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Computing interior support-free structure via hollow-to-fill construction

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ABSTRACT

Shape optimization often takes into account both inner and outer surfaces to achieve the design goals. The inner surface produced by existing methods is usually not support-free, which results in additional interior support structures during the printing process, thereby disrupting the design goals. In this paper, we present a simple and novel hollow-to-fill algorithm to guarantee the support-free property of inner surfaces for shape optimization. By analyzing the support-free conditions, three types of voxel-based support-free interior structures are proposed to compute inner surfaces. Given a voxelized model and the optimization goal, we first hollow out the model until it becomes a shell, whose thickness is determined by the physical material properties, and then add the support-free structures to optimize the inner surface, and finally refine the inner surface from bottom to top to minimize the optimization objective while maintaining the support-free property. Furthermore, shape deformation and extra weights are also utilized to optimize the shape for design goals. We demonstrate the feasibility and practicability of our method in three modes of balanced object design, where the physical mass properties of rigid objects are satisfied for the purpose of 3D printing.

1. Introduction

Numerous geometric modeling softwares have been developed for interactive design or customization of 3D geometric shapes. Through a low-cost 3D printer, most of them can be fabricated easily. However, the physical rules are not strictly met in the interactive modeling process, which leads to imperfect fabrication of digital shapes through 3D printing. As a result, there is a great need for interactive modeling tools which can help ordinary users to design arbitrary objects and optimize their designs for practical printing.

A series of recent shape optimization methods have been proposed to meet design requirements, some of which optimize both inner and outer surfaces to achieve the goal. Voxel-based carving is adopted in [1–4] to manipulate inner surfaces by adjusting the mass distribution of the object for their design goals. The methods of [5,6] utilize manifold harmonics [7] to represent both inner and outer surfaces and minimize a given objective functional while satisfying a set of prescribed constraints. However, these methods only consider the design objective and ignore the support-free constraints of inner surfaces which require the overhang-angle of each point on them to be less than the prescribed threshold. So their printed objects usually contain seams (see the comparison in Fig. 1(a) and (b)) that allow users to remove the additional interior support structures generated during the printing process. Otherwise, the printed objects cannot satisfy the design goals.

If one surface is support-free, it can be fabricated without any additional support structures. The shape optimization method [8] utilizes the rhombic infill structure space, whose elements are support-free so that the resulting surfaces are support-free. However, their rhombic solution space is very limited because of the specific subdivision of rhombic cells, which may lead to more redundant material in balanced object design (see the comparison in Fig. 1(c) and (d)).

In this paper, we present a novel approach for generating interior support-free structures that contain less material and have no seams after printing. By analyzing the overhang-angle condition of support-free property, three types of voxel-based support-free structures are presented to optimize design goals. This voxel representation exhibits better flexibility than the rhombic solution space [8]. Instead of the carving operation [1], which is hard to guarantee the support-free properties of the inner surfaces and may require more material, we propose a novel hollow-to-fill scheme, which first hollows out the model into a shell, and then fills the interior void with necessary voxels so as to satisfy the overhang-angle condition of support-free structures. This hollow-to-fill strategy makes it much easier than the carving operation to generate self-supporting structures. Moveover, it tends to generate

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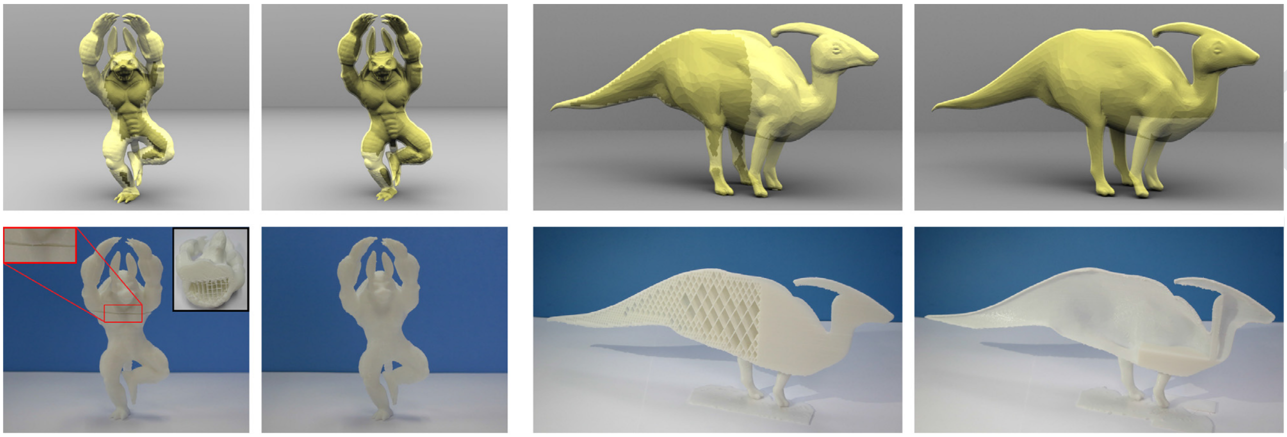

(a) [1] **(b)** Ours **(c)** [8] **(d)** Ours

Fig. 1. Balanced object design. The top figures are rendered models, where the deep yellow parts represent the inner surfaces and the light yellow transparent parts mean the outer surfaces. The bottom figures are printed objects of Armadillo (a) and (b) and Dilo (c) and (d) models. Note that without the seams (red rectangle of (a)) which are used to remove interior support structures (black rectangle of (a)) in [1] (a), our method can generate and fabricate interior support-free results (b). Comparing to the rhombic structures [8] (c) ($1.011 \times 10^5 mm^3$ used), ours are light-weight (0.335×10^5 mm^3 used) results which also meet the balancing objective (d). The original Dilo models can achieve balance, but the cut ones cannot. Thus, in the bottom of models (c) and (d), we leave the raft to take a better view. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) Q3

support-free structure with less material compared to the rhombic structure. (see the comparisons in Section 5.3).

Three modes of balancing are considered as the applications of our support-free structure design method (Fig. 7): (i) standing on a pivot, (ii) standing on a flat surface, and (iii) orientation of suspended objects. The input of our applications is a triangular mesh with a desired orientation (i.e. the gravity direction) and a number of target contact points. We combine the support-free inner surface construction with mesh deformation and extra weights to achieve the final balanced objects.

We demonstrate our approach on a variety of examples which are printed as physical objects without any seams. As can be seen throughout the paper and the accompanying video, our balanced objects can stably stand on their own or maintain balance on pivot points.

2. Related work

Numerous techniques of geometric and physical modeling for 3D printing have been developed (e.g. the surveys in [9,10]). Here we only discuss the approaches most closely related to ours.

Interior shape optimization. The interior shape is optimized to satisfy some physical constraints so as to improve models for 3D printing, e.g. cost-effective material usage [11], optimization of both the strength and weight of printed objects [12], or an analysis of the optimal topology regarding static and rotational stability [13]. Moreover, there are various methods to design balanced objects [1–6,14]. These algorithms optimize the mass distribution of an object to achieve the goal by updating both inner and outer surfaces, but the representations of inner surfaces are different, such as voxel-based surfaces in [1–4], tetrahedral meshes in [14] and manifold harmonics [7] in [5,6]. During the interactive modeling, none of them consider the support-free property of inner surfaces, which may cause a tedious post-processing to take out the additional interior support structures generated during the printing process. This post-processing makes the final printed objects contain seams as shown in the top left of Fig. 1(a). Without doing this post-process, the printed objects cannot satisfy the design goals. Wu et al. [8] first consider support-free inner surfaces during the modeling and use adaptive rhombic structures to ensure the support-free and a minimum thickness constraints. However, this method is limited in the rhombic structure space which may introduce some unnecessary filling using a lot of redundant material (Fig. 1(c)). In contrast to the rhombic structure, we present a simple support-free surface design method based on voxel representation, which is more flexible and cost-effective.

Support structures. Additional supports aim to ensure the success of object printing, but can cause many issues such as material waste, longer fabrication time and lower surface quality. To overcome these weaknesses, some approaches have been proposed to reduce the usage of support structures, such as computation of an optimal printing direction [15], generation of best printing directions through a training-and-learning strategy [16], reeducation of the area of facing down regions [17,18], or optimization of bridge structures [19–21]. Unlike these technologies designed to reduce the usage of exterior supports, we compute inner support-free surfaces to avoid the additional interior supports during the 3D printing while maintaining the design goal.

Topology optimization. There has been much research on topology optimization which is widely used for product and structure design. A high-throughput system to improve the efficiency of topology optimization on 3D solids is proposed in [22]. The shapes in the design space are represented implicitly as level sets of a higher-dimensional function [23,24]. Furthermore, there are some other representations to restrict the computational domain, such as the B-spline space [25], the medial zone [26], the dynamically changed simplicial complex [27], or the adaptive rhombic grid [8]. In this paper, our domain is restricted by the voxel-based representation which is used to change the interior structure and represent the support-free inner surfaces.

3. Interior support-free structures

In this paper, we use a voxel-based representation to construct interior support-free structures. Given a voxelized model, we first hollow it out until it becomes a shell, whose thickness is greater than a printable threshold t_{min}. The inner surface can be regarded as the interior boundary of the shell (Fig. 2) and should be optimized by filling some additional voxels such that the model can be printed without any additional support structure. Here we first introduce the overhang-angle condition (Section 3.1) and three types of voxel-based support-free structures (Section 3.2) in 2D, and then explain how to fill the interior via additional voxels to make the