Title:
A Learning Method for Automatic Reconstructing 3D Models from Sketches

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Introduction:
Presently solid modelers have become popular tools in CAD/CAM systems. However, much study and training for many operations would be required for a user when he/she makes a solid model of an object smoothly. Although many simpler solid modelers and 3D sketching systems have been developed in recent years, e.g. [2],[3], minimum operations would exist and they would become unique. Therefore, they would become very far from standard solid modelers such as CATIA. As the result, a lot of them would be disappeared naturally in the future. On the other hand, the methods to automatically reconstruct solid models from sketches have been researched, e.g. [1]. Also, we have been developing a system for the reconstruction, e.g. [4-6]. Generally sketches are convenient for expressing the shapes of 3D objects with papers. Most people can draw them without knowing drawing rules, and also they are often used when designers discuss new parts, products, etc. If our system realizes, it would become a powerful tool in CAD/CAM systems. In the system, stronger machine learning sub-systems are required and it has been an important issue. In this paper, a new learning method for the issue is proposed. In the system, firstly many simple sketch features are defined. Fig. 1 shows three samples of them.

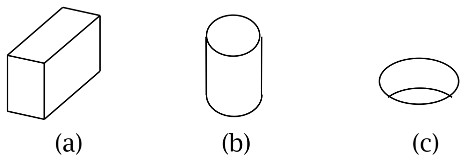

Fig. 1: Three sketch features: (a) Cuboid, (b) Cylinder, and (c) Round Hole.

When a sketch is input to the system, some sketch feature would be detected and extracted. This extraction is continued until there are no lines in the sketch. As the result, a 3D model could be obtained by combining all extracted 3D features. However, there has been an important issue that after a sketch feature is extracted, several broken lines are often generated. They would prevent the next feature extraction. Therefore, they have to be restored automatically but there are too many their patterns. We have developed some methods for learning the patterns. In the latest our paper, an inductive learning method was proposed, e.g. [6]. However, since its algorithm was too theoretical, the limitation, effectiveness and implementation techniques of that were ambiguous. In this paper, [6] would be improved strongly. In our proposed method of this paper, the limitation and effectiveness would be clearer and how to implement the method is clearer. As the result, the method would be more practical than our past learning methods.

Main Idea:
To explain our learning method, firstly the whole algorithm of our system to reconstruct 3D models from sketches is explained with Example 1 illustrated in Fig. 2(a) as follows.

(1) Input a sketch to our system. The sketch is a line drawing of an object without hidden lines. Also, it is drawn from a general view correctly and precisely on a tablet, PC, etc. Users can draw straight line segments and elliptical arcs for sketches.
(2) All straight lines are divided at their intersections except curves. At L-junctions and W-junctions of straight lines, additional lines as dotted lines can be drawn such as Fig. 2(b). (*L*1, *W*1, *W*2)
(3) Detect and extract a sketch feature. It can be converted into 3D feature with "cubic corner method", e.g. [7]. Fig. 2(c) shows the detection of a cuboid sketch, and Fig. 2(d) shows its extraction as *f*1.
(4) After a feature extraction, several isolated lines each of which does not make any closed loops of lines are often generated in a sketch. They have to be restored for the next sketch feature extraction. For the restoration, our new learning system would be applied.
(5) The feature extraction is continued unless there are no lines from the input sketch. In Fig. 2(e), the other cuboid sketch (*f*2) can be detected, and extracted as in Fig. 2(f). There are many isolated lines in this figure. If these isolated lines are restored, a round hole sketch can be detected as *f*3 as in Fig. 2(g). After the extraction of *f*3, *f*4 can be detected as in Fig. 2(h).
(6) All 3D features are combined in accordance with the input sketch inductively. So the solution would be obtained. In Example 1, the solution can be obtained such as *f*4 + *f*3 + *f*2 + *f*1 as in Fig. 2(i).

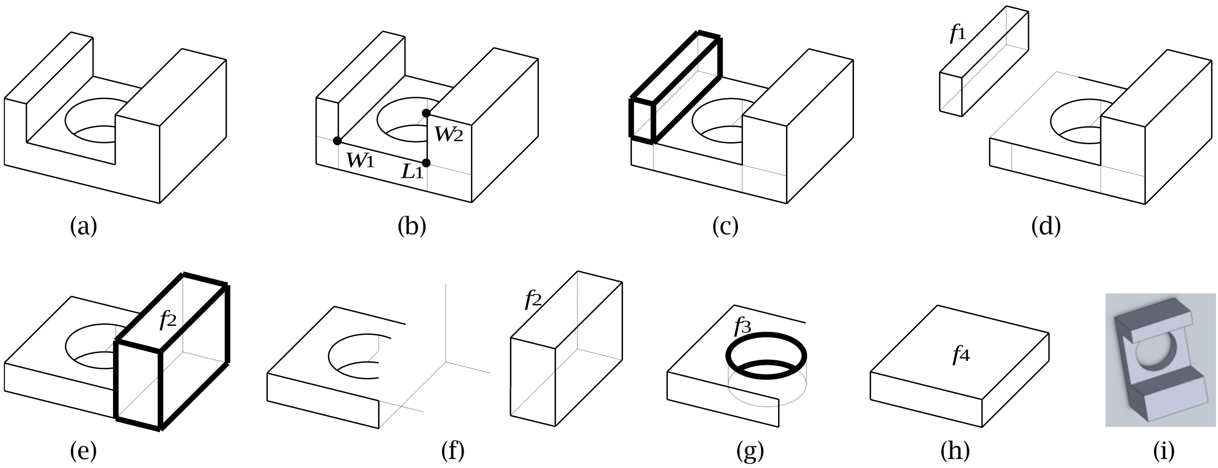

Fig. 2: Example 1 and the process to make the solution: (a) Example 1, (b) Generation of additional lines, (c) Detection of a cuboid sketch, (d) Extraction of *f*1, (e) Detection of *f*2, (f) Extraction of *f*2, (g) Detection of *f*3, (h) Detection of *f*4, and (i) The solution.

Our proposed learning method in this paper is explained with Example 2 illustrated in Fig. 3 as follows. At first, each sketch can be recognized as a set of geometric elements. Also, each geometric element is defined as a class. Therefore, a sketch consists of the instances of classes, e.g. [5]. In Example 2, the following six classes are defined as follows.

Class Point: 1)Number 2){Contact lines} 3)Number of 2) 4)Whose center point of elliptical arcs? 5)Tangent point of lines?;
Class Straight Line: 1)Number 2){Two endpoints} 3)Length 4)Direction 5){Isolated points} 6)Number of 5);
Class Elliptical Arc: 1)Number 2)Length of long axis 3)Length of short axis 4){Two endpoints} 5)Center point 6){Isolated endpoints} 7)Number of 6) 8)Ellipse?; 9)Direction of 3);
Class Relationship between Two Straight Lines: 1){Two lines} 2)Longer line 3)More isolated line 4)Angle 5)Which point is the contact point of them?;

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Class Relationship between Two Elliptical Arcs: 1) {Two arcs} 2) Longer arc 3) More isolated arc 4) Are they contacted? 5) Are their two axes the same in length? 6) If their directions are the same, which direction?;
Class Relationship between Contacted Elliptical Arc and Straight Line: 1) Elliptical Arc 2) S. Line 3) Contact point? 4) Is 3) a tangent point? 5) Is 1) ellipse?;

Each class consists of properties. For example, Cass Point has five properties. Fig. 3(a) shows a sketch of a broken cylinder, and Fig. 3(b) shows a restored that. Also, Fig. 3(c) and Fig. 3(d) are another restoration case of that. In these restorations, the following learning is executed in our method. Firstly, Fig. 3(a) and Fig. 3(b) are expressed as instances as follows.

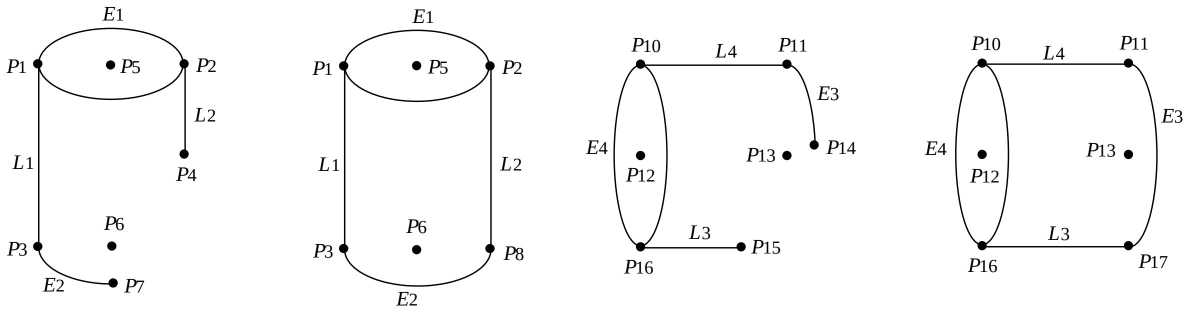

Fig. 3: Example 2: (a) A sketch of a broken cylinder, (b) Restored (a), (c) Another sketch of a broken cylinder, and (d) Restored (c).

The instances of Fig. 3(a):
(Point) 1) P1 2) {L1, E1} 3) 2 4) NA 5) yes; 1) P2 2) {L2, E1} 3) 2 4) NA 5) yes; …
(Straight Line) 1) L1 2) {P1, P3} 3) 50.0 4) 90.0deg 5) { ϕ } 6) 0; 1) L2 2) {P2, P4} 3) 24.23 4) 90.0deg 5) {P4} 6) 1;
(Elliptical Arc) 1) E1 2) 40.0 3) 20.0 4) { ϕ } 5) P5 6) { ϕ } 7) 0 8) yes 9) 90.0deg;
1) E2 2) 40.0 3) 20.0 4) {P3, P7} 5) P6 6) {P7} 7) 1 8) no 9) 90.0deg;
(Relationship between Two Straight Lines) 1) {L1, L2} 2) L1 3) L2 4) 0.0deg 5) NA;
(Relationship between Two Elliptical Arcs) 1) {E1, E2} 2) E1 3) E2 4) no 5) yes 6) 90.0deg;
(Relationship between Contacted Elliptical Arc and Straight Line)
1) E1 2) L1 3) P1 4) yes 5) yes; 1) E1 2) L2 3) P2 4) yes 5) yes; 1) E2 2) L1 3) P3 4) yes 5) no;
The instances of Fig. 3(b):
(Point) 1) P1 2) {L1, E1} 3) 2 4) NA 5) yes; 1) P2 2) {L2, E1} 3) 2 4) NA 5) yes; ...
(Straight Line) 1) L1 2) {P1, P3} 3) 50.0 4) 90.0deg 5) { ϕ } 6) 0; 1) L2 2) {P2, P8} 3) 50.0 4) 90.0deg 5) { ϕ } 6) 0;
(Elliptical Arc) 1) E1 2) 40.0 3) 20.0 4) { ϕ } 5) P5 6) { ϕ } 7) 0 8) yes 9) 90.0deg;
1) E2 2) 40.0 3) 20.0 4) {P3, P8} 5) P6 6) { ϕ } 7) 0 8) no 9) 90.0deg;
(Relationship between Two Straight Lines) 1) {L1, L2} 2) NA 3) NA 4) 0.0deg 5) NA;
(Relationship between Two Elliptical Arcs) 1) {E1, E2} 2) NA 3) NA 4) no 5) yes 6) 90.0deg;
(Relationship between Contacted Elliptical Arc and Straight Line)
1)E1 2)L1 3)P1 4) yes 5) yes; 1)E1 2)L2 3)P2 4) yes 5) yes; 1)E2 2)L1 3)P3 4) yes 5) no; 1)E2 2 L2 3)P8 4) yes 5) no;

The relationship between Fig. 3(a) and Fig. 3(b) becomes Q & A. Fig. 3(c) and Fig. 3(d) become another Q & A. The instances of them are as follows.
The instances of Fig. 3(c):
(Point) 1) P10 2) {L4, E4} 3) 2 4) NA 5) yes; 1) P11 2) {L4, E3} 3) 2 4) NA 5) yes; …
(Straight Line) 1) L4 2) {P10, P11} 3) 35.0 4) 0.0deg 5) { ϕ } 6) 0; 1) L3 2) {P15, P16} 3) 24.5 4) 0.0deg 5) {P15} 6) 1;
(Elliptical Arc) 1) E4 2) 40.0 3) 20.0 4) { ϕ } 5) P12 6) { ϕ } 7) 0 8) yes 9) 0.0deg;
1) E3 2) 40.0 3) 20.0 4) {P11, P14} 5) P13 6) {P14} 7) 1 8) no 9) 0.0deg;
(Relationship between Two Straight Lines) 1) {L4, L3} 2) L4 3) L3 4) 0.0deg 5) NA;
(Relationship between Two Elliptical Arcs) 1) {E4, E3} 2) E4 3) E3 4) no 5) yes 6) 0.0deg;
(Relationship between Contacted Elliptical Arc and Straight Line)
1) E4 2) L4 3) P10 4) yes 5) yes; 1) E4 2) L3 3) P16 4) yes 5) yes; 1) E3 2) L4 3) P11 4) yes 5) no;
The instances of Fig. 3(d):
(Point) 1) P10 2) {L4, E4} 3) 2 4) NA 5) yes; 1) P11 2) {L4, E3} 3) 2 4) NA 5) yes; …

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(Straight Line) 1) L4 2) {P10, P11} 3) 35.0 4) 0.0deg 5) { ϕ } 6) 0; 1) L3 2) {P17, P16} 3) 35.0 4) 0.0deg 5) { ϕ } 6) 0;
(Elliptical Arc) 1) E4 2) 40.0 3) 20.0 4) { ϕ } 5) P12 6) { ϕ } 7) 0 8) yes 9) 0.0deg;
1) E3 2) 40.0 3) 20.0 4) {P11, P17} 5) P13 6) { ϕ } 7) 0 8) no 9) 0.0deg;
(Relationship between Two Straight Lines) 1) {L4, L3} 2) NA 3) NA 4) 0.0deg 5) NA;
(Relationship between Two Elliptical Arcs) 1) {E4, E3} 2) NA 3) NA 4) no 5) yes 6) 0.0deg;
(Relationship between Contacted Elliptical Arc and Straight Line)
1)E4 2)L4 3)P10 4) yes 5) yes; 1)E4 2)L3 3)P16 4) yes 5) yes; 1)E3 2)L4 3)P11 4) yes 5) no; 1)E3 2)L3 3)P17 4) yes 5) no;

When the above data of two questions (Fig. 3(a) and Fig. 3(c)) are compared, many variables can be generated. Since there are too many similar points, here, this generalization is started from straight lines. When L1 and L2 are compared in Fig. 3(a), it is obvious the 6th properties are different. Also, L3, L4 in Fig. 5(c) corresponds to L2, L1 respectively in their 6th properties. Therefore, L3 and L2 can be changed into a variable straight line as Lx1. In the same way, L4 and L1 can be changed into Lx2. When E1 and E2 are compared in Fig. 3(a), it is found that the 8th properties are different. Therefore, E1, E4 and E2, E3 can be changed into Ex1 and Ex2 respectively. These variables can make variable points. For example, since Property 2) of P1 is {L1, E1} and it corresponds to {Lx2, Ex1}, {L4, E4} can correspond to P10. Therefore, P1 and P10 can be changed into Px1. In the same way, all points can be changed into variable points. As the result, the following relationships between variables and corresponding instances can be obtained.

(Straight Line) Lx1 = {L2, L3}, Lx2 = {L1, L4}. (Elliptical Arc) Ex1 = {E1, E4}, Ex2 = {E2, E3}.
(Point) Px1={P1, P10}, Px2={P2, P16}, Px3= {P3, P11}, Px4={P4, P15}, Px5={P5, P12}, Px6={P6, P13}, Px7={P7, P14}.

The above relationships can correspond to the following three relationships correctly.
(Relationship between Two Straight Lines) 1) {Lx1, Lx2} 2) Lx2 3) Lx1 4) 0.0deg 5) NA;
(Relationship between Two Elliptical Arcs) 1) {Ex1, Ex2} 2) Ex1 3) Ex2 4) no 5) yes 6) 90.0deg;
(Relationship between Contact Elliptical Arc and Straight Line)
1) Ex1 2) Lx2 3) Px1 4) yes 5) yes; 1) Ex1 2) Lx1 3) Px2 4) yes 5) yes; 1) Ex2 2) Lx2 3) Px3 4) yes 5) no;

In the same way, Fig. 3(b) and Fig. 3(d) can be generalized. In this generalization, the length of two straight lines, the size of ellipse and the direction of a cylinder become variables. When Fig. 4(a) is input as a new problem to this generalization, it is obvious that Fig. 4(b) can be obtained. In conclusion, a restoration way of a cylinder sketch can be learned in the method.

(a) (b)

Fig. 4: An application to new problems: (a) New problem and (b) The solution.

The algorithm of our learning method is as follows.
(1) Input a question as a sketch to a tablet, PC, etc. by a user. In Example 2, Fig. 3(a) is input.
(2) The user draws the answer. For example, Fig. 3(b) can be made by extending L2 and E2 until they are contacted. This Q & A data is stored and then the data is cleaned on the monitor.
(3) Input another question by the user. In Example 2, Fig. 3(c) is input. Here, this figure has to be the same as Fig. 3(a) in their shapes. But their sizes and directions have to be different as much as possible because of their generalization.
(4) The user draws the answer of (3). The process to make it has to be the same as (2) such as the extension of L3 and E3.
(5) Q & A data is generalized. Then a new question is input. If the correct answer cannot be obtained, some new Q & A data is input again for the correct generalization.

If it is difficult to use the learning system for some users such as beginners, this learning task can commit to some experts. Much more learning would realize more complete restoration system.

Examples:
At a glance, it is found that Fig. 5(a) could be restored into a cylinder by the method because all hints for this restoration are drawn in this figure. However, Fig. 5(b) is difficult because the length of the

cylinder is unknown. In this case, a user can decide the length such as 60.0. This case can be applied to Fig. 5(c) which is a rack and there are eight same cylinders. Moreover, if some fixed properties are changed to variables and some classes and/or properties are added, the method could be applied to modified cylinders such as Fig. 5(d). In this figure, when the property, "Angle", between two straight lines is free, the taper can be handled. Also, when the two straight lines are replaced to two silhouette lines, the L-shaped pipe and the grip can be handled in the method.

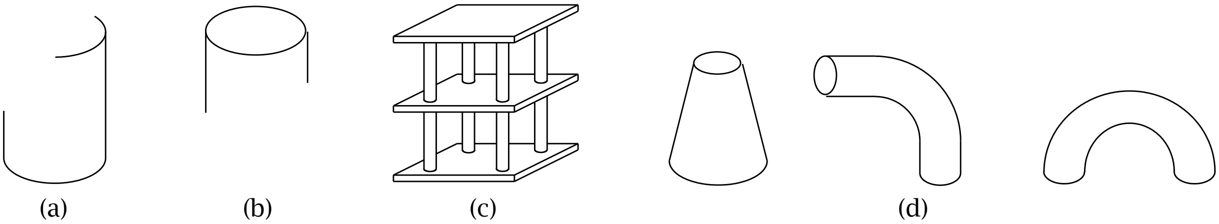

Fig. 5: Applications of our learning method: (a) A restorable case of broken cylinders, (b) An impossible case, (c) A sketch of a rack, and (d) Three sketches of modified cylinders (taper, L-shaped pipe, grip).

Discussion:

Generally deep learning would be the most popular learning technique in recent years. Although the technique usually requires huge data, simpler learning systems might be useful for solving local problems. For geometric problems, it might be easy and precise to express learning algorithm with geometric properties such as our method because huge data is not necessary and to implement of it might be not so difficult. Although sketches are usually drawn roughly, the method might learn restoring processes from rough sketches into precise sketches because this problem is also a geometric problem.

Conclusions:

In this paper, a new learning method for the restorations of broken sketches is proposed. In the method, each geometric element is defined as a class and it consists of many properties. In the method, "Machine Learning" means making variables from plural Q & A instances. To make much more variables would correspond to making much more kinds of learning. Also, when some variables are fixed intentionally, more broken sketches can be handled in the method.

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