Wrap-around Operation for Multi-resolution CAD Model

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ABSTRACT

In the design of a very complex product, the multi-resolution modeling technique plays an important role for the real time operation of the model on computers. There are many previous works to simplify or compress the geometric data to obtain a multi-resolution model from the original shape. But, most of them focused on the generation of multi-resolution model for facet-based models, not for B-rep models. The facet model is good enough for rendering purpose, but is not the basis model for many commercial CAD systems. A new multi-resolution algorithm for the B-rep model is needed to improve the interactivity in dealing with a large assembly model generated by CAD systems. We propose a new modeling operation, called *wrap-around*, to simplify a B-rep model. With this operation, a part model and an assembly can be simplified efficiently to yield multi-resolution models. Also, applying the reverse *wrap-around* operation can recover the original un-simplified model. In this paper, the structures and the processes to realize this operation are discussed in details, and some examples are also demonstrated.

Keywords: Multi-resolution, LOD, B-rep, Wrap-around, CAD

1. INTRODUCTION

As each part of a product is modeled and added to the product model in a 3D modeling system, the number of the parts in the product model increases more and more. Each part alone is composed of a lot of complex shapes, and the total number of the faces and the edges of the total product to be calculated and displayed becomes extremely large. So, efficient handling of a very large and complex assembly data is one of the most significant issues in the modern 3D modeling systems. Actually, similar kinds of the performance problems have been studied in computer graphics for the real-time rendering (time-critical rendering) for a long time. So many methods have been proposed to solve the problem, and the LOD(Level-Of-Detail) and the culling techniques are among them. These techniques make great contributions to graphic performance, but they are mostly based on the polygonal model. Polygonal model, specifically the “triangular mesh” representation, is very efficient to be rendered in the graphics pipeline, but is inadequate for the accurate shape modeling. Even though most commercial 3D CAD systems are based on the boundary representation (B-rep) with curved surface equations to describe the shape of the model, research results to solve the performance problem of the B-rep model are very few. The intention of this paper is to propose a new method for multi-resolution modeling of B-rep model, called *wrap-around* operation. This operation can be used to simplify the shape of the model, mainly in topology, in order to increase the performance in the 3D CAD system. The rest of this paper is structured as follows: Section 2 gives a brief overview on the whole algorithm. Section 3, 4 gives more detailed description of each step of the procedure. In Section 5, several examples are explored to verify the effectiveness of the algorithm finally closing remarks and discussion are made in Section 6.

2. ALGORITHM OVERVIEW

2.1 Overview

When only a rough shape of an object is desired to be shown, one of the simplest methods would be wrapping the object with a thin sheet (such as kitchen wrap). Holes and some cut-off regions will be covered and hidden, and the resulting shape will be just like the convex-hull shape of the object. The holes and some cut-off regions may be regarded as “detail shape” of the object. If detail shape elements can be identified and removed from the object, a simplified shape of the original object can be obtained. By selecting appropriate number of detail shape elements for the removal, many object shapes corresponding to various simplification levels can be derived. This is the basic idea of the part-level wrap-around algorithm proposed in this paper to realize multi-resolution. When many parts are assembled into an assembly, the detail shape elements of all the parts can be ordered in a sequence depending upon their contribution to the total shape of the assembly, and the various resolution of the assembly can be derived similarly by eliminating these detail shape elements in the proper order. This is the basic idea of the assembly-level wrap-round algorithm. In deriving the multi-resolution modeling algorithm, the following constraints were imposed; (1) the algorithm is applied to the B-rep model used in the current CAD systems, and the resulting model of the each simplification step should be also a valid solid model, (2) the computing time for searching the detailed shapes should be much shorter than that of the existing feature-recognition algorithms. To achieve these goals, the developed wrap-around is composed of the geometric operations assuring the valid solid model, and uses the simpler and faster searching algorithms focusing on only the limited types of features compared to the existing feature-recognition techniques.

2.2 Definitions

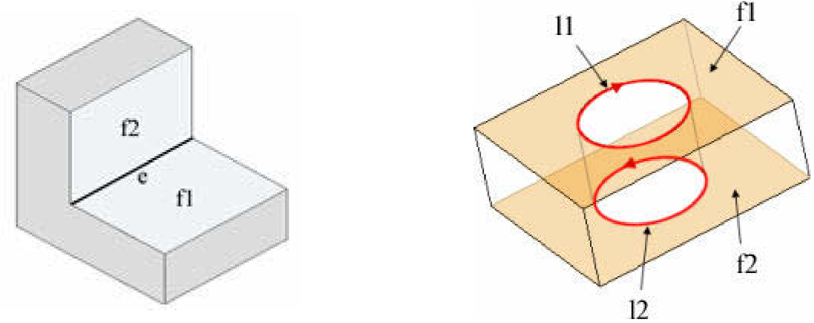
A brief definition of the terminologies frequently used in this paper is given here before proceeding to the detailed description of the algorithm.

Concave edge, concave face and concave feature

An edge *e* shown in Fig. 1(a) is called concave edge if two faces meeting at the edge have an internal angle greater than 180 degrees. In this case, these two faces, e.g. f1 and f2 in Fig. 1(a), are called concave faces. And a concave feature is defined by a set of concave faces

Hole feature

A hole feature is composed of a set of faces constructing the hole shape, and these faces are called the hole faces. In this paper we consider only a simple hole shape. A simple hole has the hole loops bounded by convex edges as its exit and entrance are shown in Fig. 1(b)

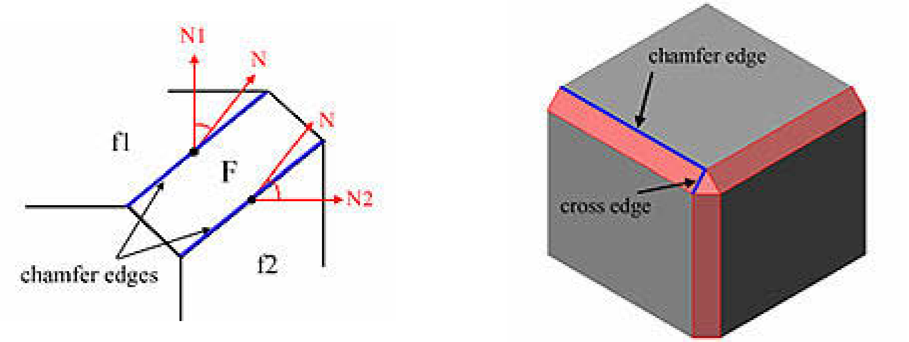


(a) Concave face and edge (b) Simple hole feature

Fig. 1. Illustration of the concave feature and hole feature

Chamfer feature

A chamfer feature is composed of a set of faces forming the chamfer shape, and these faces are called the chamfer faces. The angle between the normal vectors of the faces meeting at the chamfer edge should form an acute angle as shown in Fig. 2(a), and it means that all chamfer edges should be convex. Consecutive chamfer faces are connected by cross edges.



(a) Characteristics of chamfer feature (b) Chamfer edge and cross edge

Fig. 2. Definition of the chamfer feature

Fillet/round feature

A fillet/round feature is composed of a set of faces forming the fillet/round shape, and these faces are called as the fillet/round face. In this paper, we consider cylindrical, spherical, toroidal surface for fillet/round faces, but not complicated surfaces such as radius-variant fillet face. The only difference between the fillet features and the round features is that the fillet feature is applied to the concave edge while the round feature is to the convex edge. Each fillet/round face has the spring edge, where the fillet/round face and its neighboring face meet at C1 continuity (Fig. 3).

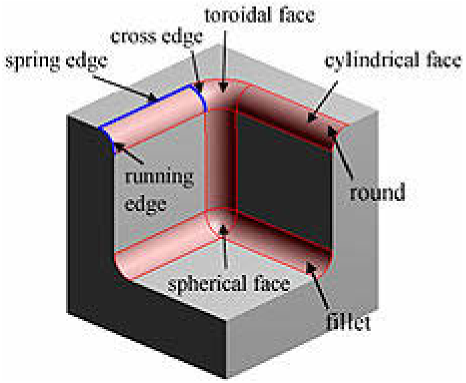


Fig. 3. Structure of the fillet/round feature

Suppressible feature

Suppressible feature is a feature that can be removed through the wrap-around operation. Each inter-connected face set is tested and evaluated if it can be a suppressible feature. In wrap-around, we consider concave feature, hole feature, fillet/round, chamfer feature as suppressible feature.

Wrap-around Forward operation / Wrap-around Backward operation

Using the wrap-around algorithm, we may simplify a model by removing the suppressible feature one by one. But, more practically, we set an arbitrary LOD(Level-Of-Detail), and the model is simplified to satisfy the desired LOD. This simplification process is called the Wrap-around Forward operation. To the contrary, the detailed shape can be recovered by adding the removed suppressible features to the simplified model again. This reversibility of the simplification process is one of the important features of the proposed wrap-around algorithm, and this recovery process is called Wrap-around Reverse operation.

3. PART-LEVEL WRAP-AROUND OPERATION

3.1 Wrap-around Forward operation

Simplification of a part model (Wrap-around Forward operation) is composed of the following processes; (1) detection of the suppressible features, (2) determination of the removing sequence of the suppressible features, (3) generation of the simplified solid model by removing successively the suppressible features.

3.1.1 Detection of suppressible features

In current Warp-around algorithm, following four kinds of features are considered to be the suppressible features: concave, hole, chamfer, fillet/round features. These features are identified in the order of (1) chamfer features, (2) fillet/round features, (3) hole features, (4) concave features following the procedure described below.

1. Mark all the faces in the part as un-visited face.
2. Select any un-visited face.
3. If a face is chamfer face, find other chamfer faces connected with the current face using cross edge of the face (Fig. 2(b)). After all the connected chamfer faces are found, save them as a chamfer feature.
4. If a face is fillet/round face, find other fillet/round faces connected with the current face. After all connected fillet/round faces are found, save them as a fillet/round feature.
5. If a face is hole face, find the other hole faces connected with the current face by visiting the adjacent faces successively. After all connected hole faces are found, save them as a hole feature.
6. If a face is concave, find other concave faces connected with the current face by visiting the adjacent faces successively. After all connected concave faces are found, save them as a concave feature.
7. Repeat 2~6 steps until there is no un-visited face.

3.1.2 Determination of removing sequence of suppressible features

Basically in wrap-around, we define a suppressible feature by a group of faces composing the feature. Since the extent of the model change can be assumed to be proportional to the size of the suppressible features, the area of the faces composing the feature can be used as a measure to define LOD. Therefore the removing order of the suppressible features is made according to the total area of the faces in each suppressible feature. There are often situations where a feature is composed of a repeated layout of its component feature. Gear teeth and circumferentially arranged bolt's holes are common examples of this kind of feature. When this kind of feature is to be suppressed, it would be natural for the whole feature group to be suppressed. This situation is detected by the repeated features with the same area. Thus, if there are suppressible features with same area, we group them into one suppressible feature group and consider it as one suppressible feature.

3.1.3 Generation of a simplified model

The simplification process starts by deleting faces of the suppressible features. But a simple deletion of the faces in a B-rep model results in an open model which is not a valid solid model. There are some previous researches to fix an invalid solid model after deleting faces in a B-rep model. S. Vekataraman and M. Sohoi presented a method to reconstruct a B-rep by expanding and contracting the faces adjacent to the faces being removed [13]. D. Sandiford and S. Hinduja presented the construction method of feature volume using topological and geometrical information found in the B-rep model [14]. H. Zhu and C.H. Menq presented the algorithm for deleting blending face such as fillet/round [7]. In this paper, we utilize the existing functions in the commercial modeling kernel, ParaSolid® to delete faces and to fix the model into a valid solid model (Fig. 4) After valid solid is built up, the deleted faces are saved for later recovery operation, so called wrap-around reverse operation.

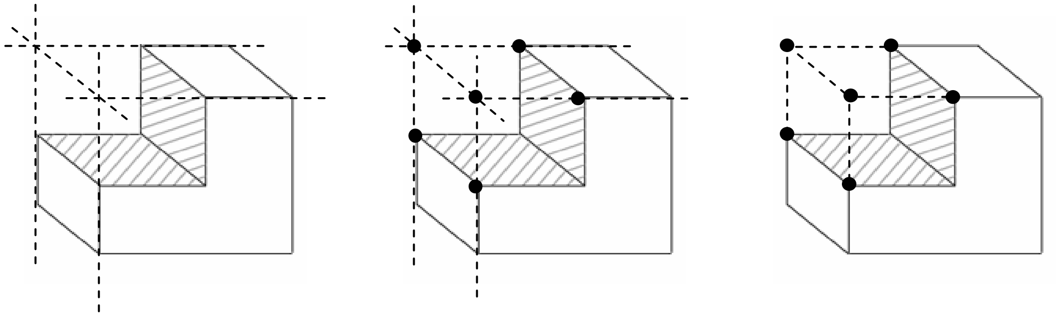


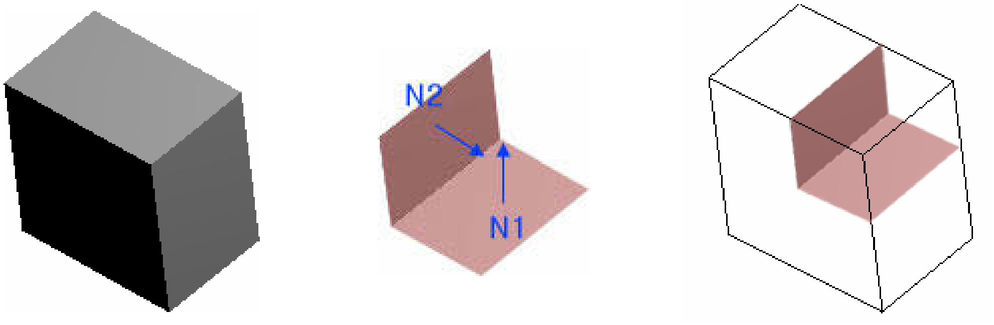
Fig. 4. Process for fixing invalid solid model.

Fig. 4 illustrates the process described above. The hatched faces are deleted and its neighboring faces are expanded and intersected each other to yield the new boundary of the neighboring faces.

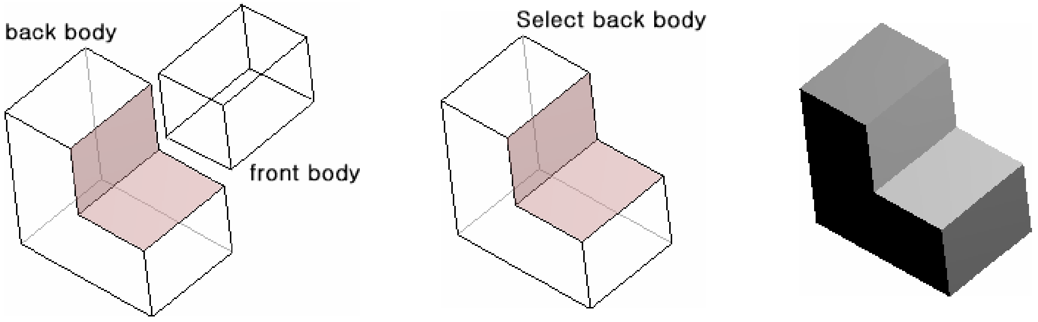
3.2 Wrap-around Reverse operation

Wrap-around forward operation is a process for removing suppressible features from a model. However it is also necessary to go back to the finer model to realize a multi-resolution operator. Two recovery processes are implemented based upon the type of the suppressible features. First of all, most of suppressible features are a minus features such as concave features, hole features, chamfer features, and round features. They are made by subtracting a certain volume. We propose a recovery method for these features as follows (Fig. 5).

1. Make a single sheet body from the faces defining the suppressible feature.
2. Implant the sheet body into the simplified model.
3. Cut the simplified model by the sheet body, resulting in two separate parts, front body and back body. Front body is located at the side pointed by the face normal vector of sheet body while back body is at opposite side.
4. Delete the front body, and we choose the back body as the original (un-simplified) model.



(a) Simplified B-Rep (b) Sheet body (c) Implanting sheet body



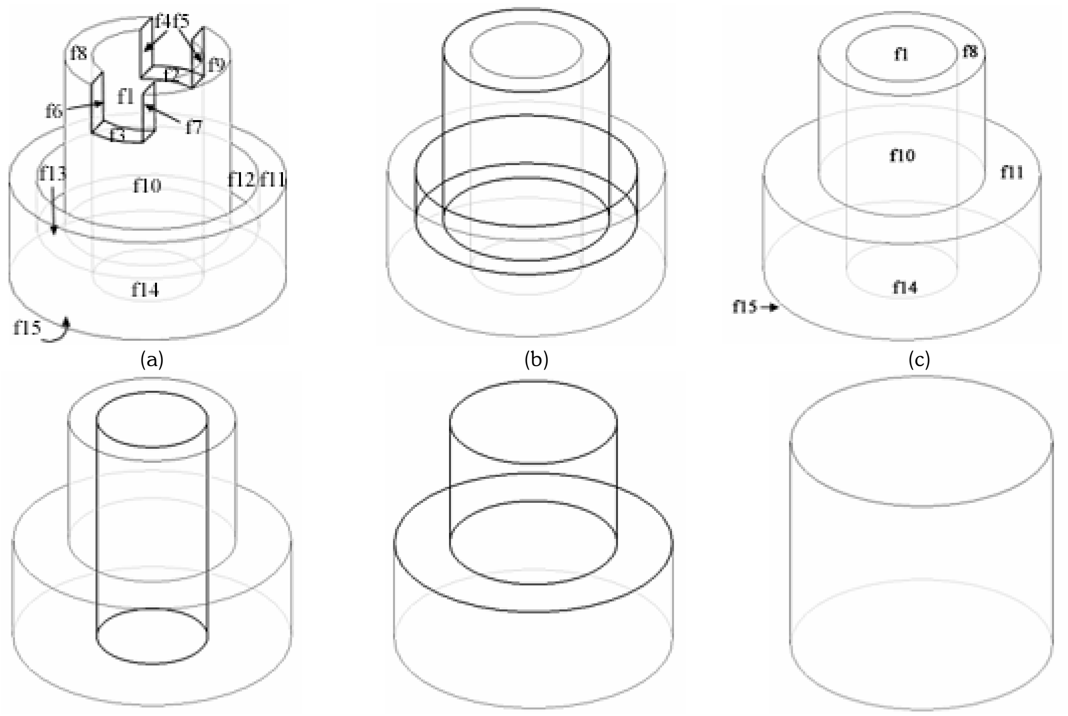
(d) Sectioning (e) Remove front body (f) Original B-Rep

Fig. 5. Recovery of original model from simplified model

To the contrary, fillet feature is an additive-volume feature. In this case, after removing fillet feature, we save the newly created edge and radius of the feature. Then the fillet feature is recreated along the saved edge using the saved radius at reverse operation.

3.3 Consideration over the multi-step LOD model

In some cases, suppressible features need to be detected recursively from the simplified model because a new hole or concave features can be generated during the simplification process. We call a model in this situation as multi-step LOD model.



(a) (b) (c)

(d) (e) (f)

Fig. 6. Example of the multi-step LOD model

In the model shown in Fig. 6, faces f2~f7 and f10, f12, f13 will be detected as the suppressible feature faces and removed. But f10 and f11 still remain as faces of a concave feature and f1 as a hole feature at the simplification level shown in Fig. 6(b). Simplification process may be stopped if the user is satisfied with this simplification step. But if further simplification is desired, remaining concave and hole features need to be detected. Then, they are removed to result more simplified models as in Fig. 6(e) and Fig. 6(f).

4. ASSEMBLY-LEVEL WRAP-AROUND OPERATION

We assume that assembly model is a group of two or more parts described by B-rep. In wrap-around assembly operation, any prior information from modeler such as topological constraints between parts is not needed. It simply detects and sorts the suppressible features for each part as if its part level operation does. But all the suppressible features are again sorted in the order of the size of the suppressible features in the whole assembly. This is because we are interested in the extent to which the whole assembly, not each part, is simplified by the suppressible features. Fig. 7 shows the simple assembly model composed of 2 parts and 3 suppressible features. Assembly-level wrap-around makes a removal list of suppressible features by the order of face area, and then operates part level wrap-around for each suppressible feature.

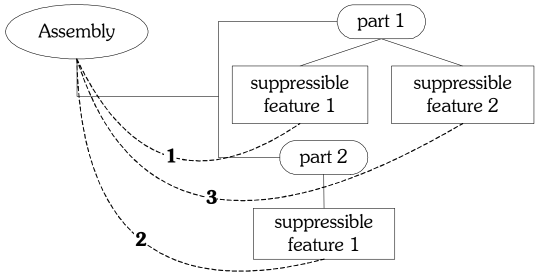


Fig. 7. Rearrange of suppressible feature in Assembly.

5. IMPLEMENTATION AND EXAMPLES

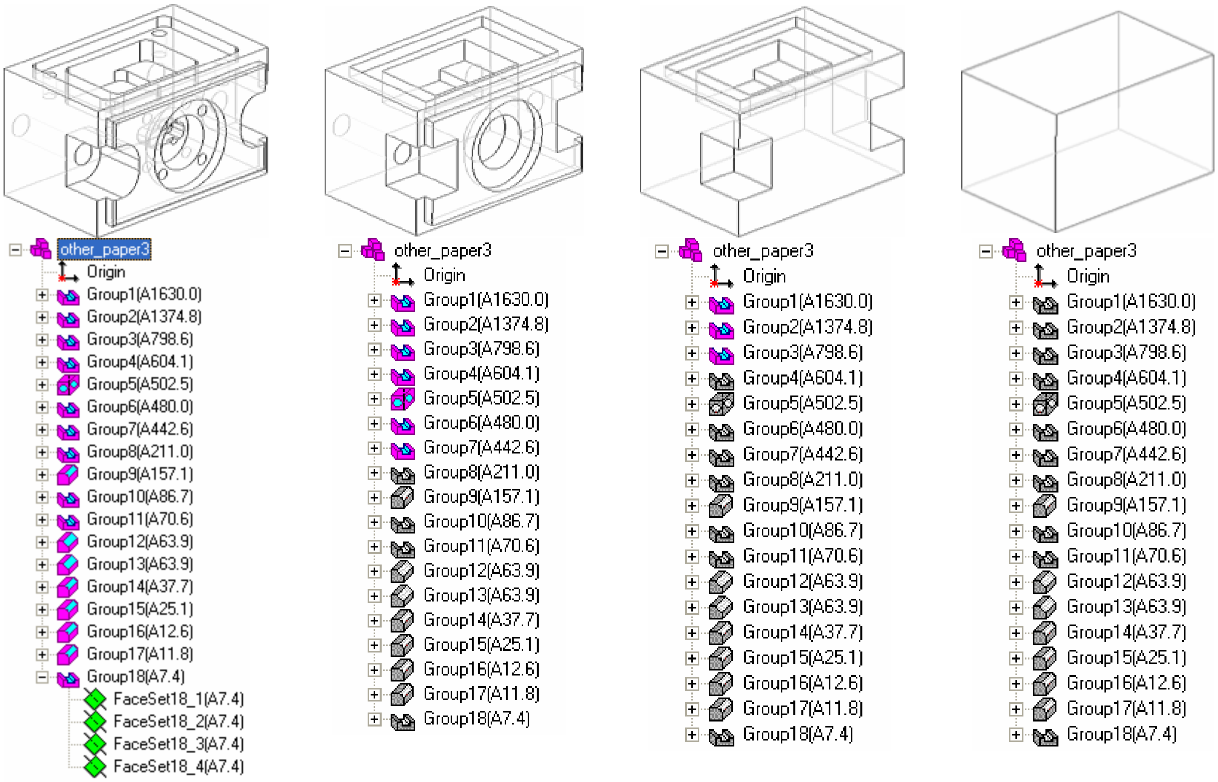
The proposed wrap-around algorithm has been implemented on the Parasolid modeling kernel (v12.1) from Unigraphics Solutions and Visual Studio v6.0 from Microsoft Corp. All 3D entities are rendered using OpenGL graphics library, and all examples are tested in Windows XP. Here we present two examples: the first one is an example for the part-level wrap-around algorithm, and the second one is for the assembly-level wrap-around algorithm. Also, to measure the amount of reduction through the algorithm, we simply define the data reduction rate (ε) of B-rep model as follows;

$$\varepsilon = 100 - \left(\frac{N_s}{N_w} \times 100\right)(\%)$$

(N_s: number of faces in the simplified model, N_w: number of faces in the original model)

5.1 Example 1 (part-level wrap-around algorithm)

First example is for the part-level wrap-around algorithm. This model is from the part library of NIST(National Institute of standards and Technology). The original part model has 19 fillet/round features; 21 concave features; 2 hole features. We added 2 chamfer features to test our algorithm for chamfer feature. Therefore the wrap-around algorithm is applied to these 44 suppressible features.



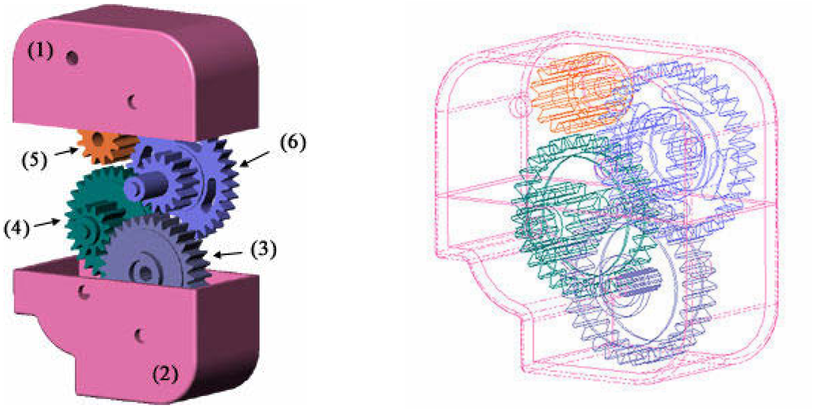
(a) Original model (Number of faces: 95)
(b) Level 1 (Number of faces: 41)
(c) Level 2 (Number of faces: 27)
(d) Level 3 (Number of faces: 6)

Fig. 8. Simplification process for the example 1A

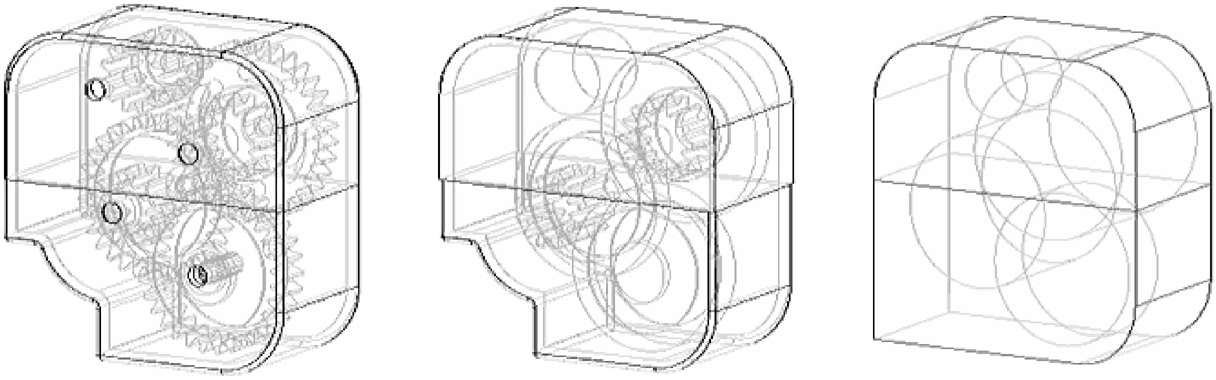
Forty-four suppressible features are grouped into 18 feature groups considering the features that are more naturally treated as a group. With the resulting feature groups are shown in a tree in Fig. 8. Each feature group can be expanded to show its component features. The number in parenthesis is the total area of the faces composing the feature or feature group. For example, in case of group 18, 4 suppressible features are grouped into group 18 and it can be noticed that each feature has the same area of 7.4. Each small icon next to the feature group shows its type. Suppressible features are sorted by its face area such that the largest feature is located at the top of the tree and vice versa. In this way, the model can be simplified by removing from the smaller suppressible features, i.e. the features from the bottom of the tree. Fig. 8(b) shows that the model is simplified up to the feature group 7 in the tree, the number of the remaining faces is 41 and ε = 56.8%. For Fig. 8(c), ε is 71.6%. After all suppressible features are removed from the original model as shown in Fig. 8(d), the data reduction ε becomes 93.7%. At any simplification level, the finer model can be retrieved by the wrap-around reverse operation we implemented.

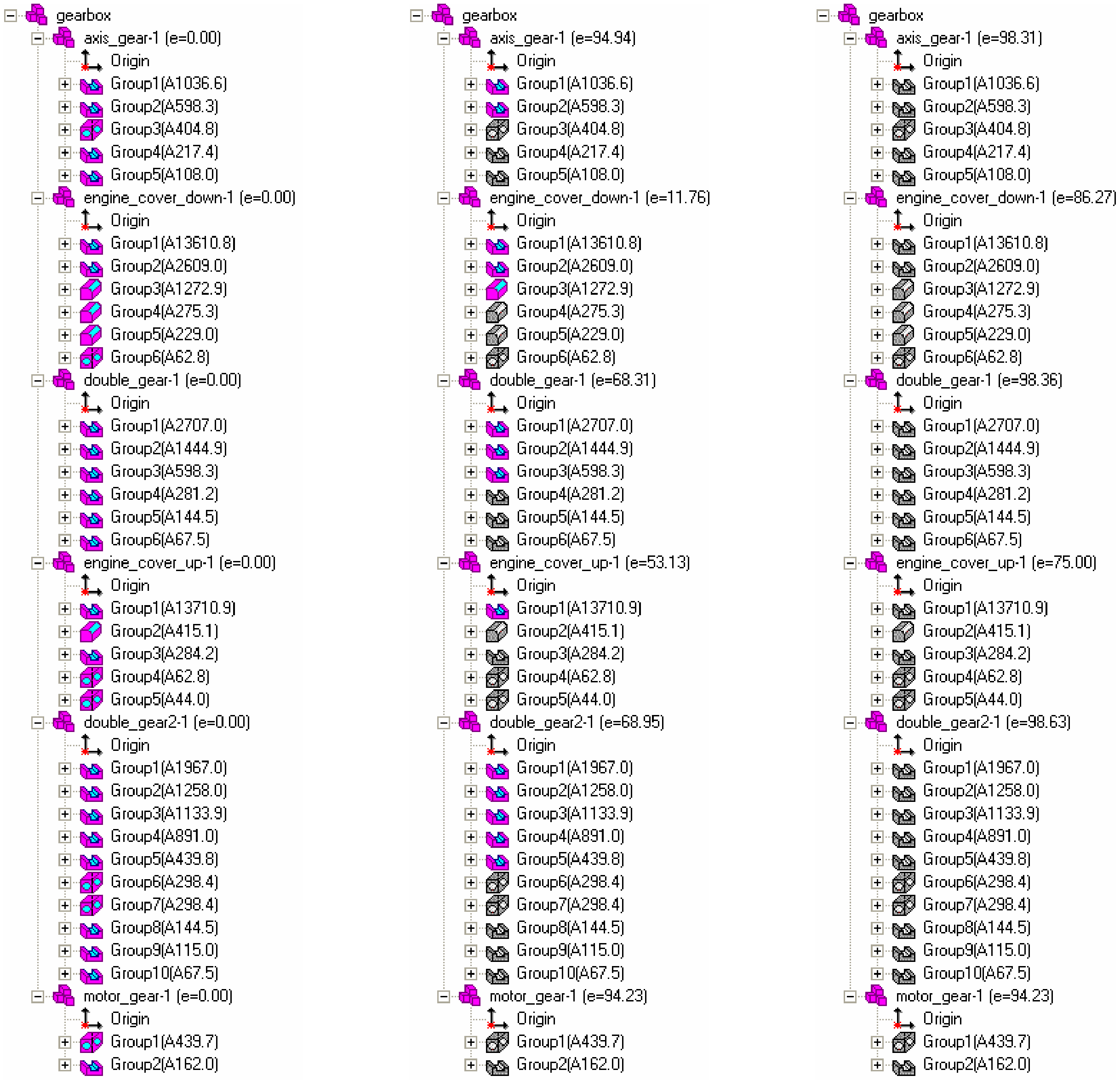
5.2 Example 2 (assembly-level wrap-around algorithm)

Second example is for a demonstration of assembly-level wrap-around algorithm. It is a gearbox in a toy car. This assembly model is composed of 4 gears and 2 cover parts (Fig. 9). In this example, the assembly has 127 concave features and 14 holes, 5 fillet/round features. From these features, 34 suppressible feature groups are classified and displayed in a tree according to their area as shown in Fig. 10. If we adjust the LOD, simplification process occurs for the whole assembly model and this affects each part model as a result. Fig. 10(a) shows an original assembly model before simplification, this assembly model has 715 faces. In the tree, we can check the status of suppressible features of each part as if we did in part level simplification example. Additionally, the tree shows the data reduction rate of each part. This shows how much effect each part simplification makes to the entire assembly simplification. Fig. 10(b) shows an intermediate resolution level between the original and the final result, specifically the level when 20 suppressible feature groups were removed. The number of faces is 198, data reduction rate ε is 72.3%. Notice that the suppressible features under the area of 439.7 were removed from all the parts at this stage. The most simplified model is showed in Fig. 10(c), where number of faces is 27 and data reduction rate ε is 96.2%.



(1) Engine_cover_up, (2) Engine_cover_down, (3)Axis_gear, (4)Double_gear, (5) Motor_gear (6) Double_gear2
Fig. 9. Example 2, gearbox, Parts





- gearbox
  - axis_gear-1 (e=0.00)
    - Origin
    - Group1(A1036.6)
    - Group2(A598.3)
    - Group3(A404.8)
    - Group4(A217.4)
    - Group5(A108.0)
  - engine_cover_down-1 (e=0.00)
    - Origin
    - Group1(A13610.8)
    - Group2(A2609.0)
    - Group3(A1272.9)
    - Group4(A275.3)
    - Group5(A229.0)
    - Group6(A62.8)
  - double_gear-1 (e=0.00)
    - Origin
    - Group1(A2707.0)
    - Group2(A1444.9)
    - Group3(A598.3)
    - Group4(A281.2)
    - Group5(A144.5)
    - Group6(A67.5)
  - engine_cover_up-1 (e=0.00)
    - Origin
    - Group1(A13710.9)
    - Group2(A415.1)
    - Group3(A284.2)
    - Group4(A62.8)
    - Group5(A44.0)
  - double_gear2-1 (e=0.00)
    - Origin
    - Group1(A1967.0)
    - Group2(A1258.0)
    - Group3(A1133.9)
    - Group4(A891.0)
    - Group5(A439.8)
    - Group6(A298.4)
    - Group7(A298.4)
    - Group8(A144.5)
    - Group9(A115.0)
    - Group10(A67.5)
  - motor_gear-1 (e=0.00)
    - Origin
    - Group1(A439.7)
    - Group2(A162.0)

(a) Number of faces: 715

- gearbox
  - axis_gear-1 (e=94.94)
    - Origin
    - Group1(A1036.6)
    - Group2(A598.3)
    - Group3(A404.8)
    - Group4(A217.4)
    - Group5(A108.0)
  - engine_cover_down-1 (e=11.76)
    - Origin
    - Group1(A13610.8)
    - Group2(A2609.0)
    - Group3(A1272.9)
    - Group4(A275.3)
    - Group5(A229.0)
    - Group6(A62.8)
  - double_gear-1 (e=68.31)
    - Origin
    - Group1(A2707.0)
    - Group2(A1444.9)
    - Group3(A598.3)
    - Group4(A281.2)
    - Group5(A144.5)
    - Group6(A67.5)
  - engine_cover_up-1 (e=53.13)
    - Origin
    - Group1(A13710.9)
    - Group2(A415.1)
    - Group3(A284.2)
    - Group4(A62.8)
    - Group5(A44.0)
  - double_gear2-1 (e=68.95)
    - Origin
    - Group1(A1967.0)
    - Group2(A1258.0)
    - Group3(A1133.9)
    - Group4(A891.0)
    - Group5(A439.8)
    - Group6(A298.4)
    - Group7(A298.4)
    - Group8(A144.5)
    - Group9(A115.0)
    - Group10(A67.5)
  - motor_gear-1 (e=94.23)
    - Origin
    - Group1(A439.7)
    - Group2(A162.0)

(b) Number of faces: 198

- gearbox
  - axis_gear-1 (e=98.31)
    - Origin
    - Group1(A1036.6)
    - Group2(A598.3)
    - Group3(A404.8)
    - Group4(A217.4)
    - Group5(A108.0)
  - engine_cover_down-1 (e=86.27)
    - Origin
    - Group1(A13610.8)
    - Group2(A2609.0)
    - Group3(A1272.9)
    - Group4(A275.3)
    - Group5(A229.0)
    - Group6(A62.8)
  - double_gear-1 (e=98.36)
    - Origin
    - Group1(A2707.0)
    - Group2(A1444.9)
    - Group3(A598.3)
    - Group4(A281.2)
    - Group5(A144.5)
    - Group6(A67.5)
  - engine_cover_up-1 (e=75.00)
    - Origin
    - Group1(A13710.9)
    - Group2(A415.1)
    - Group3(A284.2)
    - Group4(A62.8)
    - Group5(A44.0)
  - double_gear2-1 (e=98.63)
    - Origin
    - Group1(A1967.0)
    - Group2(A1258.0)
    - Group3(A1133.9)
    - Group4(A891.0)
    - Group5(A439.8)
    - Group6(A298.4)
    - Group7(A298.4)
    - Group8(A144.5)
    - Group9(A115.0)
    - Group10(A67.5)
  - motor_gear-1 (e=94.23)
    - Origin
    - Group1(A439.7)
    - Group2(A162.0)

(c) Number of faces: 27

Fig. 10. Simplification process for the example 2

6. CONCLUSIONS

In this paper, a new modeling operator, wrap-round operator, is proposed to realize the multi-resolution modeling on B-rep models. This limits the range of the suppressible features to be handled in the current wrap-around as follows. First, this algorithm can't handle every possible concave feature. In particular, concave features having extruded branches inside or complex rib features attached over multiple faces can be identified, but they can't be simplified by the proposed algorithm. In this case they are left as they are, and then the process continues for next features. Second, as mentioned earlier, we consider simple holes, fillet/rounds, and chamfers with constant radius. Third, we didn't consider the simplification of free-form surfaces in CAD models. However, more efficient and powerful algorithms for detecting those features are under development and the scope and speed of this algorithm will be improved, especially with the increasing computing power of the conventional computers. In this point of view, the current wrap-around algorithm deserves to be one of the key elements for realizing the multi resolution of the CAD models represented by

B-rep. With the simplification process, we also provide the reverse operation to recover the finer model of any level, which is a unique feature not offered by other simplification approaches. In addition, this algorithm handles not only the individual parts but also the whole assembly. In the assembly wrap-around operation, every suppressible feature is rearranged depending upon their contribution to the complexity in the whole assembly level instead of each part level. These features of wrap-around will be very useful to the future CAD system architecture in response to the rapidly growing needs of handling huge and complex CAD models.

7. ACKNOWLEDGEMENT

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