Feature-Based Multi-Resolution Modeling of Solids Using History-Based Boolean Operations — Part II : Implementation Using a Non-Manifold Modeling System —

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We propose a feature-based multi-resolution representation of B-rep solid models using history-based Boolean operations based on the merge-and-select algorithm. Because union and subtraction are commutative in the history-based Boolean operations, the integrity of the models at various levels of detail (LOD) is guaranteed for the reordered features regardless of whether the features are subtractive or additive. The multi-resolution solid representation proposed in this paper includes a non-manifold topological merged-set model of all feature primitives as well as a feature-modeling tree reordered consistently with a given LOD criterion. As a result, a B-rep solid model for a given LOD can be provided quickly, because the boundary of the model is evaluated without any geometric calculation and extracted from the merged set by selecting the entities contributing to the LOD model shape.

Key Words : Non-Manifold, Solid, Multi-Resolution, Feature, Boolean Operation

1. Introduction

Multi-resolution modeling for the feature-based B-rep solid models is becoming more suitable for computer-aided design (CAD) when compared with the conventional polygon-based multi- resolution modeling in computer graphics (Choi et al., 2002 ; Koo and Lee, 2002 ; Kim et al., 2003 ; Lee, S. H. et al., 2002 ; Lee, J. Y. et al., 2002 ; Lee et al., 2004). The object of multi-resolution modeling is a solid model and the suppressed objects are form features that are at an even higher level of modeling entities than the topological entities. The applications are mainly engineering tasks such as analysis, network-based collaborative design, virtual prototyping and manufacture. In engineering analysis, as shown in Fig. 1, the multi-resolution representation of a solid part model provides simplified analysis models at various levels of detail (LOD), as such simplified models are often required rather than the full details of the part (Armstrong, 1994 ; Belaziz et al., 2000). In the distributed design

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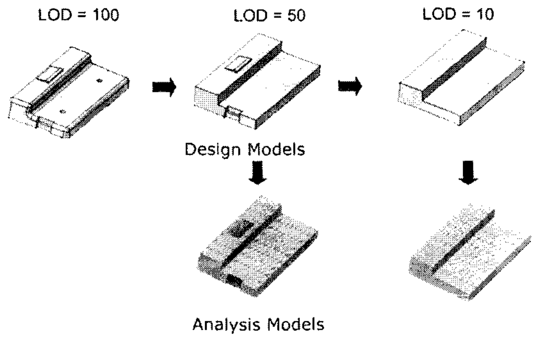

Fig. 1 An application of feature-based multi-resolution modeling to engineering analysis

environment, the efficient transmission of solid models over the network is necessary for efficient collaborative design and manufacture (Lee et al., 2004 ; Bidarra et al., 2002 ; Li et al., 2003 ; Wu et al., 2000). Multi-resolution representation allows the incremental transmission of solid models and sharing of the model at adequate LOD depending on the engineering tasks to be undertaken. In virtual prototyping and manufacture, LOD techniques are essential to perform rendering, collision detection, and various engineering analyses and simulations because a digital mockup and a virtual factory contain vast quantities of geometric data.

Previous work on multi-resolution modeling for feature-based solid models includes, first, Choi et al. (2002), who studied multi-resolution modeling for B-rep part models in feature-based solid modeling systems such as SolidWorks. In that paper, features are classified into two groups : additive and subtractive (Lee, 1999 ; Shah and Mäntylä, 1995 ; Dunn, 1992). The model at the lowest resolution is constructed by uniting all of the additive features, while the models at higher resolutions are generated by applying subtractive features in descending order of volume. To implement this, a hierarchical feature tree for the multi-resolution representation is constructed from the original feature history tree. In the hierarchical feature tree, the leaf node at the highest level contains a solid created by uniting all of the additive features, whereas the leaf nodes at the lower levels contain solids for the remaining subtractive features. The volume of subtractive feature interfering with additive features may need to be redefined, as the union and subtraction operations are not commutative. The model at a certain LOD, the LOD model, is represented by pruning the branches of the feature tree. However, their method is only applicable to the specific feature rearrangement method they suggested. If the features are rearranged in an arbitrary order, their method does not guarantee the same resulting shape as the original solid model. Moreover, their method requires considerable computation time to generate a solid LOD model because Boolean operations must be performed to transfer from the current LOD to a given LOD. As the purpose of multi-resolution modeling is to rapidly obtain the LOD models, in spite of consuming more data storage, this method is far from ideal.

Kim et al. (2003) extended the method of Choi et al. (2002) by adding two optional tasks. The first is to simplify the sketches of features. Because the feature made by a complex sketch increases the complexity of a B-rep model, a low-resolution model can be generated by simplifying its sketch. The second task is to remove insignificant additive features. If the volume of a feature is very small compared to that of the original part model, this feature can be ignored in the feature tree. However, there is no discussion of where an additive feature interferes with any subtractive features.

To reduce the computation time for the extraction of LOD models, Lee, S. H. et al. (2002) introduced the non-manifold topological (NMT) model of a cellular structure as the topological framework for a multi-resolution model. In their method, all features are first merged into an NMT cellular model, and then, if the LOD is given, topological entities comprising the LOD model are selected and displayed. Because the boundary information of all the features is stored in the NMT cellular model, no boundary evaluation is performed. As a result, a solid model at a given LOD can be provided even more quickly than in the solid-based approaches.

Lee, J. Y. et al. (Lee, J. Y., et al., 2002 ; Lee et al., 2004) applied the feature-based multi-resolution modeling method based on the NMT cellular model to network-based collaborative design. They addressed the incremental transmission of solid models through a network and sharing of the model at adequate LOD for engineering tasks. The ACIS kernel was used to implement the system. However, their study adopts the same LOD criterion and feature rearrangement method as in the approach of Choi et al.(2002). As a result, their method has the same limitations as in Choi et al.(2002): if the features are rearranged in arbitrary order, the method does not guarantee the same resulting shape as the original solid model. This means that this method is not suitable for various applications. They leave as future work research on extending the LOD criteria and including additive features for intermediate LOD models.

We propose a multi-resolution representation of B-rep solid models using history-based Boolean operations. Because union and subtraction are commutative in history-based Boolean operations, our approach guarantees the same result for an arbitrary rearrangement of features consistent with a given LOD criterion, and reasonable solid models at the intermediate LODs. In addition, the history-based Boolean operations are implemented based on the merge-and-select algorithm (Crocker and Reinke, 1991 ; Masuda, 1992 ; Kim et al., 1996) and a B-rep solid at a given LOD can be provided quickly.

The remainder of the paper is organized as follows. Section 2 proposes a data structure for feature-based multi-resolution modeling, which ensures fast generation of LOD models. Section 3 describes the implementation of history-based Boolean operations for constructing and extracting multi-resolution models. Section 4 discusses a few representative LOD criteria. Section 5 describes a case study and Section 6 presents our conclusions and future plans.

2. Data Structure for Feature-Based Multi-Resolution Modeling

2.1 A merged set in non-manifold topology

A non-manifold topological model can represent any combination of wire-frame, surface, solid, and cellular models in a unified data structure. Several data structures have been proposed to represent non-manifold models (Weiler, 1988 ; Gursoz et al., 1990 ; Rossignac and O'Conner, 1990 ; Yamaguchi and Kimura, 1995 ; Lee and Lee, 2001). We adopted a non-manifold model to represent feature-based multi-resolution models, and chose the Partial Entity Structure (Lee and Lee, 2001) as a non-manifold data structure.

Boolean operations on non-manifold models can be implemented using the merge-and-select algorithm (Crocker and Reinke, 1991 ; Masuda, 1992 ; Kim et al., 1996). To support the merge-and-select algorithm, the merged set should contain a complete description of the input primitives and all their intersections, together with historical information describing the origins of the entities in terms of the topological entities of the original

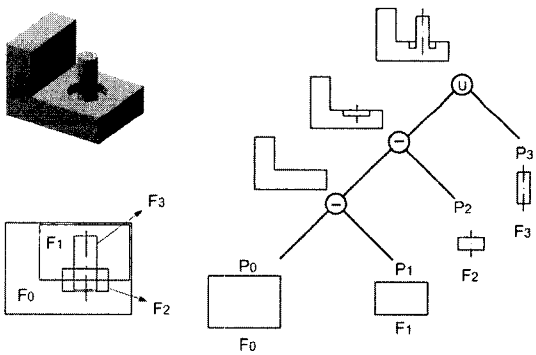

Fig. 2 A feature-modeling tree (Lee, S. H. et al., 2004)

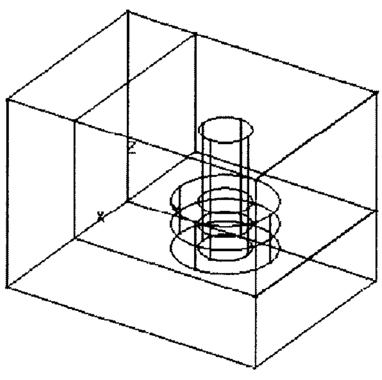

Fig. 3 A merged set for the example in Fig. 2

primitives. To meet this requirement, the Partial Entity Structure stores the historical information in the Ownership attribute of the Cell Entity class (Kim et al., 1996; Lee and Lee, 2001). The Cell Entity class is a parent class of the Region, Face, Edge, and Vertex classes. Fig. 2 shows an example of part-modeling procedure shown in the Part 1 paper (Lee S. H. et al., 2005). Fig. 3 shows a merged set of four solid primitives of the features in Fig. 2. However, to implement history-based Boolean operations, the select algorithm needs to be modified. The modification of the algorithm is discussed in Section 3.

2.2 Boolean history tables

To facilitate implementation of history-based Boolean operations, our system stores the related information in a table called a Boolean history table. As shown in Table 1, each record of a Boolean history table stores a set of attributes: LOD, the creation order, the Boolean operation type, the primitive used as the tool body, and the list of affecting primitives. The contents of an affecting primitive list may vary whenever the order of the Boolean operations is changed. The primitives written in bold characters represent those included for the natural shapes of intermediate LOD models. Table 1 represents a Boolean history table at the initial stage, before reordering.

Table 1 A Boolean history table for the example in Fig. 2

LOD	Creation Order	Bool	Primitive	Affecting Primitives
0	0	+	P_0	P_0, $\mathbf{P_1}$, $\mathbf{P_2}$, $\mathbf{P_3}$
1	1	−	P_1	P_0, P_1, $\mathbf{P_2}$, $\mathbf{P_3}$
2	2	−	P_2	P_0, P_1, P_2, $\mathbf{P_3}$
3	3	+	P_3	P_0, P_1, P_2, P_3

3. Implementation of History-Based Boolean Operations

In our approach, the non-manifold Boolean operations based on the merge-and-select algorithm are used for multi-resolution modeling. In the merge stage, all primitives are merged into a single non-manifold model called a merge set, and then in the select stage, for a given sequence of the Boolean operations, the topological entities constituting the boundary of a resulting shape are selected and marked as alive. The merge algorithm for history-based Boolean operations is the same as the existing algorithm. However, the select algorithm is modified by considering the affecting primitives of each operation. Algorithm 1 describes the modified select algorithm that searches for all vertices, edges, faces, and regions contributing to the resultant shape for a given LOD. Note that, if the Boolean type is subtractive, the closure operation is executed to complete the boundary of a solid model.

```
Algorithm 1.
HistoryBasedSelection (mset, B, LOD, E)
Input: mset  : a merged-set model
       B     : a Boolean history table. B={B_i}_{i=0}^n
       LOD   : a desired LOD.
Output: E : a list of the selected topological entities.
for k ← 0 to LOD do {
  // Get the tool body p of the k-th Boolean operation
     B_k.
  p=B_k → GetPrimitive ();
  // Get a list of the affecting primitives A of the k-th
     Boolean operation B_k.
  A=B_k → GetListOfAffectingPrimitives ();
  for each cell topological entity c of the merged set
      mset do {
    if (c is originated from the primitive p) then {
      if (any ancestor entities of c belong to affecting
          primitives A) then {
        // Add the entity c to the entity list L of p.
        L → AddEntity (c);
      }
    }
  }
  //--- Perform the k-th Boolean operation. ---//
  if (B_k → BooleanType () is '+') then {
    // Add the entities in L to the list E.
    E → UniteList (L);
  }
  else if (B_k → BooleanType () is '−') then {
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```
    // Remove the entities in L from the list E.
    E → SubtractList (L);
    // Complete the boundary of the model.
    E → ClosureOperation ();
  }
}
```

4. LOD Criteria

In feature-based multi-resolution modeling, features are rearranged to construct a multi-resolution representation consistent with a specific criterion for LOD. Criteria of LOD determine which model is at lower or higher resolution level and are dependent upon the applications or the users. Two representative criteria are discussed in this paper.

The first is the volume of the subtractive feature, which was suggested for study in previous work (Choi et al., 2002; Kim et al., 2003; Lee et al., 2004). In this method, the model at the lowest resolution is obtained by uniting all additive features, and then the models at higher resolutions are generated by applying the subtractive features successively in descending order of volume. If this criterion is applied to the example shown in Fig. 2, the multi-resolution modeling can be represented by a feature-modeling tree shown in Fig. 4. As Fig. 4 shows, in spite of feature rearrangement, history-based Boolean operations provide an invariant final shape and a set of reasonable intermediate LOD models.

The second criterion is the volume of the feature. Here, the additive and subtractive features are not distinguished and the volumes of the features are not strictly used for error measurement. Here, the difference between volumes of the previous LOD model and the current LOD model is calculated to measure the approximation error. The candidate LOD models are generated by omitting each feature one at a time. This method is applied to the example shown in Fig. 2 and the entire procedure is shown in Fig. 5. At the first step, the candidate models at LOD=2, $\{M_i^2\}_{i=0,3}$, which are obtained by applying the features except F_0 to F_3, are generated and their volumes are calculated. Then, the candidate model whose volume is the closest to the original model $M(=M^3)$ is searched, and its omitted feature is relocated to the last place. In this case, F_2 is selected as the smallest feature, and therefore M^2 is defined as $P_0 - P_1 + P_3$. At the second step, F_3 is selected as the smallest feature of F_0, F_1, and F_3, and F_3 is relocated to the place at LOD=2 and therefore M^1 is defined as $P_0 - P_1$. At the third step, F_1 is selected as the smallest feature between F_0 and F_1, and relocated at the place at LOD=1, consequently F_0 is at LOD=0, and M^0 is defined as P_0. Fig. 6 shows the three-dimensional shapes

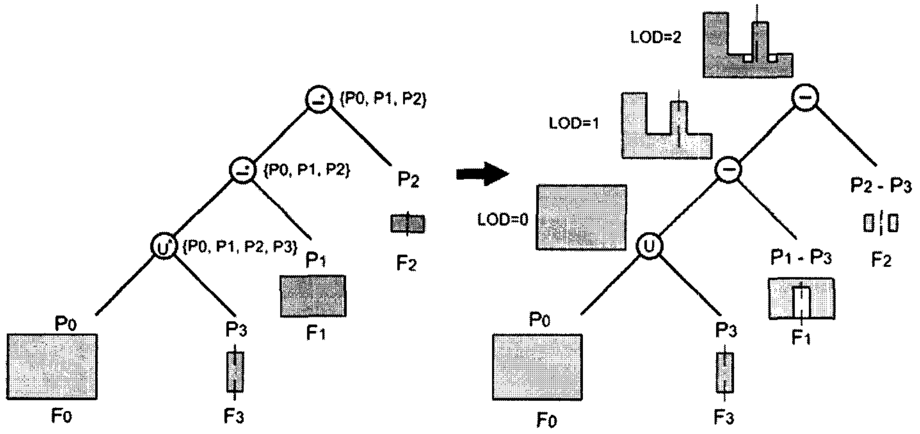

Fig. 4 A multi-resolution representation in the case where the LOD criterion is the volume of the subtractive feature together with the precedence of additive features over subtractive features

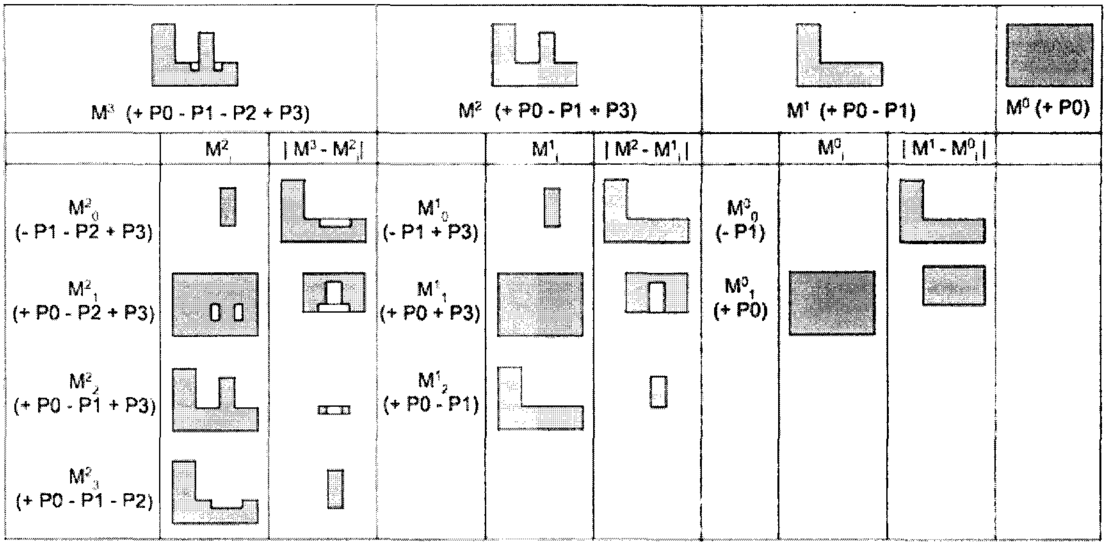

Fig. 5 A process to determine the order of features using the volume difference between two adjacent LOD models

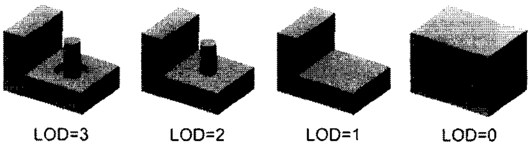

Fig. 6 LOD models determined by the process in Fig. 5

of the LOD models at the highest to lowest resolutions.

5. Case Study

Feature-based multi-resolution modeling technology is suitable for a wide range of applications, including engineering analysis and high-speed rendering. In particular, the finite element method (FEM) is currently one of the most popular engineering analysis methods. Because FEM tools frequently require simplified geometric models as input, feature-based multi-resolution modeling can provide a very acceptable tool for finding an adequate LOD of geometric model by trying multiple LOD models. In this section, we select a mechanical part model for a case study. Fig. 7 shows the initial feature-modeling process. If the volume of the subtractive feature is selected as a criterion of LOD, the LOD models

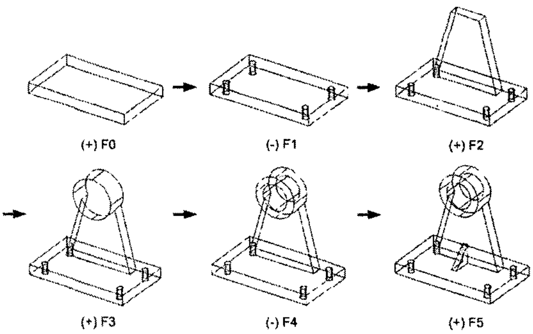

Fig. 7 Feature-based modeling process for a part model

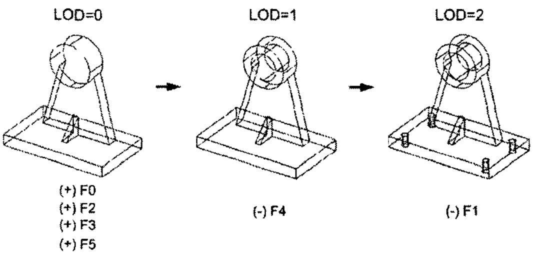

Fig. 8 Multi-resolution models where the LOD criterion is the volume of the subtractive feature together with the precedence of additive features over subtractive features

are extracted as shown in Fig. 8. Fig. 9 shows the reordered feature-modeling sequence consistent

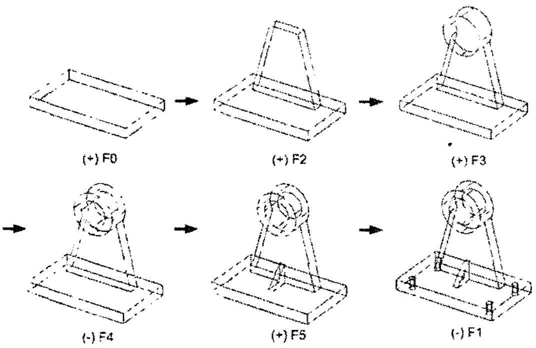

Fig. 9 Multi-resolution models where the LOD criterion is the volume of the feature, regardless of whether the feature type is additive or subtractive

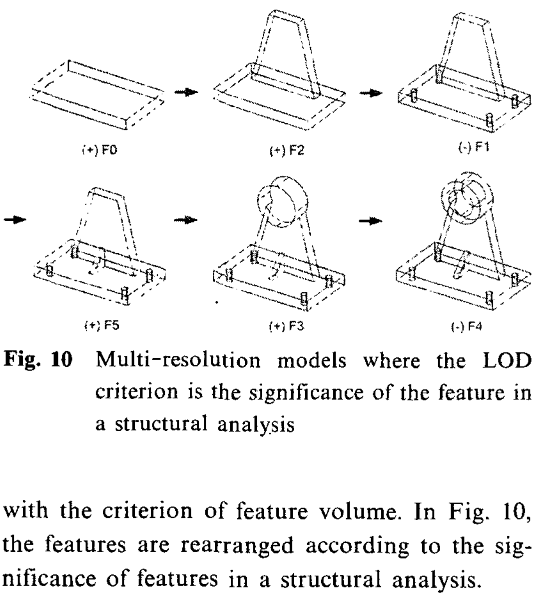

Fig. 10 Multi-resolution models where the LOD criterion is the significance of the feature in a structural analysis

with the criterion of feature volume. In Fig. 10, the features are rearranged according to the significance of features in a structural analysis.

6. Conclusion

In this paper, we propose history-based Boolean operations, which satisfy the commutative laws for union and subtraction operations, and develop an algorithm for multi-resolution modeling based on the non-manifold merged set and history-based Boolean operations. This algorithm guarantees the same resultant shape and reasonable intermediate LOD models for an arbitrary rearrangement of the features consistent with a given LOD criterion, such as the volume of the feature, regardless of whether the feature type is subtractive or additive. In addition, this algorithm can provide LOD models quickly because an LOD model is extracted from a merged set of all features by selecting the entities contributing to the LOD model shape.

In the future, first, it will be necessary to investigate more criteria for LOD for different applications because LOD criteria are usually application-dependent. Because our algorithm based on history-based Boolean operations can support arbitrary rearrangement of features, any criterion can be used to define the multi-resolution models. Second, it is critical to find an adequate multi-resolution representation for assembly models as the digital mockup and virtual manufacturing solutions become essential tools for product development. Third, it is a challenge to extend the multi-resolution modeling technique to multi-abstraction modeling that can provide geometric models at various levels of abstraction for engineering analysis. To accomplish this goal, it is necessary to integrate dimensional reduction methods with the multi-resolution modeling method, and to extend the representation domain of the history-based Boolean operations from solid to non-manifold models.

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