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

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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

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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 commonly used algorithm to create high-quality hexahedral meshes by extruding a quadrilateral surface mesh from a source surface onto a topologically similar target surface. The traditional sweeping procedure consists of four steps: (1) generate an all-quad surface mesh on a source surface; (2) project the surface mesh from the source surface to the target surface; (3) generate structured all-quad meshes on the linking surface; and (4) generate hex meshes for the volume. The source and target surfaces must be topologically equivalent. The real world geometries are mostly not automatically sweepable and require decomposition to be meshed with a hexahedral meshing scheme.

The first step to solve the decomposition problem is to extract the sweepable regions on the model, because most volumes are not automatically sweepable. It can be an art form to recognize sweepable topologies. Sweepable volumes can be comprised of many different topologies, and swept surface can be extruded through a volume that is rotated or translated. A volume with multiple target surfaces and a single source surface can sometimes be inverted and handled as a many-to-one sweepable volume, or otherwise, be treated as a many-to-many problem.

The second step is to determine the sweeping path and selecting the source and target surfaces. Based on the number of source/target surfaces, the sweeping problem can be categorized into three types: (1) One-to-one: a volume with a source surface and a target surface; (2) Many-to-one: a volume with more than one source surfaces and one target surface; (3) Many-to-many: a volume with more than one target surfaces. Sweepable volumes can also be classified by their sweeping direction, including top-to-bottom, inside-to-outside, and rotational. Sweeping paths must be compatible with adjacent volumes to ensure overlapping surfaces have the same scheme.

The third step is to create decomposition surfaces to separate all sweepable regions. The shape and position of the decomposition surface directly impact the mesh quality at the area of decomposition. The decomposition surfaces should be precise and well aligned to the features. Finally, the decomposition operations are executed to "cut" the volume into smaller sweepable piece.

Fig. 1 shows the workflow using our tool to decompose a model for all hex meshing. Based on the geometric reasoning results, our tool displays the visual guidance such as grouped sweepable medial patches (Fig. 1(a)), sweeping path for each sweepable region (Fig. 1(b)), and potential decomposition position (Fig. 1(c)). The user draws a freehand stroke at one of the potential decomposition positions (Fig. 1(c)). The freehand stroke is snapped to the potential decomposition positions, and the user uses a pen gesture to execute the extrusion command to create a decomposition surface and decompose the volume (Fig. 1(d)). After completing the decomposition that splits all sweepable regions (Fig. 1(e)), the model is finally all-hex meshable (Fig. 1(f)).

4. Overview of the user-guided decomposition tool

Our design goal is to enable beginner and professional users to successfully decompose a given model for high-quality all-hex meshing. Our decomposition tool has two key components to support all steps as discussed in the previous section to solve decomposition problems: (1) The geometric reasoning engine to extract sweepable regions (Lu et al., 2011) from the given volume and generate visual suggestions to support the users (Lu et al., 2014); and (2) the sketch-based user interface that converts user's freehand strokes to create precise decomposition surfaces and automates decomposition commands (Lu et al., 2010).

4.1. Extract sweepable regions

Fig. 2 shows an example of sweepable region extraction and the all-hex meshed result after decomposition. The geometry reasoning engine receives the volume V as input, and generates V's medial $M(V)$ using CADFix API (TranscenData, 2012). $V(M)$ and the map between $V(M)$ and V's boundary representation (B-Rep) are then stored in a data structure. The geometric reasoning engine ran the depth-first-search (Tarjan, 1972) on $V(M)$ to group sweepable medial faces into patches. Each sweepable patch and represents a

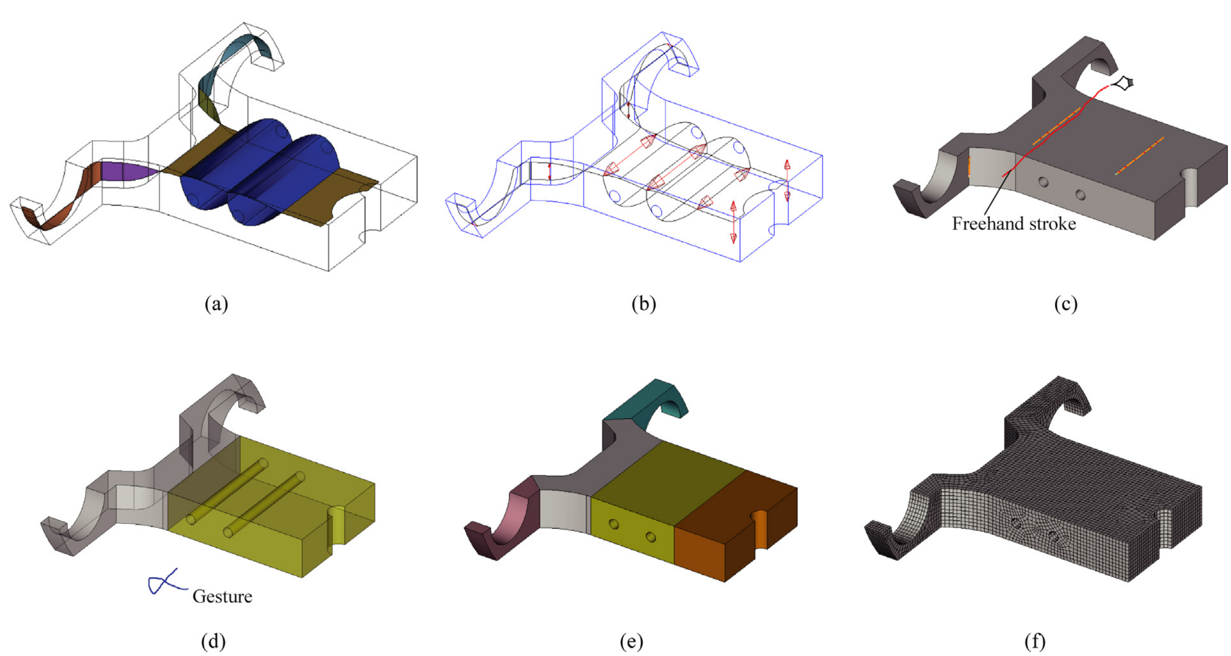


Fig. 1. The decomposition process using our tool. (a) The geometric reasoning engine detects sweepable medial patches. (b) The sweeping path of each sweepable region. (c) The potential decomposition position to help to define decomposition surfaces using a freehand stroke. (d) Extrude the snapped stroke using the pre-defined gesture. (e) Few more cuts were conducted to make all sub-domains sweepable. (f) The all hex-meshed results.

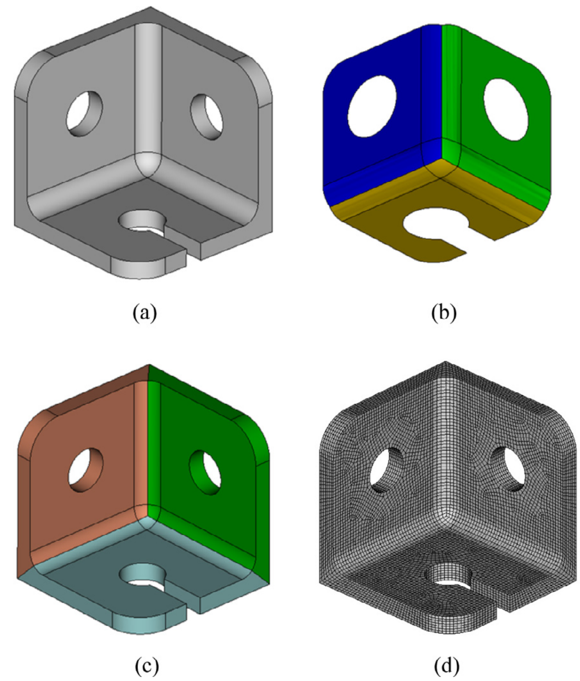


Fig. 2. An example of extracting sweepable regions. (a) The given volume. (b) The geometric reasoning engine groups sweepable medial faces into patches (shown in different colors). (c) Split the three sweepable regions. (d) The decomposition produces in an all-hex mesable volume.

sweepable region on V. Using the one-to-one correspondence between the medial and B-Rep, we can detect the sweepable region of the volume by mapping the medial to the B-Rep.

4.2. Generate visual guidance

Once the sweepable regions are recognized, the sweeping scheme (e.g., the sweeping path and the source/target surfaces) can be determined for each region. The visual guidance includes the color-coded sweepable groups on the $V(M)$, the color-coded B-Rep representing each sweepable region and the sweeping scheme: source/target surfaces, the sweeping path, and the potential decomposition position on the B-Rep. With the visual guidance, users can develop effective decomposition solutions even with limited prior experience and domain knowledge.

4.3. Sketch-based decomposition

The sketch-based UI provides an intuitive and easier way to conduct decomposition. It accepts rough graphical inputs (i.e. freehand strokes) to create precise decomposition surfaces and execute decomposition commands. We first resampled the stroke to remove noise, and then snapped the stroke to either the existing features of the volume or the proper potential decomposition positions generated by the geometric reasoning engine. We minimized the searching space of the snapping candidates based on the stroke shape and location, and retrieved nearby features or potential decomposition positions instead of the entire volume's B-Rep. The sketch-based UI offers a gesture set to quickly access commands that are frequently used.

In the last couple of decades, the CAD technology has evolved significantly and has enabled users in creating detailed CAD models; however, this has brought new challenges to the mesh generation phase. Irrelevant detailed features should be removed to obtain a conformal high quality hex mesh with a small number of mesh elements. Though much focus on automatic defeaturing has been given (Quadros & Owen, 2009), user interactions are still required in many cases, especially for hexahedral mesh generation. The volume shown in Fig. 3 contains two geometric features that are not critical to structural analysis: a thread and a slot. To remove these features with the sketch-based decomposition, the user draws two strokes (Fig. 3(a)) and extrudes the snapped strokes to decompose the threads and slots into separate sub-domains (Fig. 3(b)). After removing the two irrelevant features, more decomposition operations were conducted using smart decomposition operations. Surface E was swept along curve G and surface

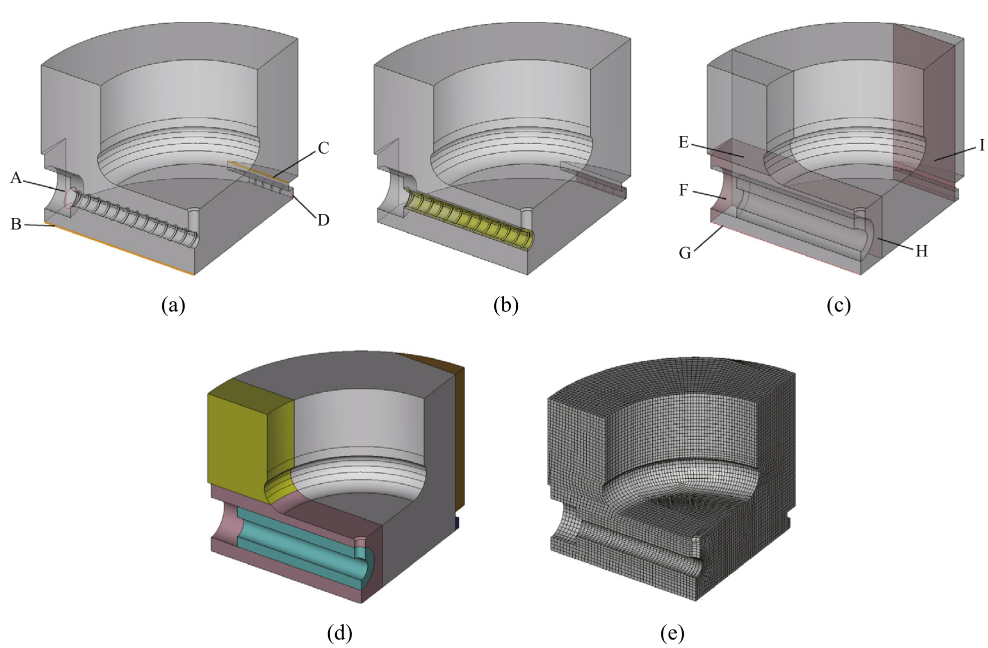
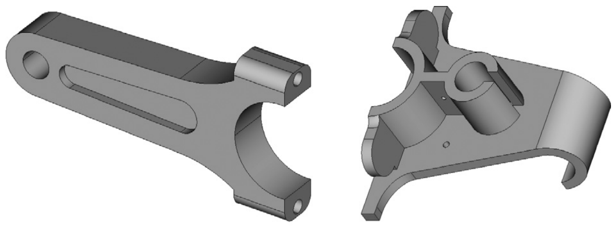


Fig. 3. An example of sketch-based decomposition. (a) Two freehand strokes, A and D, are snapped to a circle and line, respectively. Extrude A along curve B and D along curve C. (b) The two irrelevant features are decomposed (marked yellow and pink). (c) Few more decompositions are conducted: sweep F along G; and extend I. (d) Six sub-domains are created. (e) All hex-meshed result.



(a) (b)

Fig. 4. Models (a) 2 and (b) 3 used in user study 1.

H, E, I were extended to sub-divided the volume (Fig. 3(c) and (d)). Finally, the model becomes all-hex meshable (Fig. 3(e)).

5. User study 1: the usability of the visual guidance

We aim to evaluate how good the visual guidance is to assist the users to develop effective decomposition solutions, and to obtain feedback about the way we display visual suggestions. We tested the effects of the visual guidance on solutions' success rates of producing all-hex meshable results.

5.1. Subjects

We held a pre-selection section inviting 30 technology company employees, who have finite element analysis (FEA) working knowledge and a basic understanding of mesh generation process. The subjects did a self-evaluation questionnaire to rate their FEA proficiency level on a scale of 1 (limited experience – You are expected to need help when performing FEA task) to 4 (expert – You can provide guidance, troubleshoot and answer questions related to this area of expertise and the field where the FEA skill is used). We selected 21 subjects who rated themselves at level 3 or 4 from these 30 subjects to evaluate our tool.

5.2. Experiment setup

We ran the experiment in a quiet laboratory space, with subjects sitting comfortably at a desk with a display, keyboard, and mouse. The model and the visual guidance were demonstrated on the display. Subjects manipulated the views in the software to review the model and visual guidance from different angles.

5.3. Testing procedure

Before the test, we explained the concept of the visual guidance, gave a 15 min tutorial on reading the visual guidance, and demonstrated how to switch among the different guidance. After the tutorial, we gave a short quiz to ensure that subjects fully understood the logistic. Next, the subjects had another 15 min warming up period to explore the tool, manipulate views of the model and visual guidance, and ask questions if any arose. Below is the entire procedure of this user testing:

1. Tutorial
2. Warming up
3. Testing session (Model 1) 2 trials
4. Testing session (Model 2) 2 trials
5. Testing session (Model 3) 2 trials
6. Meshing 3 models
7. Feedback session

In the testing session, subjects created a decomposition solution on three industrial models (Figs. 1 and 4). There are two trials for each model, and visual guidance is only available in the second trial. To focus on how much the visual guidance could help the subject to develop effective decomposition solutions rather than how the subjects operate the decomposition commands, we asked subjects to describe their solutions on the solution sheet (Fig. 5) instead of conducting a real decomposition. A valid solution should clearly present all the sub-volumes, the position and the shape of the decomposition surfaces, and the associated sweeping scheme

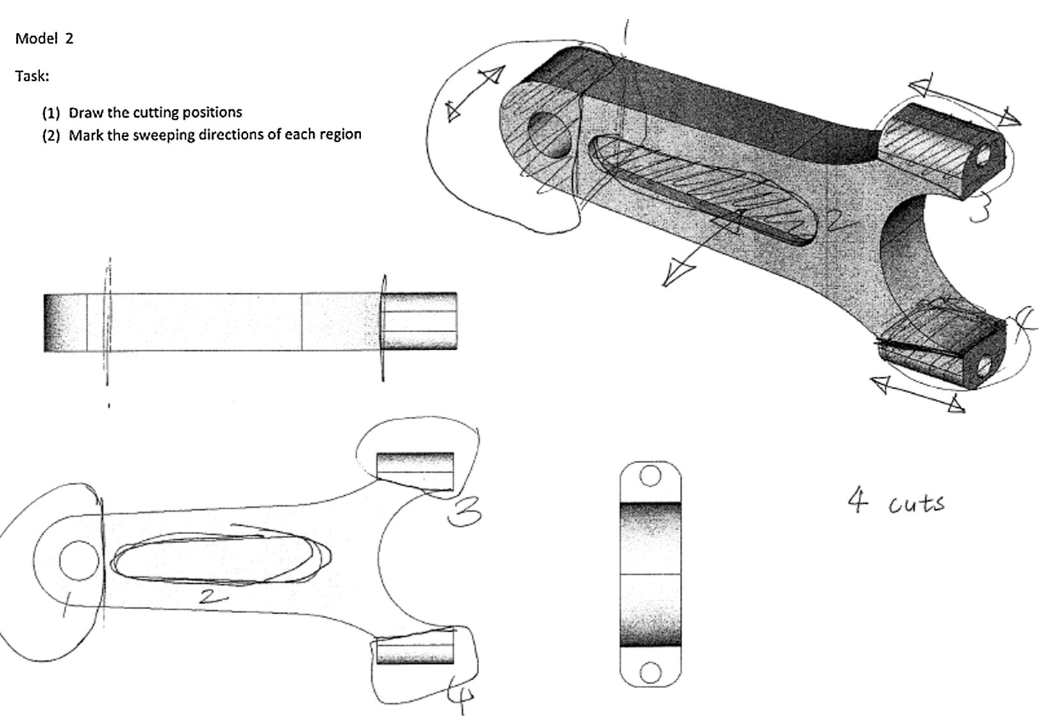


Fig. 5. The decomposition solution to model 2 marked by one of the subjects.

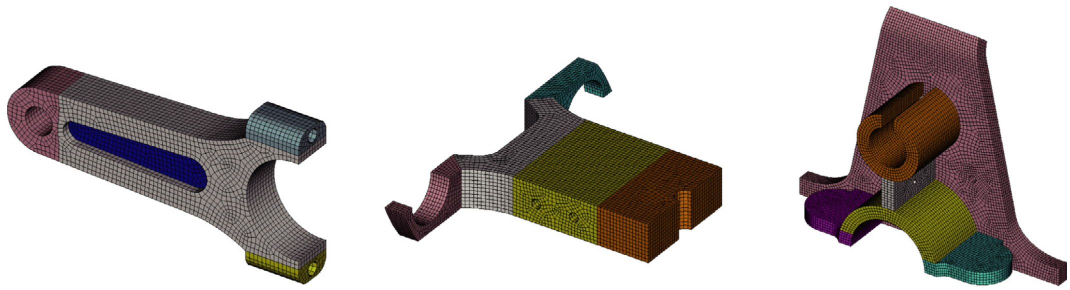


Fig. 6. Subjects' decomposition solutions make the volume all-hex meshable.

including sweeping paths and source/target surfaces. After the subject had completed the solution of a model, we followed the subject's solution to perform decomposition on the model and set up the meshing scheme. The subject confirmed the decomposition we performed had correctly followed his/her solution. Now the first trial on one model was over. At this moment, the model is not meshed yet to avoid the subjects to get extra information from the meshing result, so in the second trial we can ensure the effect (if any) on subject's performance only comes from the visual guidance. Then, we started the second trial using the same procedure with the only difference being that visual guidance was available.

A decomposition solution is considered successful if the model can be all-hex meshed, otherwise it failed. We evaluated the usefulness of the visual guidance by the successful rate of the solution instead of the complete time of the two trials, because the factors that contributed to a shorter task completion time in trial two might not only come from the visual guidance. The subjects might need lesser time in observing the same model in the second trial than the first trial.

After all the testing sessions, we meshed the model and showed the results to the subjects. Then, subjects rated each visual guidance on a scale from 1 to 4 (1 to be not at all useful, 2 to be not very useful, 3 to be somewhat helpful, and 4 to be very helpful). Even point scale was used to force the subjects to take sides and avoid middle options. Finally, a short interview was conducted to collect feedback.

5.4. Result and discussion

Successful decomposition solutions on each model from trial two are shown in Fig. 6. The success rate of trial two (74.6%) is higher than trial one (38.09%), which shows that the visual guidance can increase the success rate of the decomposition solutions. The static analysis was performed in R (R Development Core Team, 2014), and Pearson's Chi-squared test indicates that success rate strongly depends on being assisted by visual guidance or not ($x^2 = 15.6169, df = 1, p = 7.756e-05$).

Table 1 shows the usefulness ratings of the visual guidance. Subjects rated the usability of the sweeping path (3.52) and sweepable medial face group (3.43) as very useful. These two types of visual guidance helped subjects to understand the volume better from the perspective of decomposition. 70% of the subjects commented that the sweeping path is a very powerful hint to help to determine the meshing scheme, and with this guidance, the subject was more confident about his/her solution. Subjects rated the potential decomposition position (2.90) and sweepable region (2.43) as not so helpful. Eight subjects had difficulty determining decomposition surface only by looking at potential decomposition positions. Nine subjects commented that the potential decompositions should be displayed in the same color with the sweepable regions they are splitting to be easier recognizable. Half of the subjects also suggested that showing the entire decomposition surface instead of the decomposition position on the B-Rep could be more useful and easier to follow.

Table 1
Usability ratings of the visual guidance. From scale 1 to 4: 1 to be not at all useful, 2 to be not very useful, 3 to be somewhat useful, and 4 to be very useful.

Visual Aid	Mean	Median
Sweeping path	3.52	4
Sweepable medial face group	3.43	3
Potential decomposition position	2.90	3
Sweepable region B-Rep	2.43	2

6. User study 2: sketch-based interaction style for decomposition operation

We were particularly interested in the tool's ease-of-use, ease-of-learn for the beginner users, and how significant previous CAD/CAE experience would affect our tool's performance. The proposed tool has been implemented in a geometry and mesh generation toolkit, CUBIT, a full-featured software tool that supports meshing, 3D modeling, and comprehensive decomposition operations. In this user study, we compared the subject performance with and without out sketch-based decomposition tool, and used the original CUBIT to represent the existing commercial CAE packages.

6.1. Subject

Twenty-five subjects participated in the user study and three of the data sets were invalid due to timer error. Half of the subjects had prior experience using 3D CAD/CAE packages including SolidWorks (72%), Pro/Engineer (54%), MAYA (36%), and AutoCAD (36%). Half of them had no related experience before the user study. None of the subjects had been exposed to a sketch-based version of 3D CAD/CAE packages and CUBIT.

6.2. Task one: Drawing primary shapes using the sketch tool

Task one evaluated the shape recognition accuracy in the sketch-based decomposition. We also wanted to ensure the subjects were able to create the desired strokes with the current configuration. This session lasted approximately 8–10 min. We provided two types of input device: stylus/tablet and mouse. Before the test, a 10 min warm up period was given to let the subjects become familiar with the hardware configuration. Then, the subjects were asked to draw the four primary shapes frequently used in decomposition: circle, arc, line, and spine. For each shape, subjects did three trials using one of the provided input devices of their choice. To prevent the subjects from adjusting their drawing style based on the output in the next trial, each session involved data collection only, and the data was processed later.

6.3. Task two: Performing sketch-based decomposition

Task two evaluated the performance of the sketch-based decomposition. This session lasted approximately 40–60 min. Subjects were asked to use both the sketch-based decomposition and CUBIT to decompose the model (Fig. 3(a)) into sub-domains as shown in Fig. 3(d), with minimal help from us. For each tool, we gave a brief demonstration of the UIs and basic operations that might be used to the test. A 10 min warm up period was given to let the subjects become familiar with the system and hardware configuration. The order of interface types was randomized: half of the subjects started the test with CUBIT, and the other half began with the sketch-based decomposition.

Fig. 7 illustrates the study environment. Each subject was instructed to sit in front of two monitors. The subjects performed the decomposition task on the main monitor (Fig. 7(a)) with a Wacom Intuos Pro medium digital tablet (Fig. 7(c)) or a mouse. The secondary monitor (Fig. 7(b)) displayed the targeting result. Subjects could rotate the model or change the viewing angle anytime during the task, or refer to the instruction sheets (Fig. 7(d)) that illustrated the model's exploded view diagrams. After the task, the subjects rated the user experience and provided feedback.

The task involved sub-dividing of two irrelevant features (thread and slot) from the main volume, and sub-dividing the object into six sub-domains. The decomposition positions for the two irrelevant features were not required to be the same as the example, but had to be well aligned to the features: concentric to the thread, and parallel to the slot; while the other cuts must be the same as the instruction. Although we did not set any time constraints, the subjects were encouraged to complete the task within 30 min.

6.3.1. Process the data

To analyze the data correctly, we first verified that the data was normally distributed. The performance time using each tool had normal distribution (Sketch $p = 0.52$; CUBIT $p = 0.38$, Shapiro-Wilk test). The ease-of-use ratings were not normally distributed (Sketch $p < 0.005$, CUBIT $p < 0.001$, Shapiro-Wilk test). The ease-of-learn rating was not normally distributed either (sketch $p < 0.001$, CUBIT $p < 0.05$, Shapiro-Wilk test). Therefore, a Student's paired t-test was selected to analyze the task performance time and a Wilixcon signed-rank test was utilized to compare the ratings. Next, we verified if the order of tools to begin with affected the subject's performance and rating. Table 2 shows the p-value using sketch-based tool first and CUBIT first. No significant differences were found in the performance time, ease-of-use rating, and ease-of-learn rating, which designated that the tool to begin with did not affect subject's performance and feedbacks.

Table 2
The p-value of the results with different tool ordering.

	Time	Ease-of-use	Ease-of-learn
Sketch first	0.82	0.31	1.0
CUBIT first	0.85	0.38	0.39

Table 3
Comparison of average time (s) utilized by experts, beginners and both groups combined using sketch-based decomposition or CUBIT.

	Expert	Beginner	Combined
Sketch	418.3	453.9	436.1
CUBIT	687.4	951.4	819.4

6.4. Result and discussion

In task one, 168 drawing samples were collected. The accuracies were: line – 95.2%, circle – 92.6%, arc – 80.9%, and spline – 95.2%. Overall the subjects were satisfied with the recognition rate. However, the failure case for arc recognition did affect the subjects' satisfactory ratings. In the feedback section, some subjects indicated that the improvement of arc recognition rate would increase the ease-to-use rating.

Table 3 and Fig. 8 show the result of the average task performance time by expert and beginner subjects. For both groups, the sketch-based decomposition appeared to require less task performance time. Though there was no significant difference between each tool for expert subjects ($p = 0.16$, paired t-test), there was a very significant difference for beginner subjects ($p < 0.01$, paired t-test).

The beginner and expert subject had similar performance time using the sketch-based decomposition ($p = 0.17$, paired t-test). However, beginner subjects needed more time than expert subjects using the existing CAE package to complete the task ($p = 0.01442$, paired t-test), with the average time of 687.4 s for experts and 951.4 s for beginners.

For the reader to see the different decomposition workflows of the sketch-based tool and CUBIT, we recorded the user study task two by capturing screen videos. We split the screen video into three segments containing different decomposition actions. In each segment, we first show how the decomposition action can be done

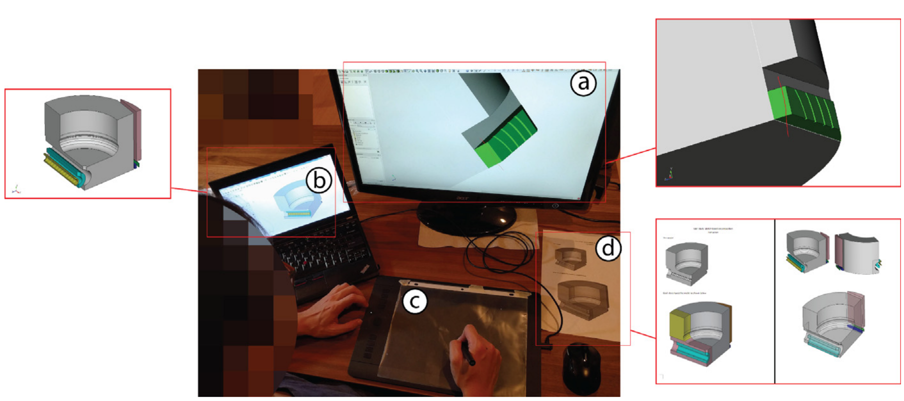


Fig. 7. The environment setup for task two. (a) A monitor displays the current task. (b) A monitor shows the targeting results. (c) A digital tablet for freehand stroke input. (d) The instruction sheet.

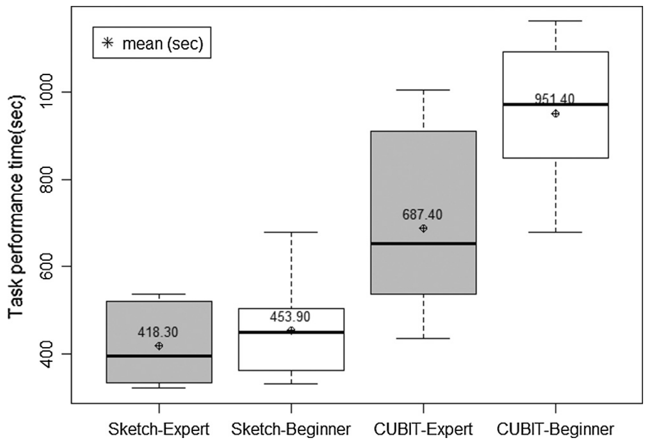


Fig. 8. Beginner and experienced subjects' decomposition task performance time with different tools.

in the proposed sketch-based tool and then in CUBIT. The video highlights that when using CUBIT, the user has to look for proper commands and entering geometry details to set up the operation. When using the sketch-based decomposition tool, the user only needs to draw freehand strokes and the system automatically captures the essential geometry details to set up the commands and selects the proper operations.

Since task two did not ask for the decomposition positions to be the same as shown on the instruction, to measure the quality of the results produced with the two systems, we obtained the mesh quality at the decomposition regions on the resulting models produced with the sketch-based tool and CUBIT. The decomposition surfaces need to be well-aligned to the existing features to obtain good quality meshes at the decomposition regions. Both expert and beginner subjects were able to obtain similar mesh quality to the instruction at the decomposition region E, F and I (Fig. 3(c)). Most of the subjects were able to obtain similar mesh quality with both tools at the blue region in Fig. 3(d), except some beginner subjects were not able to create a concentric curve as the curve A in Fig. 3(a) to the yellow feature in Fig. 3(b) using CUBIT. The resulting mesh quality was different at that region because the decomposition surface was not well-aligned.

Table 4 shows the result of the average ease-of-use rating by expert and beginner subjects. For expert and beginner subjects, the sketch-based decomposition appeared to be easier to use than CUBIT. The difference between each tool was significant for expert subjects ($p = 0.03$, Wilcoxon test). The difference between each tool was very significant for beginner subjects ($p = 0.0008568$, Wilcoxon test), which means that beginners find the sketch-based decomposition was much easier to use than existing packages.

Table 5 presents the result of the average ease-of-learn rating by expert and beginner subjects. For both groups, the sketch-based decomposition appeared to be easier to learn than CUBIT. The difference between each tool was not significant for expert subjects ($p = 0.1315$, Wilcoxon test) while the difference between each tool was very significant for beginner subjects ($p = 0.008829$, Wilcoxon test). Beginner subjects felt that the sketch-based decomposition was much easier to learn than existing packages ($p < 0.05$, Wilcoxon test) while there was no significant difference in learning both tools by expert subjects ($p = 0.14$, Wilcoxon test). The reason ease-of-learn rating of CAE did not have a significant difference from the sketch-based decomposition could be that expert subjects were already familiar with existing CAE packages, and could easily adapt their prior experience to any other new CAE packages.

To summarize, the sketch-based decomposition was easier to use and learn for both expert and beginner subjects. For beginner subjects, tool types made a significant difference in task performance time. The result showed that the tool reduced the time for the beginner users to perform a task in the sketch-based UI by 48% and saved 39% of the time for the expert users. For all the users in this study, 46% of the time was reduced when performing a decomposition task using the sketch-based decomposition as compared to using the traditional CAE tool. The sketch-based decomposition was also significantly much easier to learn and use than the existing CAE packages for the beginner subjects.

Table 4
Comparison of ease-of-use rating utilized by experts, beginners and both groups combined using sketch or cubit. Scale: 1 = hard, 5 = easy.

	Expert	Beginner	Combined
Sketch	4.43[a]	4.14[a]	4.29
CUBIT	3.43[c]	2.86[c]	3.14

$b = (p < .01)$.
[a] $(p < .05)$.
[c] $(p < .001)$.

Table 5
Comparison of ease-of-learn rating utilized by experts, beginners and both groups combined using sketch or cubit. Scale: 1 = hard, 5 = easy.

	Expert	Beginner	Combined
Sketch	4.43	4.43[a]	4.43
CUBIT	3.86	2.86[a]	3.36

$b = (p < .01)$, $c = (p < .001)$.
[a] $(p < .05)$.

7. Conclusion

We presented user evaluations of the user-guided semi-automatic decomposition tool we developed for hex mesh generation. The tool combines sketch-based decomposition and geometric reasoning engine to assist both expert and beginners users in performing decomposition easily and efficiently. The user evaluation results indicate that our tool provides useful visual guidance to lower the required expertise level in determining effective decomposition solutions and that it enables sketch-based decomposition to reduce time cost and human efforts for manual decomposition. The sweeping paths and the medial face groups of the sweepable regions are essential visual guidance for decomposition tasks and increase the success rate of user's decomposition solution by 28%. The sketch-based decomposition is easy to use and learn for beginner users and reduces 46% of the task performance time.

8. Future work

To create symmetric meshes on a symmetric model, the approach is to mesh only half of the volume and then copy the mesh onto the other half section. A potential direction to expand the functionality of the proposed tool is to support symmetry detection. One option is to have the user to draws the symmetric axis of the model using a freehand stroke, and then the system takes the stroke as a hint to finalize the symmetric analysis. Another option is to add the symmetric axis to the freehand stroke snapping option. As the radii of the maximum balls of the Medial Axis (MA) are equidistance from the boundary, MA has the potential to identify symmetric axis. The stroke can be snapped to the symmetric axis and extruded to split the model into two symmetric sections. This kind of additional decomposition option could enable the user to conduct decomposition easier and faster for hex mesh generation.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jcde.2017.05.001.

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