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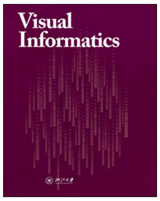

Support-free interior carving for 3D printing

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ABSTRACT

Recent interior carving methods for functional design necessitate a cumbersome cut-and-glue process in fabrication. We propose a method to generate interior voids which not only satisfy the functional purposes but are also support-free during the 3D printing process. We introduce a support-free unit structure for voxelization and derive the wall thicknesses parametrization for continuous optimization. We also design a discrete dithering algorithm to ensure the printability of ghost voxels. The interior voids are iteratively carved by alternating the optimization and dithering. We apply our method to optimize the static and rotational stability, and print various results to evaluate the efficacy.

1. Introduction

Interior shape carving is a modeling operation to hollow voids inside an object without affecting its exterior appearance. In real-world fabrication, the operation is essential for modifying physical properties, such as weight, center of mass and moment of inertia, of an object to achieve its functional purposes. Despite its usefulness, manual hollowing is a tedious trial-and-error process even for a simple task. To overcome such difficulties, recent work has investigated several computational methods to hollow digital models automatically. By using these methods and increasingly popular 3D printers, a personal user can handily design and fabricate functional objects that stand on ground (Prévost et al., 2013; Christiansen et al., 2015), spin around an axis (Bächer et al., 2014), float in fluid (Wang and Whiting, 2016) and withstand under load (Lu et al., 2014).

The mainstream 3D printing technologies, such as fused deposition modeling (FDM) and stereolithography (SLA), deposit materials layer-by-layer to build a tangible product. During printing, additional supporting structures are often necessary to avoid the falling of overhanging parts, e.g. to support the ceilings of interior voids. The supporting structures affect the computed physical properties thus must be removed from the printed object. However, this process usually leaves visually unpleasant cracks on the object surface (Zhang et al., 2015a; Wang et al., 2016). What is even worse is that supporting materials inside interior voids of the object cannot be directly taken out. Previous work tackles this issue by first cutting the model into individual parts to print and then gluing printed pieces back together, which is a cumbersome process.

Thanks to the properties of plastic materials like ABS and PLA, an FDM printer can build slanted walls without using support materials. Inspired by this observation, we realize that it is possible to make the interior voids support-free, by constraining the structures and boundary slopes (Fig. 1). An object with such interior voids can be printed as a whole, eliminating the needs of any supporting structures and shape decompositions.

In this paper, we propose a novel method to automatically generate support-free interior voids while satisfying user-specified functions. We design a voxel structure that is self-supportable during printing and use it as the basic construction unit of interior voids. Taking a step further, we incorporate the support-free voxel structure into an interior carving optimization framework to achieve functional design. Specifically, we use wall thickness to parameterize the integral terms over each voxel and use them to formulate the objective function of the optimization problem. To deal with the ghost voxels generated in the optimization, we develop an efficient dithering algorithm that ensures printability and preserves support-free property. The interior voids are iteratively carved by alternating between an application specific nonlinear programming and the ghost voxels dithering. We apply the method to design statically balanced objects and spinnable objects, and print all the results without using any support materials inside the objects.

2. Related work

The 3D printing technology provides a convenient way for fabricating objects with complex geometries, and thus draws a lot

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(a) Printing. (b) Interior voids. (c) Result.

Fig. 1. Support-free interior carving. (a) A close-up of the Horse during printing, without any supporting structures inside it. (b) A sectional view of the support-free interior voids. (c) The Horse printed as a whole can stand stably.

of attention in the computer graphics community. One line of this research optimizes different sub-steps of the 3D printing process, such as printing direction (Gao et al., 2015; Zhang et al., 2015a), slicing (Wang et al., 2015), decomposition and packing (Chen et al., 2015; Yao et al., 2015; Luo et al., 2012). The other line of this research detects and fixes structural problems of the 3D printed model itself, such as stress analysis (Stava et al., 2012; Zhou et al., 2013; Umetani and Schmidt, 2013) and cost-effective printing (Wang et al., 2013; Lu et al., 2014; Zhang et al., 2015b).

Generating economic and practical supporting structures is an active topic in 3D printing technologies. Vanek et al. (2014) proposed a method to generate tree-like supporting structure to reduce material costs. Dumas et al. (2014) used scaffolding-like structures to improve the printability of overhanging parts. Hu et al. (2014) designed a method to largely reduce the necessary supporting structures by cutting the whole object into pyramidal parts. Recently, Reiner and Lefebvre (2016) proposed an interactive sculpting system for designing support-free models. All the above methods optimize supporting structures outside the object, which are relatively easy to remove after printing. In contrast, our method focuses on the elimination of supporting structures inside the object, which are impossible to remove without breaking the object into pieces.

Our work is related to the interior carving methods for 3D printable objects. Prévost et al. (2013) generated statically balanced objects by voxelizing and hollowing the input model in a heuristic manner. Bächer et al. (2014) designed spinnable models by using an adaptive octree for volume voxelization and solving an optimization problem for the hollowing state of each voxel. Both above methods deform the outer surface of the object when interior hollowing itself cannot satisfy the functional requirements. Different from the volume-based methods, Musialski et al. (2015) optimized an offset surface of the input mesh as the interior shape and presented a subspace method to accelerate the computation. Inspired by previous work, we adopt an octree to voxelize the input model and design an iterative algorithm to optimize and merge voxels. However, instead of the simple cube, we design a specific support-free structure and use it as the voxel, such that the optimization result can be directly printed. Moreover, rather than optimizing the hollowing variables and then rounding them to the binary states, we use the wall thickness of each voxel as the optimization variable, which is inherently continuous.

Previous work has investigated how to incorporate additive manufacturing consideration into topology optimization. For example, Brackett et al. (2011) mapped a given density field to a lattice based structure with varying radius. Gaynor and Guest (2014) presented another method to prevent the generation of overhangs greater than a given angle. However, these methods either cannot completely erase overhangs during the optimization process, or sacrifice the algorithm convergence when enforcing the extra constraints. As a concurrent work, Wu et al. (2016) proposed a very similar rhombic cell which is self-supporting. While their focus is mainly on improving the mechanical stiffness, we demonstrate our method by optimizing both the static and rotational stability of 3D printed objects.

3. Support-free interior carving

We introduce a computational framework for carving support-free interior voids inside an object. Taking a 3D triangular mesh as input, we first voxelize its volume by building and refining an octree. Each voxel is a support-free rhombohedron, whose central hollow part is controlled by the wall thickness (see Fig. 2(a), (b)). We parameterize common integral terms over each voxel as analytic functions of its wall thickness. Based on the parametrization, we formulate a continuous optimization problem for desired application by using wall thicknesses of all voxels as variables. After the optimization, we dither non-printable voxels while ensuring the whole structure is still support-free. Finally, by alternating the wall thickness optimization and voxels dithering, we obtain a hollowed model which both satisfies the desired functional purposes and can be printed out without using additional supports inside the interior voids (see Fig. 2(c), (d)).

3.1. Support-free voxel

As the basic unit of our framework, we need a voxel that: (1) is self-supportable during printing; (2) can be tiled to occupy the interior voids; (3) can change its hollowing state by computational methods.

A key observation is that a hollowed rhombohedron, i.e. a cube scaled in the diagonal direction (Fig. 2(a)), satisfies all above requirements. In this unit structure, all the walls have the same slope angle α, which depends on the scaling factor s:

$$\alpha = \arctan\left(\frac{1}{2s}\sqrt{2}\right).$$

With sufficiently small α (we fix $\alpha = 30°$), the structure is safe to print without supporting structures. Using such basic unit, we

(a) Support-free voxel. (b) Voxelization. (c) Optimization + Dithering. (d) Result. (e) Interior voids.

Fig. 2. Support-free voxelization. (a) The support-free voxel. (b) The initial voxelization of the Elephant using the support-free voxel as basic unit. (c) The sectional view of interior voids generated by wall thicknesses optimization and ghost voxels dithering. (d) The printing result without using support materials inside it. (e) Highlight of the interior voids. The blue point is the ground-contact point, and the transparent/solid arrows are principal axes of the input/result. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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