Title:

Recognition of Depression and Protrusion Features on B-rep Models Based on Virtual Loops

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Introduction:

Loops are important elements in the B-rep model to link all edges corresponding to faces. It has been shown that loops can be used in feature recognition for identifying depressions or protrusions [4]. In the B-rep model, a loop is basically defined on a face only. Features in 3D CAD models, however, typically lie across multiple faces, which is beyond the data structure of current B-rep model. Therefore, to extend the capability of loops for the use in complex feature recognition, the definition of loops should be expanded and associated feature recognition algorithm should be developed.

Most researchers employ the topological relationships of adjacent entities for the recognition of features, such as face adjacency graph and attributed adjacency graph [1, 3, 6]. They all assume that all fillets must be removed before the feature recognition, which is practically difficult because the variety of fillets in real cases is complex. Several studies focus on the recognition of fillets because fillets frequently appear in CAD models and complicate the topological structure of faces [7, 9]. Further studies are also available for the recognition of depression or protrusion features [4, 10]. In [2], the loop data in the B-rep model was employed for the recognition of holes. These approaches, however, lack generalness and flexibility.

This study presents a virtual loop concept to account for all types of loop used in CAD models, and develops algorithms for recognizing various kinds of depression and protrusion features. Three types of loop are defined in this study: single, virtual, and multi-virtual loops. A single loop is the current loop recorded in the B-rep model. A virtual loop lies across faces and all edges on the loop are at least G^1 continuous. A multi-virtual loop lies across faces also, but some of the edges on the loop are G^0 continuous only. A loop recognition algorithm is developed to identify and distinguish the aforementioned loops in CAD models. With the loop data available, a feature recognition algorithm is then developed to identify various kinds of depression and protrusion features, ranging from simple circular holes locating on a face to complex irregular pockets locating on multiple faces.

Main Idea:

Real 3D models are generally complex because the features are typically filleted at the boundary and composed of multiple faces. A feature may be affected by the following four types of multiple face: (1) the base face where the feature locates may be composed of multiple faces; (2) the feature itself may be composed of multiple faces; (3) the feature is generally filleted at its boundary, resulting in one or more transition faces (blend face(s), or BF(s) in short) between the feature face and the base face; and

(4) one or more of the faces related to the feature are virtual faces, where a virtual face represents that the face is extended to other part faces or features. Fig. 1 depicts different combinations of the above four types of multiple face in several CAD models. For all the above cases, it is necessary to define and construct different types of loop recording all elements (edges/trims and faces) related to the target features, and employ such loops for the recognition of the target features.

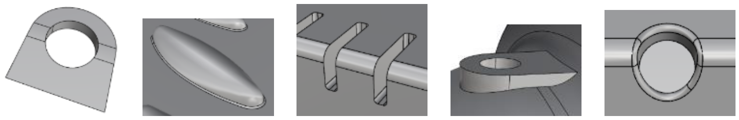

Fig. 1: Several examples expressing the compositions of multiple base faces, multiple feature faces, blend faces, and virtual face on features

Three types of loop, namely single, virtual and multi-virtual loops are defined in this study in accordance with the complexity of recognition. The single loop is exactly the same as the loop data recorded in the B-rep model. It describes a contour of edges surrounding the exterior or interior boundaries of a face. Both virtual loop and multi-virtual loop lie across multiple faces. For the virtual loop, all faces which contribute the loop are at least G^1 continuous with other faces along the loop direction. For the multi-virtual loop, however, some faces which contribute the loop may be G^0 continuous with other faces along the loop direction. Single loops in a CAD model can directly be acquired from the B-rep data structure. Virtual and multi-virtual loops, however, are not recorded in the B-rep data structure. Two separate procedures are developed in this study to detect virtual loops and multi-virtual loops, respectively.

The overall flowchart of the proposed loops- and features-recognition algorithm is depicted in Fig. 2. The inputs are the B-rep model and blend faces (BFs). Several algorithms are available for the recognition of blend faces [5, 9]. The procedures of virtual loops recognition are divided into the following four steps:

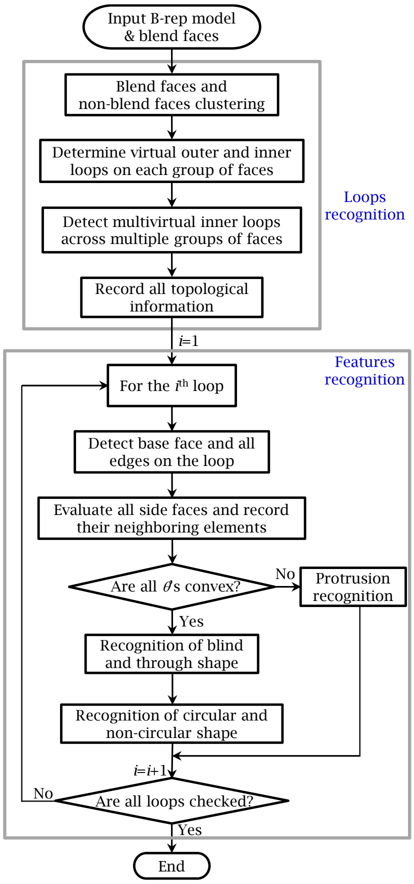

Fig. 2: Overall flowchart of proposed method for the recognition of virtual kinds of loops and features

(1) Blend faces and non-blend faces clustering: BFs are clustered alone to obtain their own groups; whereas all non-BFs which are G^1 continuous are clustered as a group. The BFs that connect to each other sequentially are considered as a group. A group of this type can contain one or multiple BFs. The clustering of BFs is not described here because each group contains a virtual outer loop only. For non-BFs, the boundary edges of the group are either adjacent to the BFs or G^0 continuous with their adjacent faces. Start from a seed face, a region growing algorithm is performed along each boundary edge. When the growing reaches an edge neighboring to the BF or an edge exhibiting G^0 continuity with its adjacent face, the growing stops in that direction. This procedure is implemented for all faces on the face list except when a face is a BF or when it already belongs to a group. Once the growing is completed, it can yield a set of groups all composed of non-BFs.

(2) Determine virtual outer and inner loops within each group of faces: For each group of non-BFs, a procedure is developed to detect all inner and outer loops. Such loops are called virtual loops. There are basically five elements in the B-rep data structure, namely, vertex, edge, trim, loop and face. The data recorded in each element includes geometric and topological data [8]. Some of the topological information related to this study is briefly described as follows. An edge is essentially a three-dimensional element and is non-directional. A trim, however, is a two-dimensional element and is directional. An edge is generally mapping onto two trims. A loop is essentially composed of trims. The problem of identifying a loop for a group of faces is equivalent to evaluate the trims surrounding the target loop. When an edge is located on the boundary of a group, its two trims should belong to two different groups. By contrast, when an edge is located inside a group, its two trims should belong to one group. Such a property is employed in the proposed algorithm for removing trims corresponding to the inner edges, as depicted in Fig. 3.

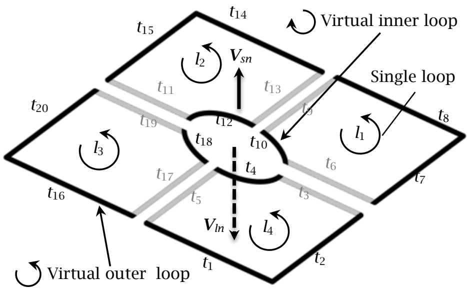

Fig. 3: Redundant trims removed to form virtual inner and outer loops, where t_i indicates trims and l_j indicates loops

The flowchart for the evaluation of virtual outer and inner loops within a group of faces is depicted in Fig. 4. The input is all groups G_i, where i denotes the group index. Since the first n_b groups belong to blend faces, each of them can be processed first to yield a virtual outer loop. It is noted that no virtual inner loop exists on the group of blend faces. The other groups remained are essentially composed of non-blend faces. Each of the groups is checked one by one to determine the virtual outer loop and virtual inner loops, respectively. For each of these groups, the redundant trims, such as the gray color in Fig. 3, are removed first. The trims left can easily form individual chains of trim, where m in Fig. 3 denotes the number of chains found.

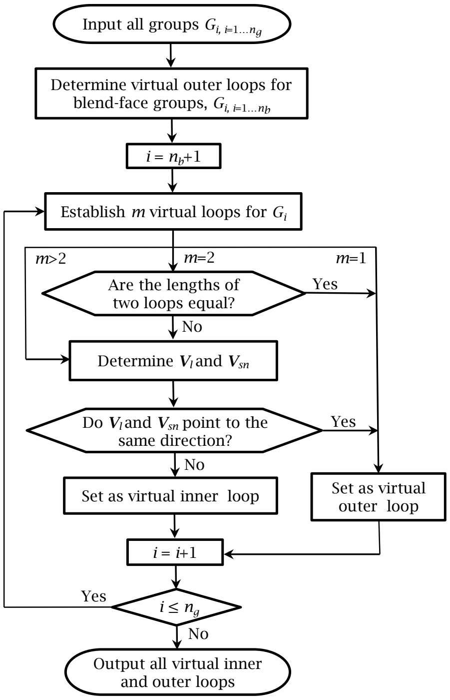

Fig. 4: Flowchart for determining virtual inner and outer loops on each group of faces

As Fig. 4 indicates, if m=1, then only the outer loop exists, and hence it can be attributed to a virtual outer loop. It is noted that trim is directional in the B-rep data structure. If m=2 and the lengths of both profiles are equal, then it indicates that the two loops represent the boundaries of a cylindrical surface, and hence the loops are regarded as virtual outer loops. When m>2 or m=2 but with different lengths, two vectors $\boldsymbol{V}_l$ and $\boldsymbol{V}_{sn}$, as shown in Fig. 3, are evaluated, where $\boldsymbol{V}_l$, a loop vector, represents the surface normal of a plane lying on the loop; whereas $\boldsymbol{V}_{sn}$ denotes the surface normal of the non-blend faces. If $\boldsymbol{V}_l$ and $\boldsymbol{V}_{sn}$ point to the same direction, this loop is regarded as a virtual outer loop; whereas if $\boldsymbol{V}_l$ and $\boldsymbol{V}_{sn}$ point to reverse direction, this loop is regarded as a virtual inner loop. Such a procedure is repeated for all groups of non-blend faces. It finally yields all virtual outer and inner loops.

(3) Detect multi-virtual inner loops across multiple groups of faces: The loops across BFs and multiple groups of faces are called multi-virtual loops. For a multi-virtual loop across multiple groups of faces, the following properties are noted. First, each trim in the loop should be derived from the virtual outer loop of a group. Second, most trims in the loop are from non-BFs. However, some of them may be derived from BFs. Third, the trims in the loop may involve G^0 and G^1 continuous at the connecting points. The overall method of the proposed algorithm in this step is as follows. After the previous step, all virtual outer and inner loops within a group can be obtained. Take the virtual outer

loops of every two neighboring groups to verify whether an additional virtual inner loop can be identified. Based on the continuity of the faces at the jointed boundary, we developed two procedures to evaluate multi-virtual inner loops. The first procedure was employed for cases where the faces at the jointed boundary are G^0 continuous; whereas the second procedure was employed for cases where the faces at jointed boundary are G^1 continuous. Fig. 5 shows the flowchart of the proposed algorithm for evaluating multi-virtual inner loops across multiple groups.

(4) Record all topological information: Delete any repeated loops, delete the trims that overlap the same path, and filter the loops where all trims are derived from BFs only. After the above procedures, all types of loop on a CAD model are detected, where all adjacent edges and faces related to each loop are recorded.

Fig. 6 depicts the loops identified for six cases, where the numbers beneath each plot represent the number of single inner loop, virtual inner loop, and multivirtual inner loop, respectively. Tab. 1 lists number of faces, various kinds of loop detected, and computing time for six cases. It is noted that only inner loops are employed for feature recognition, hence the numbers shown in Fig. 6 indicate various kinds of inner loop detected. The computing time shown in Tab. 1 clearly indicates that the overall computational speed of the proposed algorithm is very fast. Moreover, the results in Fig. 6 clearly indicate that all loops can lie on any kind of face and across multiple faces. Moreover, almost all faces are filleted at their boundary. Therefore, these results demonstrate that the proposed loop recognition method can be implemented to extract all types of loop and obtain the topological relations of edges/faces neighboring to all loops.

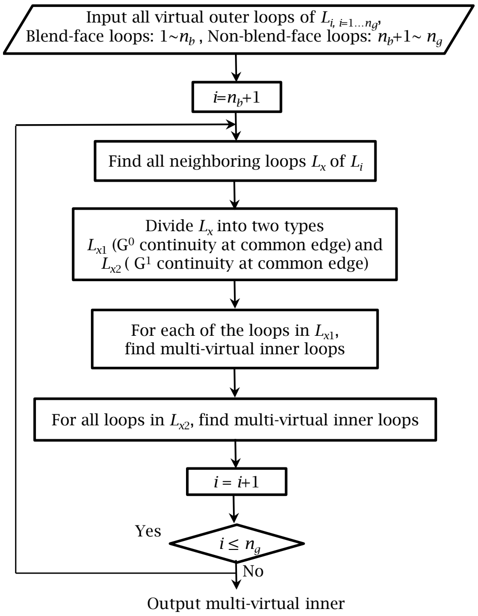

Fig. 5: Flowchart for determining multi-virtual inner loops across multiple groups of faces

The procedures for the recognition of depression and protrusion features are as follows. The face where a feature locates is called a base face; the contour at the transition of the base face and the feature is a loop; the feature faces adjacent to the loop are called side faces. For each inner loop obtained above, the base face and all edges on the loop are detected. Based on these edges, all side faces are then evaluated. A side face may be neighboring to an edge directly or indirectly with one or several BFs in between. The faces inside a loop can either be a depression or a protrusion. A set of angles θ's along the boundary loop is evaluated, which can be used for judging the feature type. For a depression feature, it can further be divided into through/blind and circular/non-circular types. Further steps are provided for identifying them. Similarly, an independent procedure is also developed for identifying different types of protrusion. Additional rules may be needed to classify and recognize different types of protrusion, if necessary.

Case	No. faces	Single loop		Virtual loop		Multivirtual inner loop	Computing time (s)
		Inner loop	Outer loop	Inner loop	Outer loop		
1	103	7	103	1	24	6	0.187
2	152	20	152	0	34	0	0.189
3	223	152	223	12	89	0	0.481
4	364	27	364	0	96	5	0.761
5	416	162	416	0	388	32	0.414
6	1275	393	1275	27	421	0	2.317

Tab. 1: Various kinds of loop recognized and computing time for six cases shown in Fig. 9.

Fig. 7 depicts the results of hole- and extrusion-recognition process by the proposed method. Four kinds of holes are identified, namely circular through holes, circular blind holes, non-circular through holes, and non-circular blind holes, printed in deep blue, red, aqua blue, and yellow, respectively. Moreover, the extrusion detected is printed in deep blue. The separation of the above-mentioned holes and extrusion provides useful information in many applications, such as the decision making in automatic mesh generation.

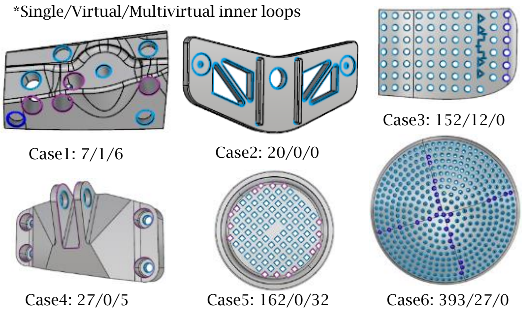

Fig. 6: Various types of inner loop recognized, single, virtual and multivirtual inner loops are printed in water blue, blue and purple, respectively

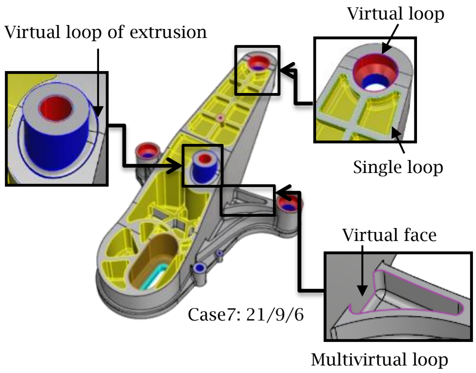

Fig. 7: Combination of loop and hole/protrusion recognition algorithms

Conclusion:

A virtual loop recognition method was proposed in this study to detect all types of loop in the B-rep model, and to enable the recognition of depression and protrusion features lying across multiple faces. The most significant contribution of the proposed method is that it can detect loops of G^0 or G^1 continuity across multiple faces, which is beyond the capability of the current B-rep data structure. With different types of loop detected, appropriate feature recognition algorithm was also developed for the recognition of several types of depression and protrusion. Further studies should consider integrating the proposed method with other feature-recognition algorithm to detect general types of feature more completely.

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