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Hexahedral mesh modification to preserve volume

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ABSTRACT

In this work, we provide a new post-processing procedure for automatically adjusting node locations of an all-hex mesh to better match the volume of a reference geometry. This process is particularly well-suited for *mesh-first* approaches, as overlay grid ones. In practice, hexahedral meshes generated via an overlay grid procedure, where a precise reference geometry representation is unknown or is impractical to use, do not provide for precise volumetric preservation. A discrete volume fraction representation of the reference geometry M^I on an overlay grid is compared with a volume fraction representation of a 3D finite element mesh M^O. This work introduces the notion of localized discrepancy between M^I and M^O and uses it to design a procedure that relocates mesh nodes to more accurately match a reference geometry. We demonstrate this procedure on a wide range of hexahedral meshes generated with the Sculpt code and show improved volumetric preservation while still maintaining acceptable mesh quality.

1. Introduction

Overlay grid methods [1–4] developed in recent years have dramatically improved the ability to rapidly and automatically generate hexahedral meshes for complex geometries in massively parallel environments. These methods utilize a *mesh-first* approach to mesh generation where an initial base grid is used to overlay the reference geometry. Procedures to modify the base grid are employed to best capture the geometry to define a conformal all-hex mesh. In contrast, *geometry-first* mesh generation approaches [5–7] rely on user-intensive procedures to first clean and then decompose the geometry to fit blocking or sweeping topologies. Because of the nature of geometry-first approaches, these methods can in most cases very accurately preserve volume of a reference geometry subject only to a user defined mesh resolution, and would therefore benefit little from the proposed work. However, as geometry-first technologies for hex meshing are not automated or do not scale for general use, mesh-first procedures, such as overlay grid, are often preferred and consequently the focus of this work.

In this work, we focus on Sandia's Sculpt [4] algorithm, which is an overlay grid procedure. Whatever the geometric input you consider (CAD model, faceted model, scanner image, volume fraction), a preprocess of the algorithm consists in building a volume fraction representation of the geometry on a Cartesian or adaptively refined grid. In general cases, this grid consists in discretizing the bounding box of the geometric model we work on. The grid is then geometrically and topologically modified to fit volume fractions as best as possible. For instance, the primal contouring approach described in [4] will adjust nodes of the base grid to conform to an approximation of the reference geometry prior to application of pillowing and smoothing operations. Because of the approximate nature of the interface reconstruction procedure combined with smoothing, the resulting full-hex mesh may not precisely conform to the reference geometry. While in most cases Sculpt meshes have proven accurate in simulation compared to pave and sweep approaches [8], we note one potential deficiency. In some cases where localized densities and material properties demand accurate volume preservation, the interface reconstruction employed by Sculpt and other overlay grid algorithms may not provide sufficient precision. The main objective of the presented work is to tackle this issue and so to improve volume conservation of each input material as best as possible.

For our purposes, we consider both *explicit* and *implicit* geometry representations with multiple components or materials. Explicit geometry includes B-Rep standards such as CAD and STL models while implicit can include 3D image data and volume fractions on a Cartesian grid. Both types of input can be meshed using overlay grid methods. For explicit geometry representations, closest-point projection to B-Rep surfaces may be employed to accurately capture the reference geometry and correctly preserve volume. However, we note that projection operations in overlay

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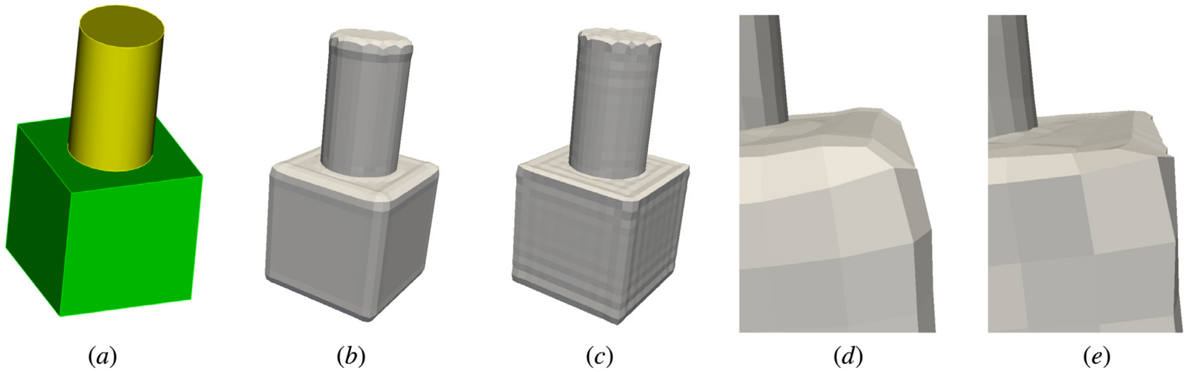

Fig. 1. (a) CAD model for the brick-cylinder case. (b) M^O mesh generated by Sculpt. (c) modified M^O mesh obtained after applying our method. (d) Close-up of one corner of the mesh shown in (b). (e) Close-up of same corner of the mesh shown in (c). Note that the proposed method better represents geometric corners.

grid methods can often create topology cases that cannot be adequately smoothed, resulting in inverted elements. For example, these can include cases where more than one face of a hex lies on a single surface or multiple edges of the same hex lie on the same curve. To correct for these instances, special case topology operations are often employed to locally improve quality [9,10]. These operations, while effective in some cases, can be complex and difficult to employ, and in many cases can result in severely distorted elements.

The proposed volume preservation algorithm concentrates instead on relocating nodes of the mesh to more accurately represent the underlying reference geometry without the need for complex topology operations. The generalized approach we propose provides both for explicit geometry, and for implicit geometry where only the localized volume fraction information is known and where exact closest-point operations are otherwise not practical.

1.1. Related works

In the present work, we focus on the ability of improving the volume of a multi-material mesh M where each cell of M is pure, i.e. is filled by a single material. The expected volume for each material is also an input of the process, and is given in the form of another mesh carrying volume fractions in each cells. This purpose is quite unusual and, to our knowledge, only a few works have focused on it. In [11], the authors extended their interface reconstruction method [12] by iteratively moving the obtained interfaces, represented by triangle surfacic meshes in 3D, combining a Laplacian smoothing and a volume control contribution. Their method is dedicated to visualization purposes and one of their concerns is to obtain "good quality" triangles; they can also adapt the surfacic meshes, depending for example on a triangle edge length criteria threshold. Such adaptation techniques would not directly apply in our context where we build full hex meshes and not triangular meshes.

Interface reconstruction methods, such as Volume-Of-Fluids [13–15] although closely related, also do not directly apply. Indeed, starting from volume fractions prescribed on any unstructured mesh, VOF methods attempt to build in-cell interfaces with strict volume preservation, precisely controlling volume inside each cell of the input. However rather than producing pure computational elements, they can yield mixed elements in the output mesh where local interfaces are defined by discrete planar geometry. Such interfaces are globally non-conforming and are typically useful for visualization processes, during the advection step in simulation codes or refinement in AMR [16] codes. On the contrary, overlay-grid algorithms such as Sculpt's algorithm provide a conformal hexahedral mesh with pure cells. This mesh can then be used directly, or its faces at material interfaces can be considered as forming a faceted geometric model used as a support for hex mesh generation using other methods [17].

1.2. Main contributions

The method we propose in this paper improves the volume conservation of an output mesh that has been constructed using an all-hex overlay grid method. Such algorithms start from a 3D input mesh M^I where each cell can be pure or mixed. As an output, they produce an unstructured hexahedral mesh M^O, where each cell is pure, i.e. "filled" by only one material. Although meshes produced in this manner will maintain watertight, smooth and contain manifold interfaces between materials, they do not precisely control for the overall volume of the mesh. To overcome this issue, we propose:

1. The definition of a localized discrepancy between M^I and M^O, which helps us to compute volume differences in a local manner (see Section 3);
2. An heuristic algorithm to geometrically modify the location of the nodes of M^O that are on the interface between at least two materials (see Section 4);
3. A variety of different samples to illustrate the impact and the benefits of the proposed solution (see Section 5).

2. A brief presentation of the overlay-grid strategy in Sculpt

In order to illustrate the general behavior of overlay-grid algorithms, we consider the Sculpt algorithm [4], which handles both implicit and explicit geometry representations. Sculpt uses an interface reconstruction procedure that relies on a volume fraction representation of the geometry on a Cartesian or adaptively refined grid. Let us consider Fig. 2 to understand the basic Sculpt procedure, beginning with a Cartesian grid as the input mesh M^I, shown in Fig. 2(a). Provided as input, or computed from a CAD or STL description, volume fractions that satisfy Eq. (1), serve as the basis for the Sculpt procedure. Fig. 2(b) shows a representation of a field of gradient vectors that are computed from the scalar volume fraction data using finite differences of neighboring cells and a least squares approximation of the localized data. Locations where interfaces will most likely cross the virtual edges connecting cell centers are then computed as illustrated in 2(c). Using the local gradient and edge cross locations, node locations of the base grid are repositioned to approximate the interfaces of the reference geometry as shown in 2(d). Fig. 2(e) then shows conformal layers of hexes or pillows inserted at the interfaces to provide additional degrees of freedom to allow for improvement using smoothing. Finally, in Fig. 2(f), combined Laplacian and optimization-smoothing operations are performed, constraining nodes at interfaces to remain on the approximated surfaces and interior nodes repositioned to optimize mesh quality.

The aim of our work is to relocate the nodes of the mesh shown on Fig. 2(f) to best fit the volume fraction provided as an input and shown on Fig. 2(a).