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A New CAD Models Retrieval Method Based on Shape Similarity

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Abstract: The CAD model retrieval based on shape similarity is the research focus of computer graphics and computer-aided design field. To obtain higher retrieval precision and efficiency, a new CAD model retrieval method based on shape similarity is proposed. The method is divided into two steps. Firstly, breadth-first-search-based spanning tree algorithm is applied to obtain an initial boundary matching between retrieval object and retrieval condition. Secondly, the topology adjacency approximation algorithm is put forward to find the optimal boundary matching based on the initial boundary matching by the cycle and approximation process and the matching result is used to calculate the shape similarity between retrieval object and retrieval condition. In order to calculate the similarity between various types of boundary faces, a new similarity calculation method is present. Finally, a CAD model retrieval system on the platform of UG is developed based on the proposed method. Experimental results show that the proposed method is feasible and effective.

Key words: CAD, similarity calculation, retrieval, topology adjacency approximation, boundary matching

INTRODUCTION

CAD model is one kind of most important engineering information and used to express the structure and shape of product. With the increase of CAD models, the reuse of CAD models becomes the key problem in product design. As the key technology of CAD model reuse, the CAD model retrieval based on shape similarity has been the research focus of CG and CAD field.

Content-based model retrieval method is the better solution to the problem. The so-called content-based retrieval method takes structures, shapes or other properties of model as the retrieval information and the specific descriptor is set to calculate the similarity between retrieval object and retrieval condition (Wan Li *et al*., 2007). Research on content-based retrieval method has been performed by many organizations or universities, such as Purdue University (Pu and Ramani, 2005; Lou *et al*., 2003; Hou and Ramani, 2007), Princeton University (Shilane *et al*., 2004), Carnegie-Mellon University (Zhang and Chen, 2001) and University of Maryland (Ip Cheuk and Gupta Satyandra, 2007). Most of them set focus on the retrieval method of mesh model and research on the retrieval method of CAD models are insufficient. Main methods of CAD model retrieval include the method based on statistics (Wang *et al*., 2006; El-Mehalawi and Miller Allen, 2006), the method based on graph-isomorphism algorithm (Liu and Hi, 2006; Rea *et al*., 2004; Pitta and Michael, 2005; Gal and Cohen-Or, 2007; Ou-Yang and Liu, 1999; El-Mehalawi and Miller Allen, 2006; Gao *et al*., 2006; Sundar *et al*., 2003; Hong *et al*., 2006; Bespalov *et al*., 2003) and the method based on boundary matching (Wang *et al*., 2007, 2008a, b; Ma *et al*., 2008) and the method based on boundary matching is considered as the best solution.

Wang *et al*. (2007, 2008a, b) applied the optimal matching algorithm of bipartite graph to find the optimal boundary matching between retrieval object and retrieval condition. The time complexity of the method is $O(n^3)$, since the time complexity of Kuhn-Munkres algorithm (Yin and Wu, 2003) is $O(n^3)$. Ma *et al*. (2008) used the shape-location code to describe the geometry and topology characteristics of boundary faces on CAD model and the shape-location codes of faces constitute the shape-location code matrix. The similarity between shape-location code matrices represents the similarity of CAD models. The average retrieval time of this method is about 0.4 sec. Wang *et al*. (2008c) built the attributed graphs of CAD models and applies sub-graph isomorphism algorithm to solve the problem on the partial structure retrieval of CAD models. The time complexity of the method is the interval $(O(m), O(n!)/(n-m)!))$. Where, n and m are the numbers of vertices in the big graph and the small graph, respectively.

In earlier mentioned methods, the boundary matching processes are all completed by one-step recycling. As known, boundary faces of CAD model are interdependent with topology adjacency relationships. In fact, the optimal boundary matching cannot be obtained by one-step recycling and the self-adaptive adjustment process is

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necessary during boundary matching process. Thus the retrieval precisions of these methods cannot be improved well.

In order to solve the problem, this study proposes the topology adjacency approximation algorithm and applies the algorithm to adjust the boundary matching process between retrieval object and retrieval condition self-adaptively. The relatively accurate similarity can be gotten by the algorithm. Moreover, this study proposes a uniform method to calculate the similarity between various types of faces. Finally, a retrieval system on UG platform is developed according to the proposed method and the retrieval effect of the proposed method is verified by experiments.

TOPOLOGY ADJACENCY APPROXIMATION

The similarity calculation between retrieval object and retrieval condition is the basis of CAD model retrieval. The differences lie in the similarity calculation method between retrieval object and retrieval condition for different retrieval methods. This study proposes the topology adjacency approximation algorithm and applies it in the similarity calculation of CAD models. The framework of the method is shown in Fig. 1.

Figure 1 shows that the method divided into two steps. The first step is the initial boundary matching process and the second step is the topology adjacency approximation process. The first step provides the initial boundary matching for the second step and an appropriate initial boundary matching will accelerate the convergence of the method. The initial boundary matching is obtained by comparing the geometrical similarities of faces between retrieval object and retrieval condition. Thus the geometry similarity calculation of faces is the key problem during initial boundary matching. The topology adjacency approximation algorithm is a cycle and approximation process. For each cycle, the

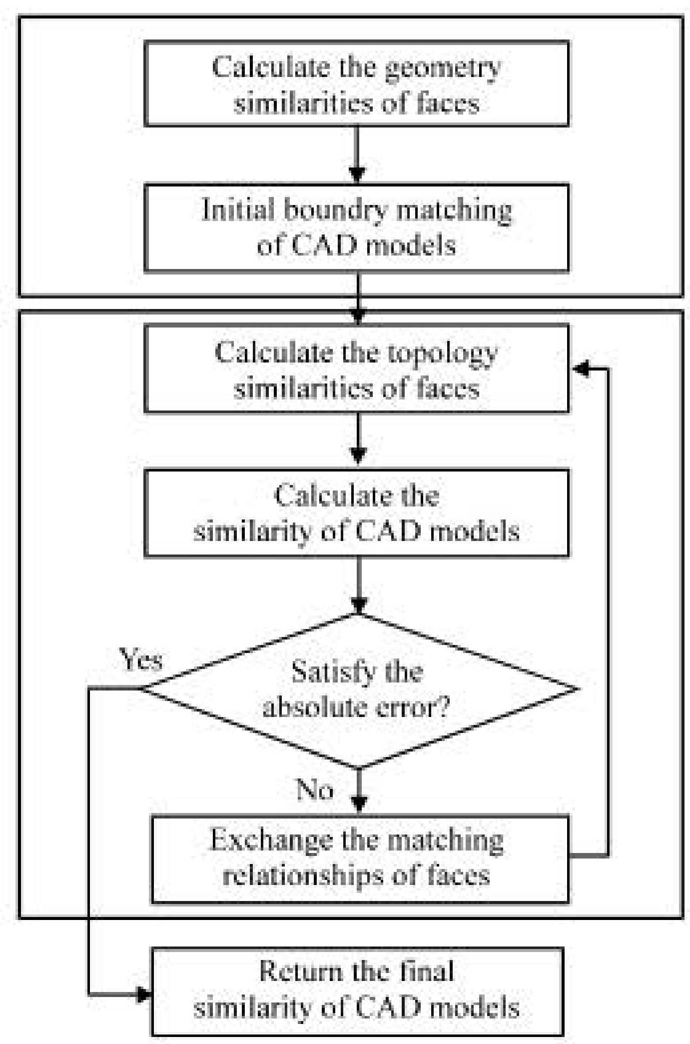


Fig. 1: Framework of the proposed method

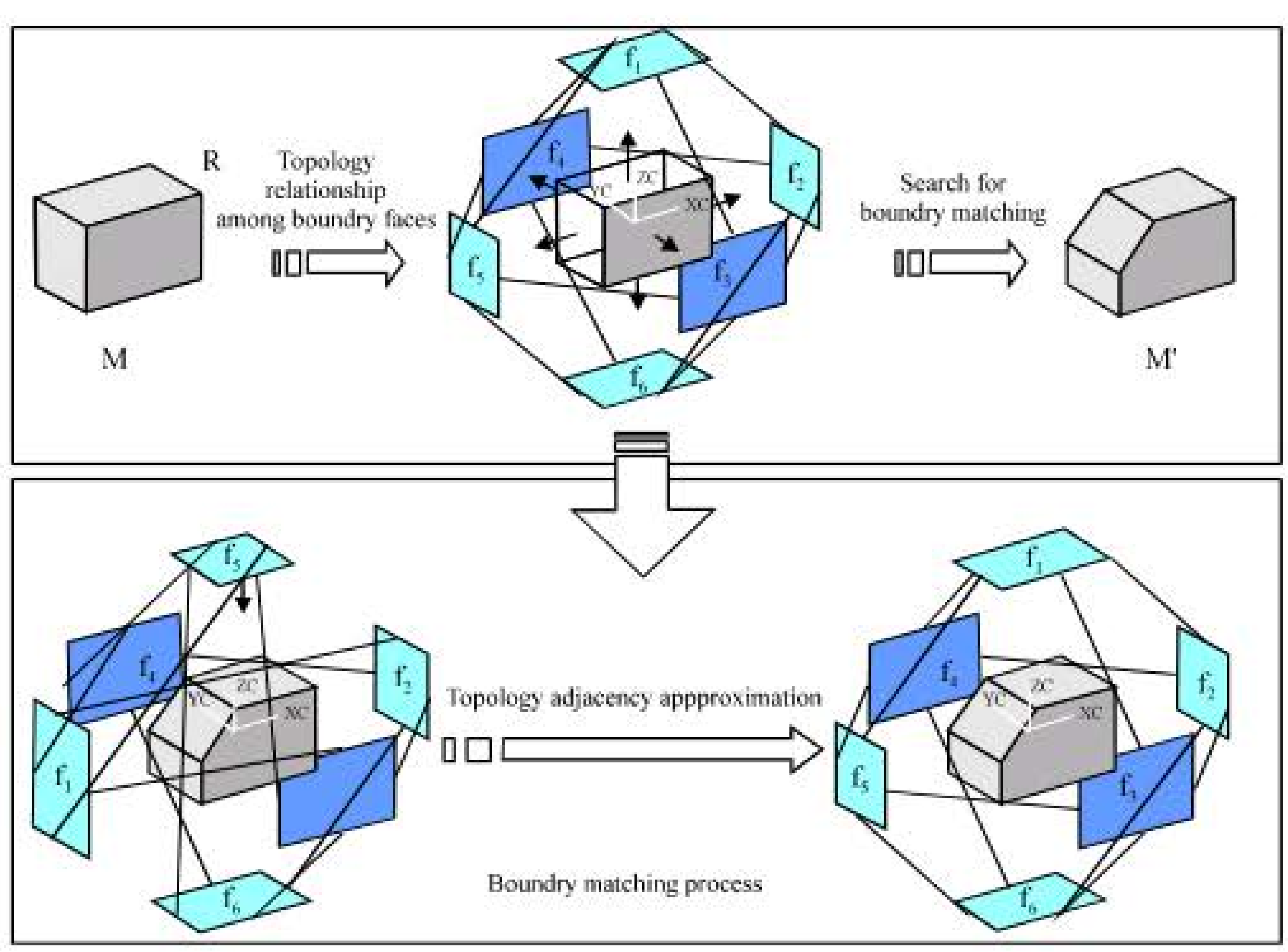


Fig. 2: The topology adjacency approximation process

boundary matching between retrieval object and retrieval condition will be adjusted. The matching relationships of boundary faces will be exchanged for arbitrary two couples of matched faces if the exchange will increase the similarity value between retrieval object and retrieval condition. With each cycle process, the topology similarity of boundary faces will be recalculated between retrieval object and retrieval condition, since the boundary matching is changing constantly with the topology adjacency approximation process. Figure 2 shows the topology adjacency approximation process during searching for the optimal boundary matching.

SIMILARITY CALCULATION OF BOUNDARY FACES

Geometry similarity calculation: For two boundary faces f and f', if the shape of f is similar to that of f' in vision sensation, f and f' are considered as a couple of geometry similar boundary. However, other methods cannot calculate the geometry similarity between arbitrary two boundary faces if the types of them are different. This study proposes a uniform method to calculate the geometry similarity between different types of faces.

Curvature similarity calculation between boundary faces: Figure 3 shows an boundary face f and the centroid of f is denoted as W_f. On f, P is the closest point from W_f. The normal vector of f is tagged as $\vec{n}$ at point P. If the vector from P to W_f is expressed as $\vec{r}$, the dot product between $\vec{r}$ and $\vec{n}$ will be $l = \vec{r}.\vec{n}$.

For a couple of matched boundary faces f and f', the curvature description information of both them is as shown in Fig. 3. The curvature similarity $S_c(f, f')$ between f and f' can be calculated by Eq. 1.

$$S_c(f,f') = S_m(f,f') \cdot S_a(f,f') \quad (1)$$

In Eq. 1, $S_m(f, f')$ and $S_a(f, f')$ are the curvature similarities between f and f' in direction of maximal curvature and direction of minimum curvature, respectively. The direction of maximal curvature is the tangent direction of boundary face at certain point, in which the absolute value of curvature reaches the maximal. Correspondingly, the direction of minimum curvature is the tangent direction of face at certain point, in which the absolute value of curvature reaches the minimum. $S_m(f, f')$ and $S_a(f, f')$ can be gotten by function g(x) and g(x) is as follows:

$$g(x) = \begin{cases} \dfrac{e^{-x} - e^{-\eta}}{1 - e^{-\eta}}, 0 \le x \le \eta \\ 0, x \ge \eta \end{cases} \quad (2)$$

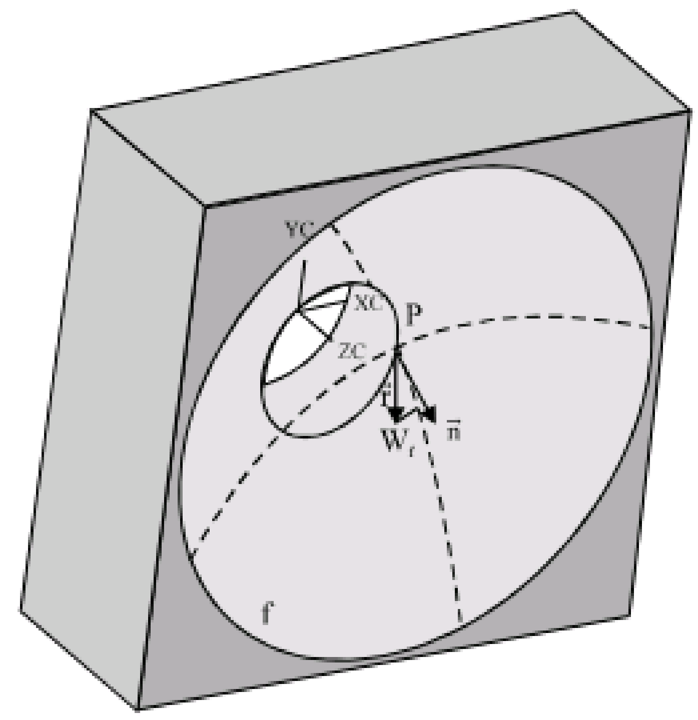


Fig. 3: Curvature description of boundary face

While Eq. 2 is applied to calculate $S_m(f, f')$, $x = \left| |k|_{max}(\vec{r}\cdot\vec{n}) - |k'|_{max}(\vec{r}\cdot\vec{n}) \right|$. While Eq. 2 is used to calculate $S_a(f, f')$, $x = \left| |k|_{min}(\vec{r}\cdot\vec{n}) - |k'|_{min}(\vec{r}\cdot\vec{n}) \right|$. Where, k and k' are the curvatures of f and f' at the centroids of them separately. η is defined as a threshold which limits the comparable scope between the curvatures of f and f' in directions of maximal curvature and minimum curvature. If x is less than η, the curvature similarity between f and f' will be zero. The curvature similarity describes the curvature similarity, the curvature direction similarity and the area distribution similarity between boundary faces.

Shape-position similarity calculation between boundary faces: For arbitrary boundary face, the shape of it can be represented by the external loop of it. This study codes the binary code of external loop to describe the shape and position of boundary face. For a boundary face f, the external loop of f can be denoted as directed edges set $L_{Ext}(f) = \{e_1, e_2,...,e_n\}$, in which any edge is connected to the next edge of it in counter clockwise. The binary code of f is denoted as SP(f) and SP(f) is gotten by Eq. 3.

$$SP(f) = 2^{n-1}BIN(e_1) + 2^{n-2}BIN(e_2) + \cdots + 2^0 BIN(e_n) \quad (3)$$

The function BIN is the code function. The binary code of convex edge will be 1 and that of concave edge is 0. For CAD model in Fig. 4, the external loop of f is express as directed edges set $L_{Ext}(f) = \{e_1, e_2, e_2, e_4\}$. The concavity-convexity code of f is SP(f) = 1010. Obviously, the external loop of boundary face is divided into several sections and the concavity-convexity characteristic of all directed edges in same section is same. Such a section is called concavity-like section or convexity-like section if all edges in the section are convex or concave.

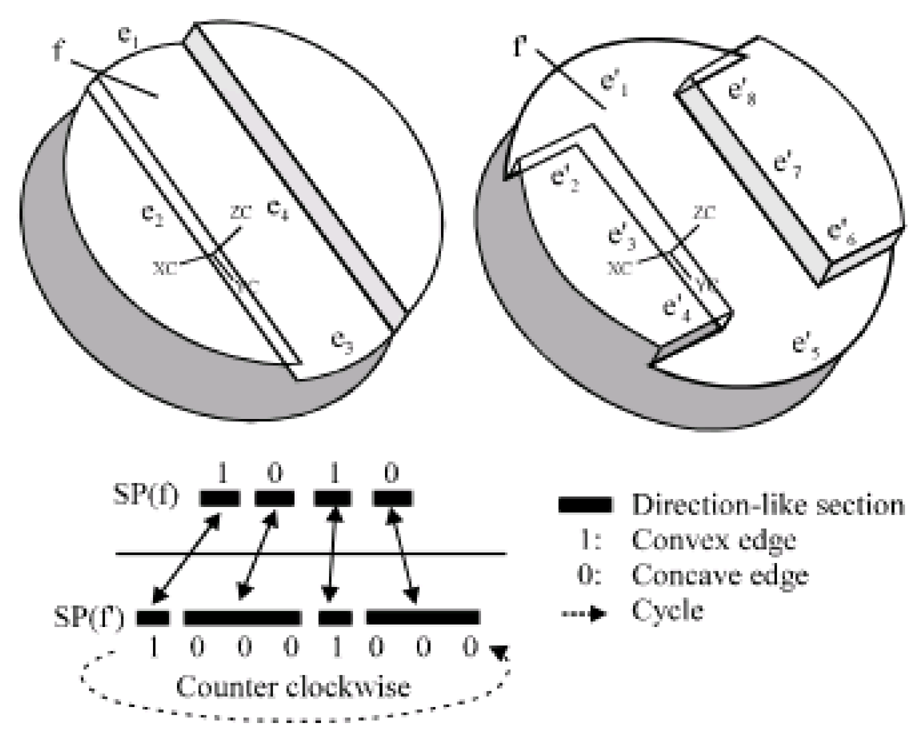


Fig. 4: Calculation of shape-position similarity

Both concavity-like section and convexity-like section are called direction-like section uniformly.

Figure 4 shows an example for calculation of shape-position similarity between boundary faces. It is hypothesized that the numbers of directed edges on the external loops of f and f' are n, respectively. t and t' are the numbers of direction-like sections on the external loops of f and f', respectively. The following relationship will be satisfied:

$$m = \sum_{i=1}^{t_1} m_i \qquad n = \sum_{i=1}^{t_2} n_i \tag{4}$$

In Eq. 4, m_i and n_i are the number of directed edges on the ith direction-like section on the external loop of f and that of f' individually. If t>t', the shape-position similarity between f and f' is denoted as $S_p(f, f')$ and $S_p(f, f')$ is computed by Eq. 5.

$$S_P(f,f') = \max(S_{P,0}(f,f'), S_{P,2}(f,f'), \cdots, S_{P,j}(f,f'), \cdots, S_{P,t-1}(f,f')) \tag{5}$$

It is demanded that the binary code of f' should be compared with that of f circularly, since each directed edge is connected to the next edge of it circularly on the external loop of boundary face. $S_p(f, f')$ should take the maximal element in set $\{S_{p,j}(f, f') | 1 \le j \le t-1\}$. $S_{p,j}(f, f')$ is the shape-position similarity obtained by the jth comparison between f and f'. Equation 6 is used to calculate $S_{p,j}(f, f')$.

$$S_{P,j}(f,f') = \begin{cases} \frac{1}{m} \cdot \sum_{i=1}^{t'} \lambda_{j+i,i} \frac{\min(m_{j+i}, n_i) \cdot m_{j+i}}{\max(m_{\Delta t+i}, n_i)}, & j+t' \le t \\ \frac{1}{m} \cdot \left(\sum_{i=1}^{t-j} \lambda_{j+i,i} \frac{\min(m_{j+i}, n_i) \cdot m_{j+i}}{\max(m_{j+i}, n_i)} + \sum_{i=t-j+1}^{t'} \lambda_{i+j-t,i} \frac{\min(m_{i+j-t}, n_i) \cdot m_{j+i-t}}{\max(m_{i+j-t}, n_i)}\right), & j+t' > t \end{cases} \tag{6}$$

In Eq. 6, λ is a Boolean variant. λ = 1, if the type of direction-like section on the external loop of f' is same to the type of its corresponding section on the external loop of f, otherwise λ = 0.

Geometry similarity between boundary faces: $S_c(f, f')$ and $S_p(f, f')$ constitute the geometry similarity $S_G(f, f')$ between f and f' and Eq. 7 is applied to calculated $S_G(f, f')$.

$$S_G(f,f') = S_C(f,f') \cdot S_P(f,f') \tag{7}$$

For arbitrary couple of matched faces, the geometry similarity between them is gotten by Eq. 1-7, though their types may be different.

Topology similarity calculation: It is hypothesized that M and M' are different CAD models. M is taken as the retrieval condition and M' is the retrieval object. The set of boundary faces on model M is denoted as FS and FS = $\{f_1, f_2, ..., f_n\}$. Where, n is the number of boundary faces on model M. For arbitrary boundary face $f_i (1 \le I \le n)$ on M, f_1' is the matching face of $f_i$on M'. The number of adjacent boundary faces of $f_i$on h_i and the number of adjacent boundary faces of f_i is h_i. The adjacent boundary faces of f_i are $f_{i,1}, f_{i,2}, ..., f_{ihi}$ and the matching faces of them are $f'_{i,1}, f'_{i,2}, ..., f'_{i,h_i}$ on M', respectively. Figure 5 shows the mapping relationship of boundary faces from M to M'.

On the topology adjacency graph of M', the distances from f_i' to $f'_{i,1}, f'_{i,2}, ..., f'_{i,h_i}$ are defined as $d(f_i', f_{i,j}')$ $(1 \le j \le h_i)$, respectively. The average value of $d(f', f'_{i,j})$ $(1 \le j \le h_i)$, is expressed as $\bar{d}_i$ and Eq. 8 is applied to calculate $\bar{d}_i$.

$$\bar{d}_i = \frac{\sum_{j=1}^{h_i} d(f_i', f_{i,j}')}{h_i} \tag{8}$$

The topology similarity between f_i' and f_i is denoted as $S_T(fi, f_i')$. The value of $S_T(f_i, f'_i)$ is obtained by Eq. 9.

$$S_T(f_i, f_i') = \left(\zeta \cdot \frac{\min(h_i, h_i')}{\max(h_i, h_i')}\right)^{\bar{d}_i - 1}, 0 < \zeta < 1 \tag{9}$$

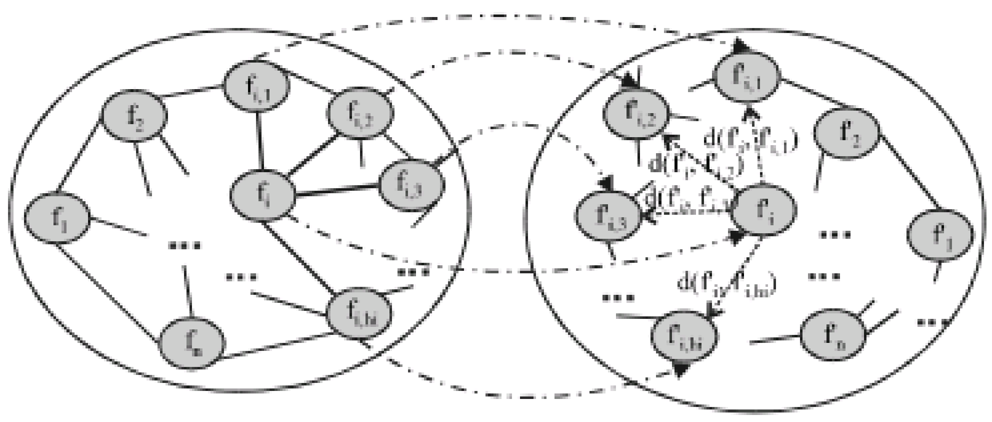


Fig. 5: Mapping relationship of boundary faces from M to M'

In Eq. 9, ζ is named topology factor. Equation 9 shows that the topology similarity will increase with decrease of average distance $\bar{d}_i$.

SIMILARITY CALCULATION OF CAD MODELS

Initial boundary matching: In order to calculate the boundary matching between retrieval object and retrieval condition, Wang *et al*. (2007, 2008a, b) applied K-M algorithm to find out the boundary matching. Because, the time complexity of K-M algorithm is $O(n^3)$ and all matching faces cannot converge to some partial structure, the efficiency and accuracy of this CAD model retrieval is lower. Aiming at solving these problems, this study proposes a boundary matching method based on the spanning tree algorithm. Though, the matching result of this method cannot be used to calculate the exact similarity between CAD models, it can be taken as the input of the topology adjacency approximation algorithm. The tree is spanned from the topology adjacency graph of retrieval condition. All matching faces of retrieval condition are obtained with the spanning process of the tree. It is hypothesized that M_1 and M_2 are retrieval object and retrieval condition, respectively. The set of boundary faces on M_1 is FS_1 and $FS_1 = \{f_{1,1}, f_{1,2},...f_{1,n}\}$. n is the number of boundary faces on M_1. The set of boundary faces on M_2 is FS_1 and $FS_2 = \{f_{2,1}, f_{1,2},...f_{2,m}\}$. M_2 is the number of boundary faces on M_2. The method is described as follows:

Geometry similarity calculation between boundary faces: $f_{1,i}(1 \le I \le n)$ and $f_{2,j}(1 \le I \le n)$ are boundary faces on M1 and M_2, respectively. The geometry similarity between $f_{1,i}$ and $f_{2,j}$ is denoted as $S_G(f_{1,i}, f_{2,j})$. $S_G(f_{1,i}, f_{2,j})$ is calculated by Eq. 1-7. The geometry similarity matrix is expressed as $A_{n \times m}$.

$$A_{n\times m} = \begin{pmatrix} S_G(f_{1,1},f_{2,1}) & S_G(f_{1,1},f_{2,2}) & \cdots & S_G(f_{1,1},f_{2,m}) \\ S_G(f_{1,2},f_{2,1}) & S_G(f_{1,2},f_{2,2}) & \cdots & S_G(f_{1,2},f_{2,m}) \\ \vdots & \vdots & \ddots & \vdots \\ S_G(f_{1,n},f_{2,1}) & S_G(f_{1,n},f_{2,2}) & \cdots & S_G(f_{1,n},f_{2,m}) \end{pmatrix}$$

Seeking the root node of spanning tree: $S_G(f_{1,i}, f_{2,j})$ ($f'_{1,i} \in FS_2$, $1 \le I \le n$) is located on each row of $A_{n \times m}$ and $f'_{1,i}$, is the matching boundary face of $f_{1,i}$. The following relationship should be satisfied.

$$S_G(f_{1,i}, f'_{1,i}) \ge S_G(f_{1,i}, f_{2,j}) \; (1 \le j \le m)$$

If $f_{1,i,k}$ ($1 \le k \le h_i$, $f_{1,i,k} \in FS_1$) is the adjacent faces of $f_{1,i}$, $S_G(f_{1,i,k}, f'_{1,i,k})$ ($f'_{1,i,k} \in FS_2$) should be gotten and the following relationship should be satisfied.

$$S_G(f_{1,i,k}, f'_{1,i,k}) \ge S_G(f_{1,i,k}, f_{2,j}) \; (1 \le j \le m,\ f_{2,j} \notin \{f'_{1,i,1}, f'_{1,i,2}, \cdots, f'_{1,i,k}, f'_{1,i}\})$$

The average distances $\bar{d}_i$ from $f'_{1,i}$ to $f'_{1,i,k}$ ($1 \le k \le h_i$) is calculated by Eq. 8. Finally, a couple of matched faces $f_{1,r}$ and $f'_{1,r}$($f_{1,r}$, FS_1, $f'_{i,r} \in FS_2$) should be obtained and $\bar{d}_r \le \bar{d}_i \, (1 \le i \le n, i \ne r)$. $f_{1,r}$ will be the root of spanning tree.

Initial boundary matching based on spanning tree algorithm: $f_{1,r}$ is taken as the root node of the spanning tree. The spanning tree is generated by using Breadth First Search (BFS) algorithm to traverse the topology adjacent graph of M_1. With the growth of the spanning tree, it is necessary to search for the matching face of newly generated tree node on M_2. If $f_{1,i}(1 \le I \le n)$ is a tree node of the spanning tree and the matching face of $f_{1,i}$ is denoted as $f'_{i,i}$ ($f'_{i,i} \in FS_2$), $f'_{i,i}(1 \le I \le n)$ constitutes the set $FS_1' = \{f'_{i,r} | 1 \le I \le n\}$ and $FS_1' \subseteq FS_2$.

Initial similarity calculation between CAD models: If the similarity between M_1 and M_2 is denoted as $S(M_1, M_2)$, will be expressed as the following equation.

$$S(M_1, M_2) = \frac{1}{n}\sum_{i=0}^{n-1} w_i \cdot S_G(f_{1,i}, f'_{1,i}) \cdot S_T(f_{1,i}, f'_{1,i}) \qquad (10)$$

In Eq. 10, $S_T(f_{1,i}, f'_{1,i})$ is the topology similarity between $f_{1,i}$ and $f'_{1,i}(1 \le I \le n)$. w_i is a value which represents the weight of $f_{1,i}$ in the similarity between M_1 and M_2. Equation 11 is applied to calculate w_i.

$$w_i = \frac{h_i}{\sum_{j=0}^{n-1} h_j} \qquad (11)$$

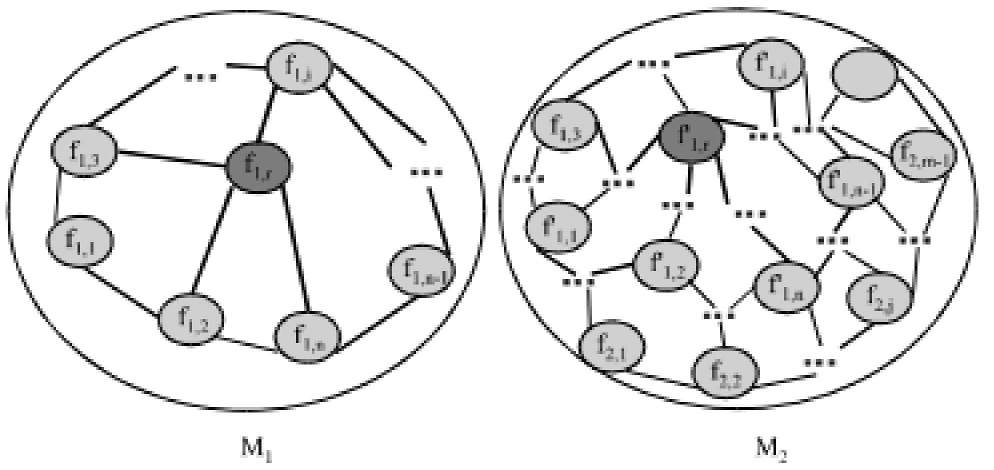


Fig. 6: Initial boundary matching

```
Begin;
Define the iteration error δ and the limit of absolute error ε and let
  δ = |1.0−S_0|;
Do while δ≥ε
  Define cycle variable I and let I = 1;
  Do while I≤n
    Define cycle variable j and let j = 1;
    Do while j≤m
      If f_{2,j} ∈ FS_2−FS'_1
            Calculate S_G(f_{1,i}, f_{2,j}) and S_T(f_{1,i}, f_{2,j});
        If S_G(f_{1,j}, f_{2,j}) S_T(f_{1,j}, f_{2,j})>S_G(f_{1,i}, f'_{1,i}) S_T(f_{1,j}, f'_{1,i})
              FS'_1←FS'_1−{f'_{1,i}};
           FS'_1←FS'_1∪{f'_{2,j}};
           f'_{1,i}←f_{2,j};
          End If
      End If
      If f_{2,j} ∈ FS'_1 and is the matching face of f_{1,k} (1≤k≤n, k≠I)
              Define ΔS and let ΔS = S_G(f_{1,i}, f'_{1,i}) S_G(f_{1,i}, f'_{1,i}) +S_G(f_{1,k}, f_{2,j})
            S_G(f_{1,k}, f_{2,j});
            Define ΔS' and let ΔS' = S_G(f_{1,i}, f'_{2,j}) S_T(f_{1,i}, f'_{2,j}) +S_G(f_{1,k}, f'_{1,i})
            S_T(f_{1,k}, f'_{1,i});
         If ΔS'>ΔS
           f'_{1,k} ←f'_{1,i};
          f'_{1,i} ←f'_{2,j};
         End If
      End if;
       j = j+1
    End while;
     I = I+1;
  End while;
  Calculate S(M_1, M_2) according to the updated boundary matching
  between M_1 and M_2;
  δ = | S(M_1 M_2)−S_0|;
  S_0 = S(M_1 M_2);
End while;
Return S_0;
End;
```

Fig. 7: Topology adjacency approximation algorithm

Figure 6 shows the process of initial boundary matching. The time complexity of initial boundary matching process is $O(n^2)$, since the time complexity of BFS-based spanning tree algorithm is $O(n^2)$. The advantages of above-mentioned method is that the initial boundary matching process can accelerate the convergence of topology adjacency approximation algorithm.

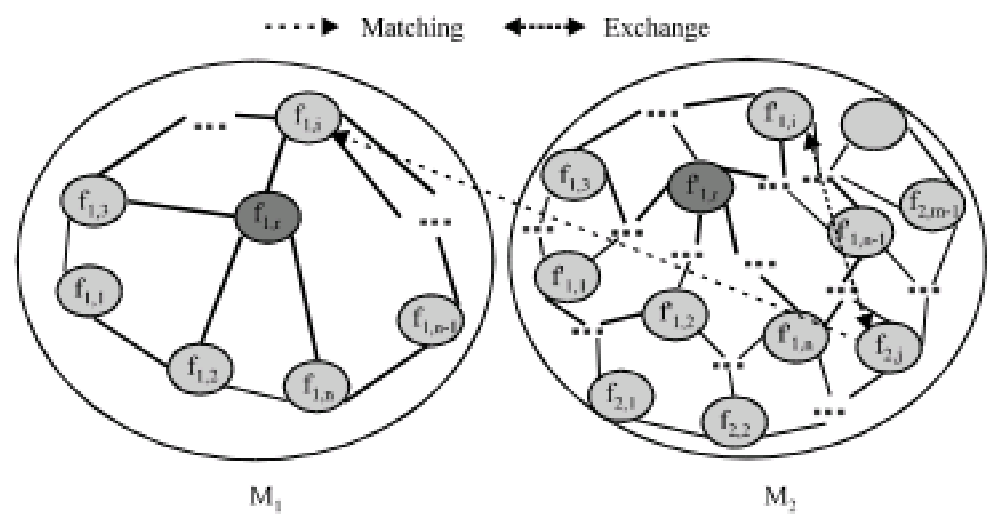


Fig. 8: Process of topology adjacency approximation

Topology adjacency approximation algorithm: The topology adjacency approximation algorithm is proposed to search for the optimal boundary matching between retrieval object and retrieval condition and make the boundary matching converge to the global optimal solution. The global optimal solution should meet the requirement of the absolute error. It is hypothesized that the initial similarity between M_1 and M_2 is denoted as S_0. Figure 7 shows the topology adjacency approximation algorithm.

Figure 8 also shows the detailed process of topology adjacency approximation. The kernel process lies in that the matching relationship between arbitrary two couple matched faces should be exchanged if the exchange can make the similarity increase. In fact, the topology adjacency approximation algorithm makes the boundary matching reach a stable status. In the status, the similarity between M_1 and M_2 will converge to an accurate value relatively.

Furthermore, the topology adjacency approximation algorithm is proven convergent by more experiments and its total cycle number is about $\gamma \times n \times m$. Further experiments show that $\gamma \leq 5$. Therefore, the time complexity of the algorithm is $O(n^2)$. Moreover, the time complexity of initial boundary matching is also $O(n^2)$. Thus, the total time complexity of the proposed CAD model retrieval method will be $O(n^2)$.

APPLICATION IN CAD MODEL RETRIEVAL

Function and implementation: A CAD model retrieval system based on CAD platform is developed according to the above-mentioned method. The retrieval system takes CAD model or structures of CAD model as the retrieval condition. The system is divided into two modules. The first module is used to extract the retrieval condition from CAD model and the second is the retrieval engine used to search for the retrieval results by calculating and ordering the similarities between retrieval objects and retrieval condition. The functions of two modules will be analyzed in the following:

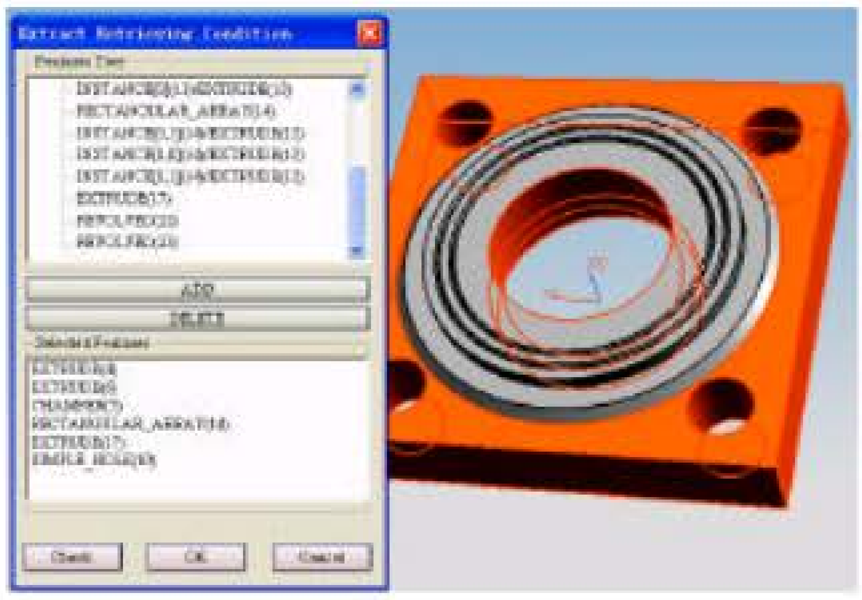


Fig. 9: The interface of condition extraction module

Condition extraction module: The geometry information is extracted from CAD model on level of feature by condition extraction module. For example, F is a feature of CAD model and the set of boundary faces on F can be denoted as $F = \{f_1, f_2,...,f_n\}$. n is the number of boundary faces on F. For any structure S on CAD model, the boundary information of S should be expressed as $S = F_1 \cup F_2 \cup ... \cup F_m$ and m is the number of features on the structure S. Therefore, the condition extraction process is the extraction process of features $F_1, F_2,...,F_m$. Moreover, all boundary faces of the extracted structure should be keep interconnectivity and all the boundary faces constitutes a connected graph. Thus a connectivity detection algorithm should be necessary. This study uses the Breadth-First-Search (BFS) algorithm to check the connectivity of graph composed of all boundary faces on the structure. This study developed the condition extraction module on UG platform by VC++6.0 and the internal application programming interface of UG system. The interface of the condition extraction module is shown in Fig. 9.

Retrieval engine module: The similarity between retrieval object and retrieval condition is calculated by retrieval engine module. The similarity shows whether there is the structure being similar to the retrieval condition on the retrieval object. Thus, retrieval engine module is the main module used to realize the retrieval function. Retrieval engine module includes two main functions. The first function is to extract the geometry information from retrieval object and the second function is to calculate the similarity between retrieval object and retrieval condition. Whereas, the extraction function of geometry information of retrieval engine module is different from that of the condition extraction module. The retrieval engine module directly extracts all geometry information of retrieval object by traversing all boundary faces of retrieval object. All boundary faces of retrieval object constitute a connected graph. The retrieval engine module calculates the similarities between every retrieval objects and retrieval condition one by one. The model retrieval is completed by sorting the similarities between all retrieval objects and the retrieval condition and the retrieval results meeting the retrieval threshold will be returned. The retrieval threshold is input by users. This study developed the retrieval engine module on UG platform by VC++6.0 and the external application programming interface of UG platform. The interface of the retrieval engine module is shown in Fig. 10.

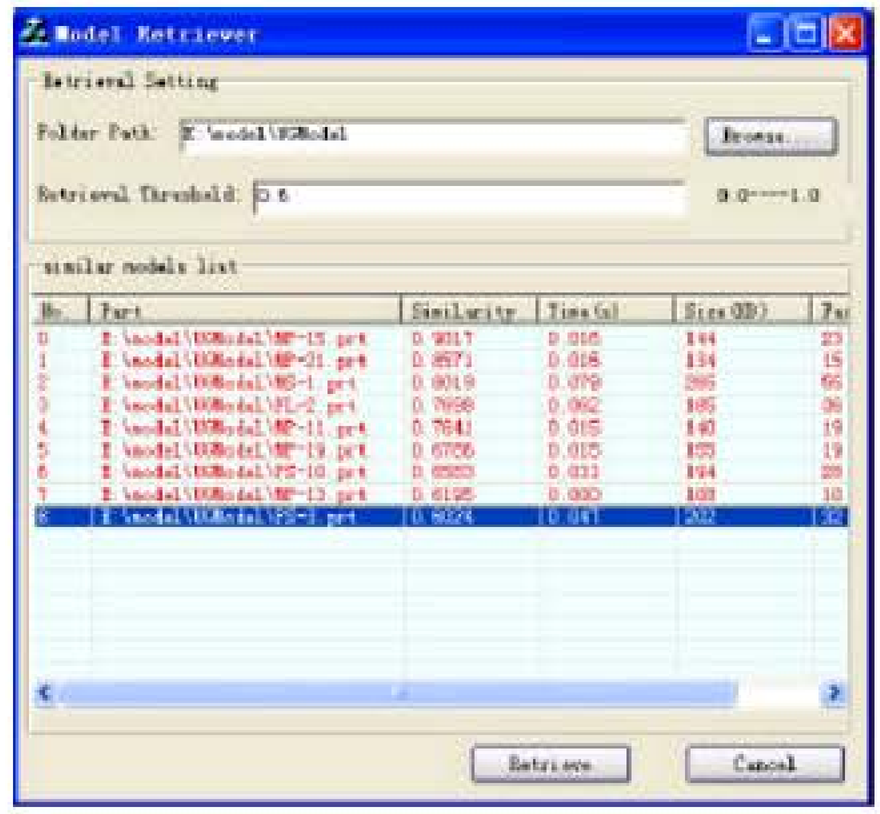
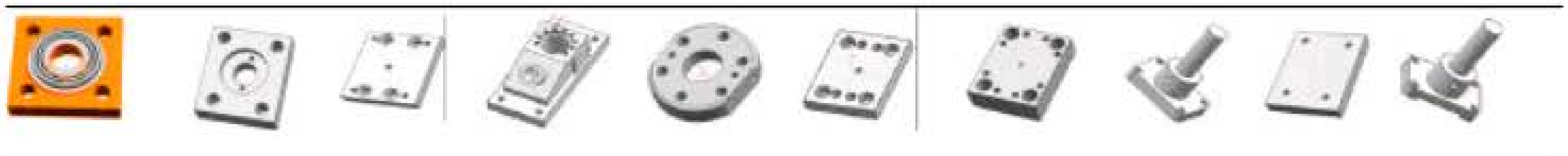


Fig. 10: The interface of retrieval engine

Retrieval precision: Precision and recall are the most important indexes to evaluate the retrieval method. As pointed out by Shilane *et al*. (2004), a precision-recall plot describes the relationship between precision and recall in a ranked list of matches. For each retrieval condition model in class C and any number K of top matches, recall (the horizontal axis) represents the ratio of models in class C returned within the top K matches, while precision (the vertical axis) indicates the ratio of the top K matches that are members of class C. A perfect retrieval result produces a horizontal line across the top of the plot (at precision = 1.0), indicating that all the models within the retrieval object's class are returned as the top ranked matches. Otherwise, curves that appear shifted up represent superior retrieval results. In order to describe the precision curves of the model retrieval system, 867 UG models are built as retrieval samples with reference to the models' shapes in the Engineering Shape Benchmark (ESB) of Purdue University (http://shapelab.ecn.purdue.

Table 1: Retrieval results

Retrieval conditions	Retrieval results								
									
Similarity	0.9017	0.8571	0.8019	0.7598	0.7641	0.6783	0.6583	0.6195	0.6024
									
Similarity	1.0000	1.0000	1.0000	1.0000	0.8030	0.7006			

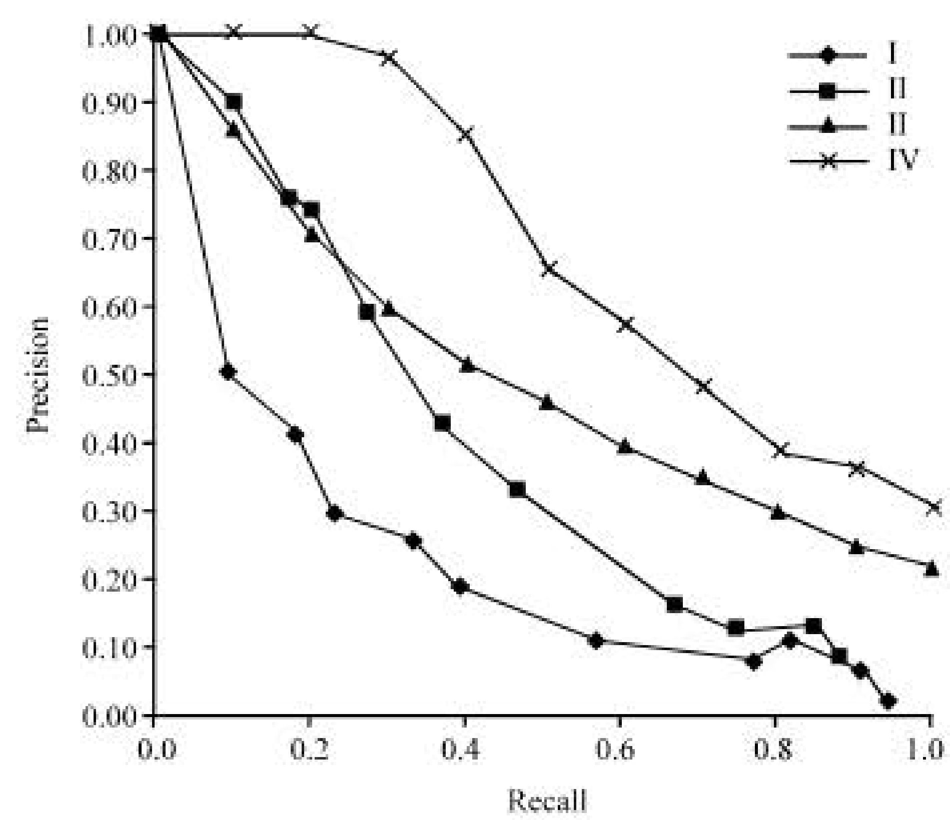


Fig. 11: Precision-recall curves

edu/Benchmark.aspx) and a large number of experiments are conducted. The precision-recall plot is drawn by analyzing the experimental results. Figure 11 is the precision-recall plot. The curve I-IV represent the precision-recall curves which are obtained, respectively by the retrieval methods proposed by Wang *et al*. (2006, 2007) and Ma *et al.* (2008) and present study.

Figure 11 shows that the precision of the method is higher than those of other methods in same condition of recall ratio. Especially the method has obvious superiority to other methods in recall interval (0, 0.5).

EXPERIMENTS

Many retrieval experiments have been conducted. In order to demonstrate the retrieval effect of the proposed method, two CAD models in the 1st column of Table 1 are taken as the retrieval conditions and ζ, ε and the retrieval threshold are taken as 0.50, 0.0001 and 0.6, respectively. The retrieval results are returned and shown in the 2nd column of Table 1.

CONCLUSIONS

In summary, this study investigates the CAD model retrieval based on boundary matching. A new retrieval method based on topology adjacency approximation algorithm is proposed. The proposed retrieval method is applied to develop the CAD model retrieval system based on UG platform. Experimental results show that the proposed method is feasible. The performances of the model retrieval system are as follows:

- The adaptability of the proposed method is better than other method. It is not only used in the CAD model retrieval but also applied in the partial structure retrieval of CAD model
- The model retrieval is higher efficiency and its time complexity is about $O(n^2)$
- The precision-recall plots shows that the precision of the proposed method is higher

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