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Automatic balancing of 3D models[☆]

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HIGHLIGHTS

- We revisit a number of 3D print technologies and discuss their characteristics.
- We present an automatic, optimization based method for balancing 3D models.
- The balance is improved by creating internal cavities and by rotating the model.
- We pay special attention to make FDM printed models stand.

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ABSTRACT

3D printing technologies allow for more diverse shapes than are possible with molds and the cost of making just one single object is negligible compared to traditional production methods. However, not all shapes are suitable for 3D print. One of the remaining costs is therefore human time spent on analyzing and editing a shape in order to ensure that it is fit for production. In this paper, we seek to automate one of these analysis and editing tasks, namely improving the balance of a model to ensure that it stands. The presented method is based on solving an optimization problem. This problem is solved by creating cavities of air and distributing dense materials inside the model. Consequently, the surface is not deformed. However, printing materials with significantly different densities is often not possible and adding cavities of air is often not enough to make the model balance. Consequently, in these cases, we will apply a rotation of the object which only deforms the shape a little near the base. No user input is required but it is possible to specify manufacturing constraints related to specific 3D print technologies. Several models have successfully been balanced and printed using both polyjet and fused deposition modeling printers.

1. Introduction

Injection molding has been one of the important pillars of mass production throughout the twentieth century, continuing to this day. It is a method that allows us to create vast numbers of plastic parts each of which takes mere fractions of a second to produce. Nevertheless, recent years have seen a growing excitement around a number of other fabrication technologies referred to as additive manufacturing, or simply 3D print. While these processes are very different, they tend to share the common trait that they are far slower than molding when many objects are to be made but much faster at producing a single object since no mold is needed. Another important advantage of 3D print is that we are generally quite unconstrained when it comes to what shapes that can be produced, the main restriction being on the size of the object. This is in stark contrast to objects produced using a mold since we have to be able to extract the object from the mold. Thus, as the speed of 3D printing increases, we are likely to face a future with much more variety in the shapes of manufactured objects.

Because of the variety of shapes and the low cost of producing few objects, the time consuming part shifts from manufacturing to modeling, and from producing the object to designing the object. Furthermore, it is often desired that the designed model has suitable geometric characteristics. Recent years have seen quite a few examples of work related to the aspect of making a 3D shape suitable for fabrication, a process known as *rationalization* in architecture. In this paper, we are specifically concerned with automatically ensuring that objects are balanced and thus able to stand without support after production.

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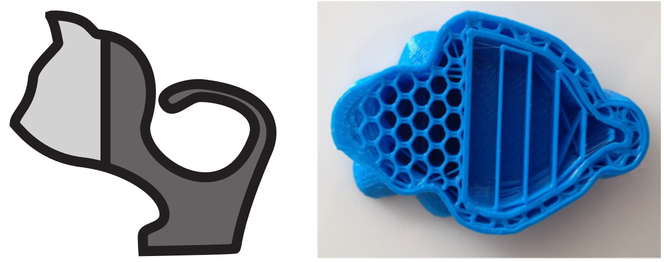

(a) Illustration. (b) Example.

Fig. 1. Figure (a) illustrates the situation when using an FDM 3D printer to produce a model with internal cavities. The thick black lines are the shell of the 3D model which is printed solid. The dark gray regions are infill whereas the light gray region is a cavity. Although such a cavity could be printed empty, in practice it may contain support structures with up to 20% aggregate density. Figure (b) shows an example, with 30% hexagonal-pattern infill and 10% support structures inside an interior cavity.

We make the following contributions.

1. We revisit a number of 3D print technologies and discuss their characteristics and affordances and how these pertain to the problem of producing objects that are balanced.
2. We present an automatic, optimization based method for balancing 3D models. The 3D model is embedded in an adaptive tetrahedral mesh. The balance is then improved by creating internal cavities and by rotating the model around its base. Apart from rotation the exterior of the model is not changed.
3. While this method may be used to balance 3D objects regardless of the production method, we pay special attention to fused deposition modeling (FDM). FDM is a common, cheap technology with characteristics that would confound a method that did not take these characteristics into account.

Prévost et al. [1] proposed a technique with the same capabilities as the presented method. However, it differs in nearly all particulars. With the presented method, cavities are generated by relabeling tetrahedra and moving internal surface nodes rather than labeling fixed cuboid voxels. Furthermore, Prévost et al. allow the user to equip the model with deformation handles used to perform automatic, affine transformations of parts of the model. While this strategy appears effective, it can make quite noticeable changes to the shape compared to a rotation around the base of the model which we propose.

2. 3D printing

The majority of 3D printing or *additive manufacturing* (AM) technologies operate by sequentially accumulating thin parallel layers of material in a vertical direction. As noted above, this provides great freedom in terms of 3D shape complexity. However, each different mechanism for realizing 3D printing involves quite different capabilities and constraints. These constraints are highly relevant to any algorithm which will attempt to alter a shape to satisfy some fabrication goal. Hence, we will review some properties relevant to the problem of making a shape stand.

The simplest case is when the model is printed completely solid. In this case, to balance a shape without deforming it our only recourse is to leave internal cavities. With printing technologies such as laser sintering (SLS), powder-bed, or stereolithography (SLA), printed *support* material will be trapped in any internal voids, and so escape holes (in some cases of considerable size) must be inserted into the model surface, or the model must be printed in parts and assembled. Each strategy is tedious and becomes increasingly intractable as the internal cavities grow in complexity.

A more complicated case is fused-deposition modeling (FDM), in which a thin stream of thermoplastic is extruded from a moving print head. This is the most common type of 3D printer today, in part because FDM has been rapidly commoditized in consumer hardware (Makerbot, RepRap, etc.). When using FDM, we have three types of regions (see Fig. 1):

1. Shell: exterior and interior surfaces are printed solid.
2. Infill: the interior is printed with a sparse pattern.
3. Cavity: internal cavities may be empty, or may contain support structure.

Although many FDM printers use a single material, they do not print in uniform density. To save material and print time, FDM printers generally print an outer *shell* several layers thick, and then fill the rest of the model with a sparse *infill* pattern. Printing internal *cavities* is also more complex with FDM printers. For most non-trivial objects, at some layers of the in-progress print there will be floating components which lack a direct connection to the print bed. Something must hold up each of these components, lest they succumb to gravitational forces. In FDM printing this is accomplished by adding *support* structures to the model. In addition to local height-minima, with FDM it is also necessary to support any parts of the model that have too shallow a *draft angle* relative to the print bed, as overlapping layers of the filament stream must have a sufficient area underneath them. Areas without adequate support will *droop*, which affects print quality and can even result in print failures. Generally, FDM support structures are snapped off after printing, but with internal cavities the support cannot be removed. Hence, internal cavities may have non-zero density. Since the density depends on the shape of the cavity, and on the particular support strategy in use, modeling it accurately is quite complex.

Clearly, to balance a 3D object, it is critical to take the difference in density between infill and cavity into account. Further compounding this issue is that internal cavities are also surrounding by solid shells, so adding a cavity can actually result in a local increase in density. This complicates both the analysis and optimization, and the previous work has not taken this variable density into account [1].

3. Method

In the following, we formulate the goal of balancing a 3D model, while making as few changes to the surface as possible, as an optimization problem. Consequently, the method is fully automatic. We will apply two optimization strategies. The first optimization strategy, hollowing (Section 3.1), creates cavities filled with a lighter or heavier material, for example air or copper inside a plastic model. Hollowing can also be used to simulate the infill and support structures created by FDM printers. Furthermore, it improves balance and does not deform the surface of the model. However, most 3D printers can only print in one material, or multiple materials with approximately the same density, and often cavities of air is not enough to make the model stand. Consequently, in these cases, a rotation around the base of the model will be applied (Section 3.2). The same rotation is applied to all surface nodes except the nodes which touch the ground. Therefore, the only deformation of the model will be close to the ground.

We assume that the initial 3D model is represented by a triangle surface mesh. Then, both the inside and the outside of the model are discretized into tetrahedral elements using TetGen [2]. Here, the tetrahedra do not overlap and each point in the domain is either inside or on the boundary between tetrahedra. Consequently, the mesh, illustrated in Fig. 2, is a simplicial complex. Furthermore, each tetrahedron has an associated material. The surface is then represented by the faces shared by two tetrahedra labeled with different materials. Therefore, the original and unchanged triangle mesh is embedded as a sub-complex in the tetrahedral mesh.