (AM), supporting structures need to be inserted to support the overhanging regions. The adding of supporting structures slows down the speed of fabrication and introduces artifacts onto the finished surface. We present an orientation-driven shape optimizer to slim down the supporting structures used in single material-based AM. The optimizer can be employed as a tool to help designers to optimize the original model to achieve a more self-supported shape, which can be used as a reference for their further design. The model to be optimized is first enclosed in a volumetric mesh, which is employed as the domain of computation. The optimizer is driven by the operations of reorientation taken on tetrahedra with 'facing-down' surface facets. We formulate the demand on minimizing shape variation as global rigidity energy. The local optimization problem for determining a minimal rotation is analyzed on the Gauss sphere, which leads to a closed-form solution. Moreover, we also extend our approach to create the functions of controlling the deformation and searching for optimal printing directions.

1. Introduction

AM has emerged as one of the most important methods for realizing the fast fabrication of freeform solids. *Stereolithography Apparatus* (SLA) and *Fused Deposition Modeling* (FDM) are two widely used approaches in AM because they achieve a very good balance

☆ This paper has been recommended for acceptance by Myung-Soo Kim.

* Corresponding author. Tel.: +852 39438052; fax: +852 26036002.
E-mail address: cwang@mae.cuhk.edu.hk (C.C.L. Wang).

http://dx.doi.org/10.1016/j.cad.2015.03.001
0010-4485/

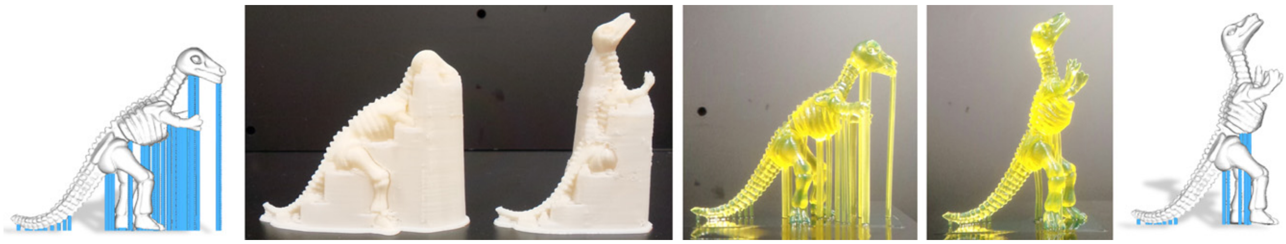


Fig. 1. An orientation-driven shape optimization approach is presented in this paper to show how a given model can be deformed so that the usage of the support structure is significantly reduced in AM with a single material. Layered fabrication based on the FDM method (middle left) and on the SLA method (middle right) can both benefit from this work to improve the efficiency of the manufacturing and the quality of the finished models.

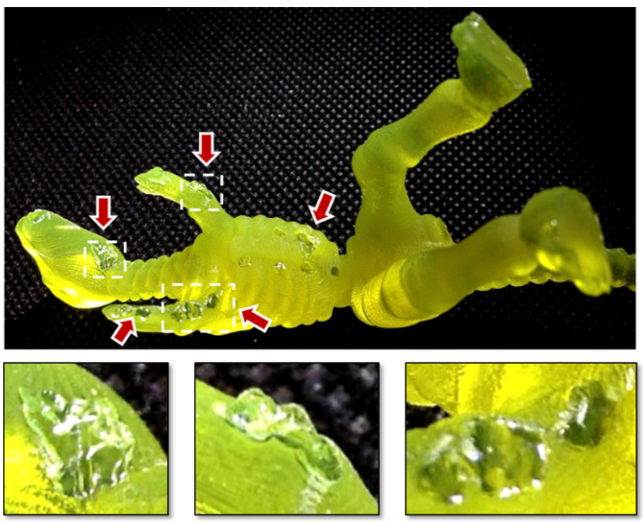


Fig. 2. Artifacts are left on the surface of finished models after removing the support structures—the photograph is of a model fabricated by MIP-SLA. Examples of single-material FDM can be found in [3].

between the cost and the quality. Both SLA and FDM fabricate models in a layer-by-layer manner, where supporting structures (also simply called *support*) need to be added during the manufacturing process. Specifically, the manufacturing material cannot be deposited on a layer where there is insufficient material on the previous layer. For example, the overhangs with a large hanging area can easily collapse under gravity. The problem is solved by adding supports to the originally designed models (Fig. 1). Recent developments in AM allow us to generate the supporting structures automatically (e.g., [1,2]).

1.1. Problems caused by support

When the support is fabricated by a dissolvable material which is different from the one used to print the designed model, the support can be removed automatically by a post-process (Ref. [4]). However, for those manufacturing techniques with a single material (e.g., SLA and the low-cost FDM machines), the supporting structure poses many problems to users. Firstly, the volume of the support could be large compared to the designed model, which leads to a significant waste of materials, energy and time—our study shows that up to 63.6% of the manufacturing time in FDM could be spent on the fabrication of the support. Although the increase of fabrication time in the *Mask-Image Projection based Stereolithography Apparatus* (MIP-SLA) [5] is not significant, because it is proportional only to the number of layers, another problem caused by the supports in single-material AM is common. This is the difficulty in removing the supports automatically. When the support is fabricated in the same material as the design model, it is linked to the model by many thin columns. After fabrication, the support is separated from the main object by being torn away at the top of the columns. This step is always performed manually. More seriously, the surface of the main object is easily damaged by the visual artifacts which are left on its surface (see Fig. 2 for an example). Note that although the process of drop-on-powder based AM and *Selective Laser Sintering* (SLS) is self-supported by the powders, a large group of machines using FDM and SLA suffer from the problem of support.

1.2. Tool for design pipeline—motivation of this work

In the literature of design-for-manufacturing, many applications allow the shape of a model to be adjusted before finalizing the design so that a better manufacturability can be achieved. After designing a shape with the help of modern geometric modeling techniques, designers start to take the 'self-supportness' into consideration when they wish to fabricate the physical model by single-material AM. In many cases, designers manually change the shape of a design and then verify the self-supportness by applying the support generation tools. Such a trial-and-error process is tedious and can take up much time and effort. Little research attention has been paid in the literature to the automation of this procedure. In this work, we provide a support slimming optimizer in the design pipeline to help designers to generate better self-supported intermediate models as references for finalizing their designs. A new design pipeline after integrating our shape optimizer is shown in Fig. 3.

1.3. Main results

We propose a novel shape optimization approach to optimize the shape of a designed model $\mathcal{M}$ into a 'self-supported' state for AM (see Fig. 1). The optimizer is formulated on a volumetric mesh $\mathcal{T}$ enclosing $\mathcal{M}$ (Section 3.1). The global shape of $\mathcal{M}$ is preserved by minimizing the energy of rigidity defined on $\mathcal{T}$ (Section 3.2). The benefit of taking the computation on $\mathcal{T}$ is twofold. Firstly, the computation is more efficient and easier to converge when the mesh density of $\mathcal{T}$ is coarser than $\mathcal{M}$. Secondly, geometric details on $\mathcal{M}$ can be preserved during the optimization. The procedure of optimization is driven by reorienting the tetrahedra with 'facing-down' surface facets. Being a major technical contribution of this work, a closed-form solution is derived from the analysis on the Gauss sphere to determine the minimal rotations (Section 4). This work provides a tool (with error control) for manipulating the shape of a designed model to reduce the usage of supporting structures. Our optimizer can be integrated into the design pipeline to relieve the designers from carrying out tedious work (Fig. 3). To the best of our knowledge, this paper is the first one which tackles the shape optimization problem so as to reduce the usage of supporting structures in AM.

2. Related works

Shape and topology optimization techniques have been widely employed in a variety of engineering applications (Ref. [6,7]).