Journal of Computational Design and Engineering 4 (2017) 330–338

Contents lists available at ScienceDirect

Journal of Computational Design and Engineering

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

Evaluation of user-guided semi-automatic decomposition tool for hexahedral mesh generation

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ARTICLE INFO

Article history:
Received 14 August 2016
Received in revised form 15 December 2016
Accepted 11 May 2017
Available online 23 May 2017

Keywords:
Decomposition
Hex meshing
Sketch-based interaction
Visual guidance
User study

ABSTRACT

Volumetric decomposition is essential for all-hexahedral mesh generation. Because fully automatic decomposition methods that can generate high-quality hexahedral meshes for arbitrary volumes have yet to be realized, manual decomposition is still required frequently. Manual decomposition is a laborious process and requires a high level of user expertise. Therefore, a user-guided semi-automatic tool to reduce the human effort and lower the requirement of expertise is necessary. To date, only a few of these approaches have been proposed, and a lack of user evaluation makes it difficult to improve upon this approach. Based on our previous work, we present a user evaluation of a user-guided semi-automatic tool that provides visual guidance to assist users in determining decomposition solutions, accepts sketch-based inputs to create decomposition surfaces, and simplifies the decomposition commands. This user evaluation investigated (1) the usability of the visual guidance, (2) the types of visual guidance essential for decomposition, (3) the effectiveness of the sketch-based decomposition, and (4) the performance differences between beginner and experienced users using the sketch-based decomposition. The result and user feedback indicate that the tool enables users who have limited prior experience or familiarity with the computer-aided engineering software to perform volumetric decomposition more efficiently. The visual guidance increases the success rate of the user's decomposition solution by 28%. The sketch-based decomposition significantly reduces 46% of the user's time on creating decomposition surfaces and setting up decomposition commands.

1. Introduction

Since hexahedral meshes are preferable to tetrahedral meshes in most engineering analyses (Benzley, Perry, Merkley, Clark, & Sjaardema, 1995; Blacker, 2000; Blacker, 2001), fully automatic methods for quality hex mesh generation have been under research and development for several decades (Folwell & Mitchell, 1999; Blacker & Meyers, 1993; Price, Armstrong, & Sabin, 1995; Price & Armstrong, 1997). Due to the geometry properties and constraints (Shepherd & Johnson, 2008) of hex elements, a fully automated method that can generate high-quality hexahedral meshes for arbitrary volumes has yet to be realized. The current practical method is to manually perform volumetric decomposition, a process of subdividing a volume into smaller meshable regions, and then assign proper meshing schemes to each region.

Studies have shown that manual decomposition is one of the most time-consuming steps in the meshing process for users (Hardwick, 2005). Research efforts have been made to automate this process. For example, Price et al. (1995) and Price and Armstrong (1997) defined a set of solid primitives suitable for hex meshing and used the medial surface to subdivide a large class of geometries into these primitives. These primitives are then meshed with the midpoint subdivision technique (Li, McKeag, & Armstrong, 1995). Sheffer, Etzion, and Bercovier (1999) used an embedded Voronoi graph to decompose simple shapes into sweepable sub-domains. Their approach prevents sharp angles at the boundaries, and uses sweeping algorithm to generate good quality meshes. However, it only works for simple shapes, and sometimes over decomposes the volume. White, Mingwu, Benzley, and Sjaardema (1995) parameterized the surface mesh nodes to decompose the volume into mappable sub-volumes with virtual geometry inside the volume. The team of White, Saigal, and

Peer review under responsibility of Society for Computational Design and Engineering.

[1] Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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http://dx.doi.org/10.1016/j.jcde.2017.05.001
2288-4300/

Owen (2004) decomposed multi-sweepable volumes into many-to-one sweepable sub-volumes using structured side mesh, and then performed many-to-one sweeping to generate hexahedral meshes. Lu, Gadh, and Tautges (1999) classified edge loops based on convexity and used the edge loops to recognize swept volume. The edge loops then formed decomposition surfaces to decompose the model at one step. Wu and Gao (2014) analyzed all surfaces of the model with heuristic rules to extract potential local sweep directions of the volume and incrementally determined all the swept volumes. The common drawback of all these methods is the limited class of shapes that can be handled.

To date, there are no fully automatic decomposition methods that work for complex generic volumes, and manual decomposition is still required frequently. Manual decomposition is a laborious process and requires a high level of user expertise. Therefore, a tool to reduce the human effort and require lower level expertise is necessary. We have been developing a user-guided semi-automatic decomposition tool (Lu, Song, Quadros, & Shimada, 2014) with the following chief design goals:

- Guiding the users to develop effective decomposition solutions.
- Reducing human efforts in decomposition operations (e.g., creating decomposition surfaces, and setting up decomposition commands).

Our tool provides visual guidance to assist users in determining decomposition solutions, accepts sketch-based inputs to create decomposition surfaces, and simplifies decomposition commands. The tool consists of two key components presented in our previous works: the geometric reasoning engine extracting decomposition features of a volume (Lu, Song, Quadros, & Shimada, 2011), and the sketch-based user interface (UI) designed for manual decomposition (Lu, Song, Quadros, & Shimada, 2010). The tool creates visual guidance based on the extracted sweepable regions to assist users in developing an effective decomposition solution. The visual guidance includes the sweepable regions of the volume, each region's sweeping scheme, and the potential decomposition positions to separate each region. The sketch-based UI offers an intuitive and easy way to perform decomposition operations. Freehand strokes are accepted to define precise decomposition surfaces or set up geometric operations. The decomposition surfaces are automatically aligned to existing feature to enhance mesh quality at the decomposition region.

Currently, only a few user-guided or semi-automatic decomposition methods have been proposed. A lack of user evaluation makes it difficult to improve upon this approach. Based on our previous work, in this paper, we present two user studies involving 43 subjects to evaluate the user-guided semi-automatic decomposition tool. We first provide an extensive description of our user-guided semi-automatic decomposition tool as the first technique that combines the geometric reasoning engine and sketch-based UI to reduce human intervention in volumetric decomposition (Section 4). Secondly, this work provides an evaluation of the visual guidance usability presented. We tested what types of visual suggestions are essential for users to understand the target volume from a decomposition perspective and lead to effective decomposition solutions (Section 5). Third and final, we present an evaluation of the sketch-based decomposition effectiveness. We tested how much performance time could be reduced using the sketch-based decomposition and compared the performance difference between beginners and experienced users (Section 6).

The evaluation result and user feedback found that the visual guidance increased the success rate of decomposition solutions. The sweeping paths and the sweepable regions are essential for users to develop effective solutions. The sketch-based decomposition significantly reduces the user's time on creating decomposition surfaces and setting up decomposition commands. Our user-guided semi-automatic tool enables users who have limited prior experience or familiarity with the computer-aided engineering software to perform volumetric decomposition more efficiently.

2. Related work

While fully automatic decomposition algorithms for general shapes are yet to be realized, an interactive tool that guides the user through the decomposition process and automates some manual efforts could reduce user task performance time and make the entire process easier. The "Immersive Topology Environment for Meshing" (ITEM) (Lu, Gadh, & Tautges, 2001) is an interactive meshing tool that guides the user through a typical mesh generation process implemented in CUBIT (National, 2015). CUBIT is a full-featured software toolkit for mesh generation and geometry preparation. ITEM uses the same strategy as this paper, which is reducing human intervention, to improve the decomposition process. Instead of trying to solve the decomposition problem automatically, ITEM maintains user interaction by guiding the user through the decomposition process and providing the users with potential options or solutions that the user may consider.

ITEM firstly runs a diagnose algorithm (White & Tautges, 2000) to determine whether a volume is mappable or sweepable. For volumes which mapping, sub-mapping or sweeping cannot be automatically determined, a set of decomposition solutions are generated using a feature recognition method (Lu et al., 2001) and presented to the user. The user then makes the decision as to whether a particular decomposition is useful to create meshable sub-volumes.

Each time a decomposition solution is selected, additional volumes (the sub-volumes) are created. ITEM iterates the above diagnosis procedure on the newly added volume until the entire volume is successfully decomposed into a set of mappable or sweepable sub-volumes.

Using this approach, certain level of user understanding of the topology and sweeping algorithm is required. The ordering of decomposition becomes critical in this method, as each decomposition suggestion is generated "locally" on the sub-volume without taking the entire volume into consideration. Not every solution will result in a volume that is closer to being successfully hex-meshed, and may result in a region that is neither mappable nor sweepable.

Our approach not only detects the sweepable regions and suggests the potential decomposition solutions, but also visualizes the sweepable regions and their sweeping schemes. This way, users with limited domain knowledge can easily identify if newly generated sub-volumes are sweepable or not, and what sweeping scheme should be assigned to each of the sub-volume. Our tool also provides an intuitive sketch-based method to conduct decomposition. While ITEM users can only choose from the pre-generated decomposition solutions, our users can use rough graphic inputs to define precise decomposition surfaces corresponding to the visual guidance. This way, beginner users with limited CAD/CAE tool experience can efficiently complete the decomposition task.

3. Practical volumetric decomposition in hex meshing

Our tool is designed to assist the user in performing decomposition tasks easily and efficiently. In order to achieve the goal, we first studied practical way of decomposition for hex meshing to determine aspects that could be automated or could obtain added guidance.

In real world applications, many geometry models can be constructed by sweeping (i.e. extrusion) in 3D modeling software such as Solidworks and Pro/Engineer. In mesh generation, sweeping is a