Handling Chains, Springs, and Screws for Automatic Conversion of Mechanical Sketches into 3D Models

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Abstract. Sketches in the form of line drawings are important for designers to directly express overviews of objects, especially mechanical objects. Numerous methods have been proposed for the automatic conversion of sketches into 3D models. However, no practical conversion systems have been developed thus far. We have developed a sketch feature-based conversion method (SFBCM) for this conversion. In SFBCM, when a sketch is input, sketch features (SFs), which are simple sketches of objects such as cubes and cylinders, are detected and extracted as 3D features step-by-step. Consequently, a 3D model was obtained by combining these in accordance with the sketch. In addition, abstract sketch features (ASFs) were introduced to predict the hidden shapes of sketches in SFBCM. However, several problems remain unresolved. One of the problems is handling sketches of the chains, springs, and screws. In this study, we attempted to address this problem. For this conversion, we introduced accessorial sketch features (ACSFs). Generally the shapes of the chains, springs and screws contain many types of repetitive features in their sketches. Therefore, we defined these features as ACSFs. In this study, our new method including SFBCM with ACSFs is explained in detail, with many examples to indicate its effectiveness.

Keywords: Accessorial Sketch Feature, Sketch, Conversion, 3D Model, SFBCM.
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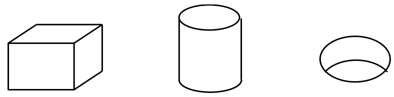
1 INTRODUCTION

Sketches in the form of line drawings are commonly observed in magazines, books, manuals, etc. Sketches are also important for designers, particularly mechanical designers, when inventing new ideas for products and their parts. Automatic conversion of sketches into 3D models is advantageous for several applications. Moreover, it is expected that robots will be able to understand sketches using converted 3D models in the future. Over the last 50 years, numerous methods have been developed for automatically converting sketches into 3D models. However, to date, no actual conversion system has been developed. We have been developing methods for converting sketches into 3D models for approximately eight years. Consequently, we have proposed a sketch feature-based conversion method (SFBCM) to achieve this conversion [16-18]. Fig. 1 shows three basic sketch features (SFs) indicating a cuboid, cylinder, and round hole. For example, in the definition of a cuboid sketch, three parallelograms share three straight lines that form a *Y*-junction as explained below. A more detailed explanation of this phenomenon is provided in [16-18]. In SFBCM, each sketch consists of straight lines, ellipses, elliptical arcs, and cubic Bezier curves and is drawn correctly, such as the examples in this study, using 2D CAD systems. Nowadays, freehand sketches can be drawn using digital tools such as an Apple pencil on an iPad. Therefore, a system will be required that can convert freehand sketches on tablets into correct drawings can be applied to our method. Several studies have focused on handling freehand sketches for their conversion to 3D models. For example, Company et al. [5] investigated techniques for detecting junctions from hand-drawn sketches using the result of experiments showing sketches to many subjects. In recent years, we also considered handling freehand sketches. In conclusion, this issue may be transformed during the implementation of our method on existing 3D CAD systems because the optimal solution to the issue would be guided by user collaboration. Therefore, we only pursue the feasibility of our method in the present step.

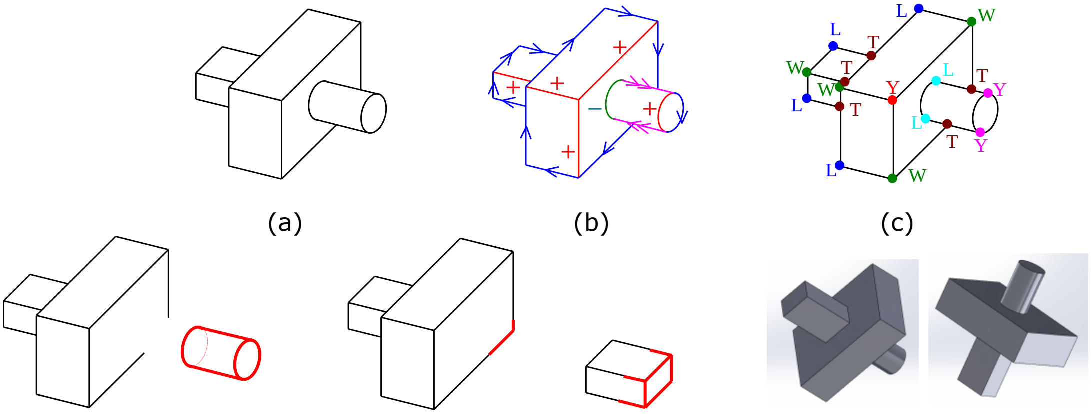


(a) (b) (c)

Figure 1: Three basic SFs: (a) Cuboid, (b) Cylinder, and (c) Round hole.

In SFBCM, when a sketch is input, its 3D model can be obtained by detecting and extracting SFs as 3D features step-by-step and then combining them in accordance with the sketch. Fig. 2(a) shows Example 1, which is a sketch of the mechanical part. When Example 1 is input to the SFBCM, first, each line segment is labeled as shown in Fig. 2(b), and then, all vertices are classified into several types of junctions, as shown in Fig. 2(c). This line labeling technique is called Huffman-Clowes labeling [3],[9]. In this technique, each line segment is labeled as "+" (convex line), "-" (concave line), or with an arrow (occluding line). In addition, the vertices of the lines are classified as *L*, *W*, *T*, and *Y*-junctions. The relationships between the labeling and the junctions are summarized in a junction dictionary. For example, if three "+" line segments form a *Y*-junction, they form a convex shape in their 3D model. Although this technique has been applied only to polyhedrons, Malik [10] created a junction dictionary for curved lines in sketches. For example, a straight-line segment corresponding to the limb line of a cylindrical sketch is labeled with double arrows in the dictionary. In Fig. 2(b), arrowed, double arrowed, "+," and "-" lines are colored blue, pink, red, and green, respectively. In Fig. 2(c), the four blue points are *L*-junctions, and the two light blue points are *Curvature*-*L*-junctions [10]. In SFBCM, they are regarded as *L*-junctions. The red point represents the *Y*-junction, and the two pink points represent *three-tangent* points [10]. In SFBCM, they are regarded as *Y*-junctions. In addition, the four green points are *W*-junctions, and the five brown points are *T*-junctions.

As shown in Fig. 2(c), the second step of SFBCM is the detection and extraction of the SF. In this figure, a cylindrical sketch can be detected and extracted as a 3D feature (red), as shown in Fig. 2(d). The two broken straight lines in this figure can be restored using SFBCM, as shown in Fig. 2(e). Thus, a cuboid sketch can be detected. After the extraction of the cuboid, five lines remain. Although they cannot form SFs, they can be detected as an abstract sketch feature (ASF) of a cuboid sketch in SFBCM. The ASF can be predicted using a cuboid sketch, as shown in Fig. 2(f). Consequently, two cuboid sketches can be detected and extracted as 3D features from Fig. 2(e). A detailed explanation of the ASFs is provided in [15]. The solution as a 3D model for Example 1 can be obtained by combining the three 3D features in accordance with Fig. 2(a). Fig. 2(g) presents two overviews of the solution.



(a) (b) (c)

(d) (e) (f) (g)

Figure 2: Example 1: (a) Example 1, (b) Line labelling, (c) Junctions, (d) Extraction of a cylinder, (e) Restored two broken lines, (f) Predicted cuboid, and (g) Two overviews of solution.

In [15], the handling of the screw and spring sketches was a problem. In this study, we attempt to handle sketches of springs, screws, and chains. Although their sketches are usually complex, they are important machine elements; therefore, they cannot be avoided in SFBCM. To handle these sketches, we introduced accessorial sketch features (ACSFs) into SFBCM. Generally, sketches contain several types of repetitive features. These features are defined as ACSFs. Fig. 3(a) shows a schematic of the spring. Although it is difficult to detect an SF or ASF from a sketch, there are three repetitive arcs colored red, blue, or green, as shown in Fig. 3(b). This can be defined as ACSFs. The remainder of this paper is organized as follows. In Section 2, works related to this study are explained. In Section 3, we describe our new SFBCM using ACSFs. In Section 4, two advanced examples are presented. In Section 5 and 6, several issues are discussed, and conclusion is presented.

(a) (b)

Figure 3: Example of ACSFs: (a) Spring sketch and (b) Three repetitive arcs.

2 RELATED WORKS

Studies concerning the conversion of sketches into 3D models have been surveyed in [2],[4]. The Huffman-Clowes labeling method described above is important [3],[9]. In this labeling technique, the objects of the sketches are limited to trihedral polyhedrons, and each sketch is an orthogonal opaque projection of an object viewed from a general position. Varley et al. [21] studied high-order junctions such as *K*- and *X*-junctions. Malik [10] developed a junction dictionary for the curved lines described above. Varley et al. [21] identified a cubic corner based on [12] from a convex *Y*-junction. In their methods, when a *Y*-junction is given in an *x*-*y* coordinate system and three lines form a cubic corner, their equation can calculate all *z* values of the terminals in the lines. Consequently, the *Y*-junctions expressing cubic corners in sketches can be converted into 3D cubic corners using 3D models. However, the results of this equation often do not fit human perception. For example, people can recognize a cuboid as shown in Fig. 1(a). However, there are no rectangles in the cuboid sketches.

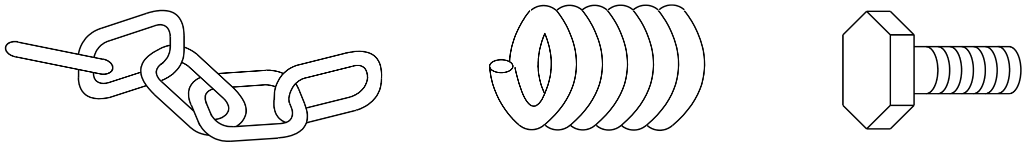
Therefore, SFBCM allows this figure to be a cuboid sketch using the human perception that people want to draw and see sketches as isometric as they can, and also simplifies the implementation of the conversion [16]. In addition, ASFs have been proposed for predicting hidden shapes in sketches [15].

Recently, Company et al. [5] has handled hand-drawn sketches. Gryaditskaya et al. [6] used hand-drawn sketches to create 3D shapes that can be expressed in 2D drawings from novel viewpoints. Plumed et al. [13] introduced datum information to complete a CSG feature tree and solids from sketches of polyhedral shapes. Interactive or semiautomatic systems for conversion were previously proposed although they are not fully automatic systems for conversion, e.g. [1],[23]. Furthermore, 3D sketching systems have been developed [7-8] although they are no more than new types of solid modelers, such as CATIA and SolidWorks. Neural network techniques, particularly deep learning techniques, have been actively used for conversion [11],[14],[20],[22]. These techniques are effective for simpler shapes, such as polygons, and known objects, such as tables, chairs, and cups, because they are essentially based on image processing. However, it is difficult to precisely and geometrically convert sketches of mechanical objects, especially creative ones, into 3D models using the present techniques. In summary, although all the studies described above are effective for conversion, the shapes of the convertible objects are limited to simpler ones. The method proposed in this study aims to extend the limitation of convertible objects significantly more than conventional methods by applying ACSFs to the SFBCM.

3 OUR NEW METHOD AS SFBCM WITH ACSFS

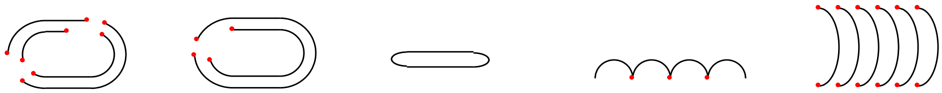
3.1 Definition of ACSFS

Fig. 4 shows sketches of the chain, spring, and screw. In this figure, when each sketch is observed, the repetitive features of the lines can be observed. We define these as ACSFs. Fig. 5 shows the five ACSFs detected from the figure.



(a) (b) (c)

Figure 4: Sketches of chain, spring, and screw: (a) Chain, (b) Spring, and (c) Screw.



(a) (b) (c) (d) (e)

Figure 5: Five ACSFs: (a) Double-lacked ring, (b) Single-lacked ring, (c) Stick-typed ring, (d) Continuous arc, and (e) Wrinkled arc.

The definition of these ACSFs are as follows.

Double-lacked ring: There are four polylines, each of which consists of straight line segment(s) and/or curved line segment(s), and the two terminals of each polyline are *T*-junctions (red). When four lines are added at the *T*-junctions to create two closed loops, they form a toroidal ring-like shape. Some double-lacked and/or single-lacked rings are connected to the ring at the *T*-junctions.

Single-lacked ring: There are two polylines, and the two terminals of each polyline are *T*-junctions. When two lines are added at the *T*-junctions to create two closed loops, they form a toroidal ring-like shape. Some double-lacked and/or single-lacked rings are connected to the ring at the *T*-junctions.

Stick-typed ring: There is a closed loop of lines, and its shape resembles a stick. Some double-lacked and/or single-lacked rings are connected at several *T*-junctions.

Continuous arc: Three or more arcs of approximately the same size are connected directly, and their contact points are *T*-junctions. These points form a straight dotted line.

Wrinkled arc: Three or more same-sized arcs are placed straight at equal intervals, similar to a wrinkle. The terminals of the arcs are *T*-junctions and form a pair of dotted parallel lines.

From the definition, an SF and three ASFs can be defined as follows.

SF of chain: Two or more ACSFs of rings connect to each other at *T*-junctions. The 3D models of the rings are identical.

Partial chain: If the terminal of a chain sketch is cut by the other SF(s), it becomes a partial chain as an ASF.

Partial spring: Two continuous arcs and a wrinkled arc were in tangential contact on both sides of the wrinkled arc.

Partial screw: A winkled arc is tangentially contacted with two parallel lines on both sides.

The SFs of springs and screws cannot be defined because they are seldom drawn alone in the mechanical sketches. Fig. 6 shows all the SFs in our new method as SFBCM with ACSFs, except for the three SFs in Fig. 1. For example, in this method, polygonal extrusion is defined as a polygon and several parallelograms; each line segment of the polygon can become a line segment of a parallelogram, and two adjacent parallelograms share a line segment. Another definition of SFs is described in [17-18]. The SF of a ring cannot be defined because it is difficult for people to perceive a toroidal shape as a ring. It appears as a tapered hole or plate sketch.

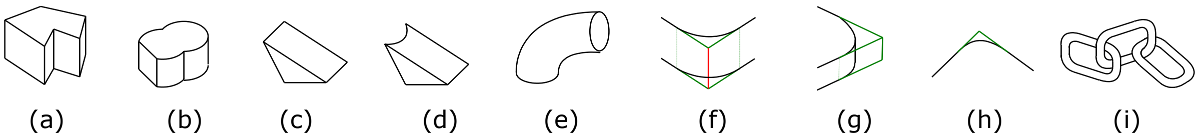


Figure 6: Nine SFs: (a) Polygonal extrusion, (b) Shape with multiple extrusions, (c) Rib, (d) Round rib, (e) Pipe, (f) Front fillet, (g) Side fillet, (h) Hidden fillet, and (i) Chain.

Fig. 7 shows nine types of ASFs obtained using this method. For example, Fig. 7(a) illustrates a partial cuboid. Each isolated terminal of the line is marked with a red point corresponding to a *T*-junction. Another definition of ASFs is given in [15]. These ASFs were partially fabricated by cutting the SFs, as shown in Fig. 6.

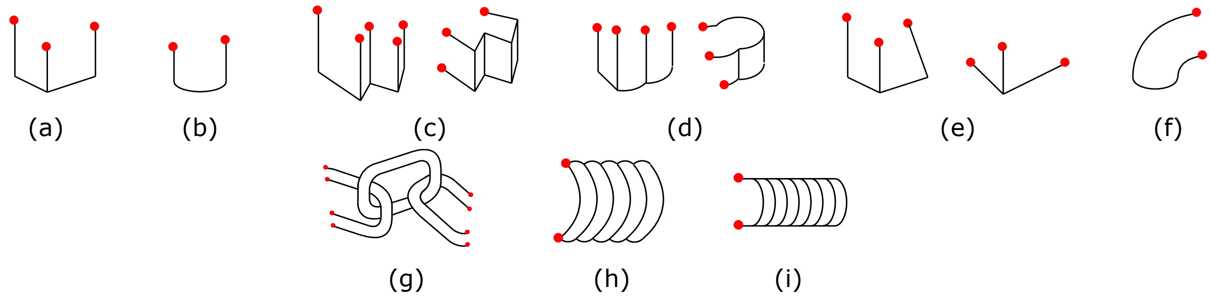


Figure 7: Nine types of ASFs: (a) Partial cuboid, (b) Partial cylinder, (c) Two types of partial polygonal extrusion, (d) Two types of partial multi-extrusion, (e) Two types of partial rib, (f) Partial pipe, (g) Partial chain, (h) Partial spring, and (i) Partial screw.

3.2 Handling of Chain Sketch

The handling of the chain sketch is illustrated in Fig. 4(a) as Example 2. When Example 2 is input into this method, all lines are first divided at their intersections. In Fig. 8(a), each line segment is colored red, blue, green, or gray. Second, all junctions are detected. In this figure, only two types of junctions are *L*-junctions and *T*-junctions. Fig. 8(b) shows all *T*-junctions as red points. In the previous SFBCM, although additional lines (dotted lines) are drawn from *T*-, *W*-, and *L*-junctions by extending their straight lines or curves to the nearest solid lines in the input sketch, it was difficult to draw them in Example 2. Therefore, the third step of this method detects ACSF(s) and their ASF(s) and/or SF(s). A detailed explanation of these additional lines is provided elsewhere [17]. As shown in Fig. 8(c), five ACSFs were detected in the rings. These are pink, green, gray, blue, and brown. They can form a chain sketch because each ring is connected to other ring(s) at *T*-junctions. Fig. 9 shows the algorithm used in this method. Three new processes, surrounded by red frames, were added to the previous SFBCM [15]. A fundamental way to implement this method from the algorithm is shown in [16] as *isometric conversion*. Furthermore, the 3D modeling platform for this implementation is SimpleModeler, a product of Aikoku Alpha Corporation, with which three authors of this paper are associated.

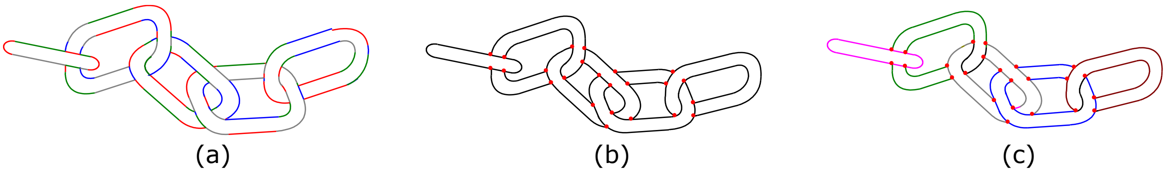


Figure 8: Example 2: (a) Each of line segments, (b) Detection of *T*-junctions, and (c) Detection of five ACSFs of rings.

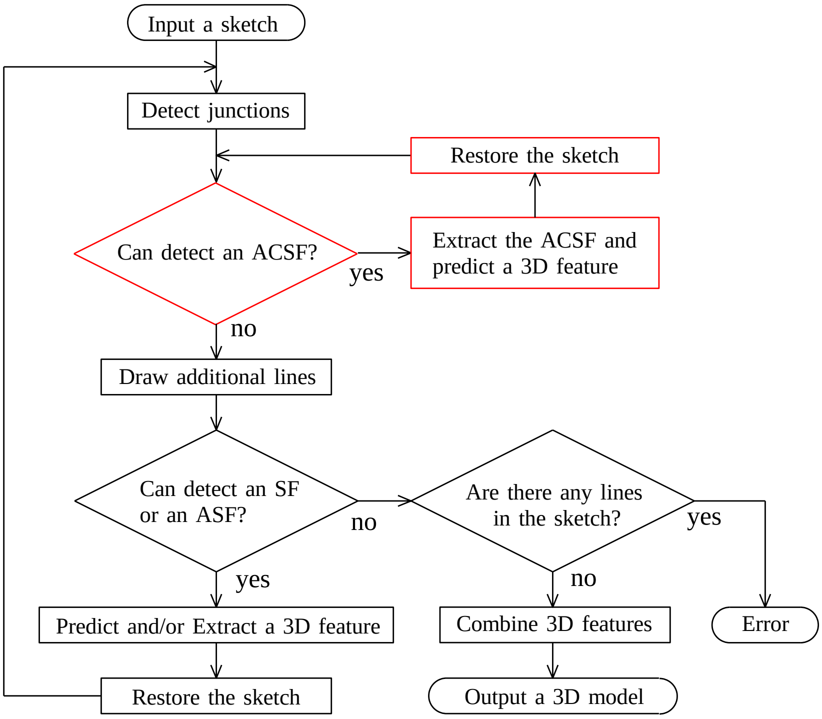
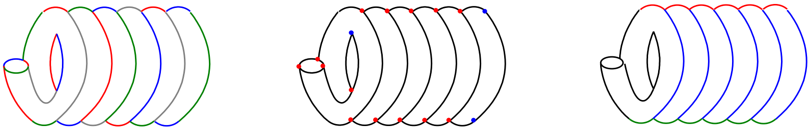


Figure 9: The algorithm of this method.

3.3 Handling of Spring and Screw Sketches

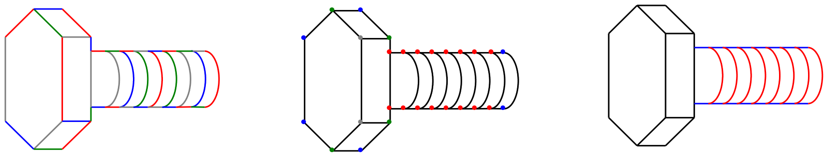
The handling of the spring sketch is illustrated in Fig. 4(b), as Example 3. When Example 3 was input into this method, all the lines were first divided at their intersections. In Fig. 10(a), each line segment is colored red, blue, green, or gray. Second, all junctions are detected. From this figure, 14 *T*-junctions (red) and three *L*-junctions (blue) can be detected, as shown in Fig. 10(b). Third, three ACSFs can be detected and are colored red, blue, and green, respectively, as shown in Fig. 10(c). There are two continuous arcs and one winkled arc. These ACSFs form the ASF of a partial spring. Therefore, a spring sketch can be detected from this figure by predicting the terminal of the spring, in accordance with Example 3.



(a) (b) (c)

Figure 10: Example 3: (a) Each line segment, (b) Detection of *T*-junctions and *L*-junctions, and (c) Detection of three ACSFs forming an ASF of partial spring.

The handling of the screw sketch is illustrated in Fig. 4(c), as Example 4. Fig. 11(a) shows each of the line segments colored red, blue, green, or gray. Fig. 11(b) shows all junctions. There are 16 *T*-junctions (red), six *L*-junctions (blue), four *W*-junctions (green), and two *Y*-junctions (gray). From this figure, a winkled arc can be detected, which is colored red, as shown in Fig. 11(c). A partial screw can be detected from the winkled arc and two straight blue lines. The head of the screw as a hexagonal cylinder can be detected as an SF of polygonal extrusion; therefore, the prediction of the partial spring to create the 3D model of Example 4 can be easily performed. A detailed explanation of the prediction method is presented in [15].



(a) (b) (c)

Figure 11: Example 4: (a) Each line segment, (b) Detection of junctions, and (c) Detection of an ACSF of winkled arc and an ASF of partial screw.

4 TWO ADVANCED EXAMPLES

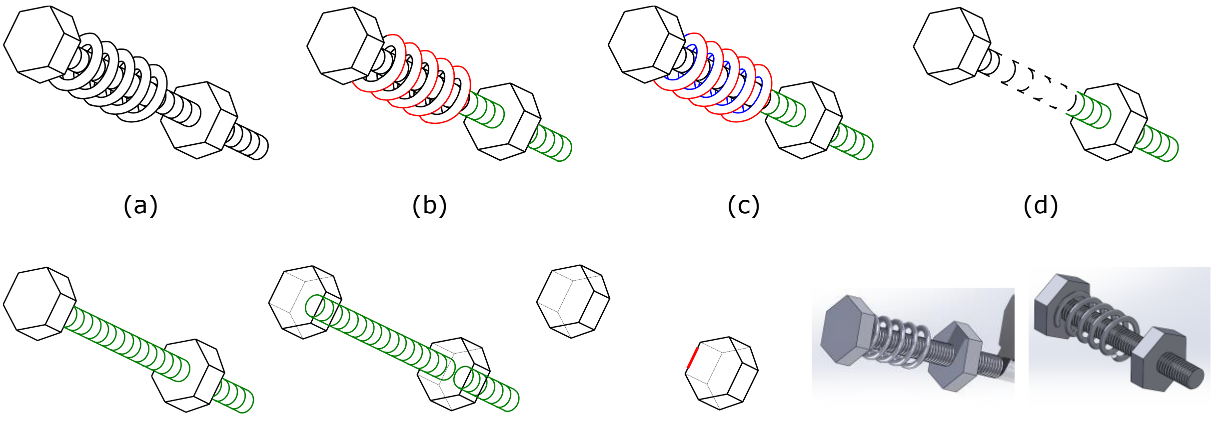
4.1 Example 5

Fig. 12(a) shows Example 5, which is a sketch of a spring screw. When Example 5 is input into this method, a partial spring (red) and two partial screws (green) are first detected, as shown in Fig. 12(b). In general, many spring shapes exist; therefore, it is difficult to define all of them. In this example, if equal or downsized arcs or curves of the spring are present, they can be regarded as parts of the spring and are colored blue, as shown in Fig. 12(c). Therefore, it is possible to extract a spring by predicting its hidden shapes. The spring is extracted in Fig. 12(d). If the left partial screw can be restored automatically by applying the learning technique in [19], a partial screw can be drawn, as shown in Fig. 12(e). Fig. 12(f) shows the prediction of the two heads as hexagonal cylinders and two screws. This prediction technique is described in [15]. Although there should be one screw in this example, this conversion is difficult with the current step of the method. In Fig.

12(g), two screws are extracted, and an additional line (red) can be drawn using the technique of the previous SFBCM. Therefore, two hexagonal cylinders were detected and extracted. The solution for Example 5 is shown in Fig. 12(h).

4.2 Example 6

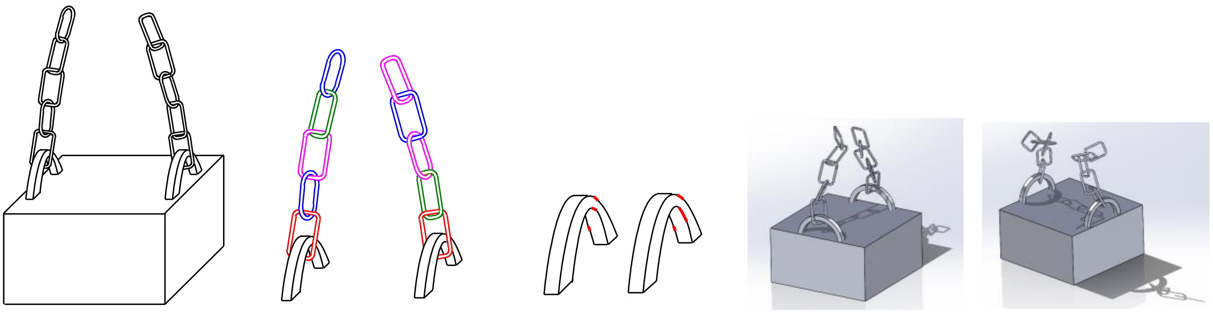
Fig. 13(a) shows Example 6, which is a sketch of a box pulled by two chains. When Example 6 is input into this method, 10 ACSFs of rings and two partial chains can be detected, as shown in Fig. 13(b). In this figure, each ACSF in the ring is colored red, blue, green, or pink. Although the shapes of the two red rings were partially occluded by the two hooks, these occluded parts could be restored by adding additional lines to the previous SFBCM. Therefore, the two-chain SFs were detected and extracted. After the chains were extracted, two SFs of the polygonal extrusion, as two hooks, could be detected and extracted by adding additional lines (red), as shown in Fig. 13(c). Finally, a cuboid sketch was detected and extracted. Thus, the solution for Example 6 is obtained as shown in Fig. 13(d).



(a) (b) (c) (d)

(e) (f) (g) (h)

Figure 12: Example 5: (a) Example 5, (b) Detection of three ASFs, (c) Detection of the several parts of the spring ASF, (d) Extraction of the spring, (e) Detection of two screws, (f) Relationship between two hexagonal cylinders and two screws, (g) Extraction of screws and an additional line (red) in a hexagonal cylinder, and (h) Two overviews of the solution.



(a) (b) (c) (d)

Figure 13: Example 6: (a) Example 6, (b) Detection of two partial chains, (c) Detection of two polygonal extrusions as hooks, and (d) Two overviews of the solution.

5 DISCUSSION

There are many issues of the method as SFBCM with ACSFs. When more complex sketches, including chains, springs, and/or screws, are input into this method, it may be difficult to obtain solutions. Therefore, we demonstrate the possibility of handling sketches including them using this method. The introduction of ACSFs is fundamental for recognizing sketches of chains, springs, and screws for human perception. Moreover, if new complex mechanical parts such as these appear in sketches, the introduction of ACSFs would be effective for automatic conversion to 3D models. The other issues can be summarized as follows:

1. The SF of the ring cannot exist because the sketches of rings appear to be tapered plates or holes. Similarly, the definition of ACSFs and ASFs without SFs may be effective for mechanical parts whose shapes contain many curved faces. Furthermore, convertible sketches of curved objects may be limited because it is difficult to detect curved SFs from them. However, their application has becomes an issue.
2. There are several types of objects and sketches of chains, screws, and springs. Therefore, a more generalized definition of ACSFs is required. In addition, the correct conversion of sketches into 3D models is challenging.
3. The restoration process of a sketch after ACSF extraction tends to be difficult, as shown in Fig. 12(d) and 12(e). In addition, the correct prediction of the terminals and/or hidden shapes is difficult, as shown in Fig. 10(c) and 12(f). Therefore, more-precise restoration and prediction techniques are required. This has become an issue with this method.
4. In the algorithm of this method, the detection of ACSF(s) is prior to the detection of SF(s) and ASF(s). However, in many cases, solutions could not be obtained because of the detection sequence. For example, in Example 5, if the detection of screws occurs before the detection of a spring, it becomes difficult to obtain a solution. Therefore, a more detailed algorithm is required for the detection sequences of SF(s), ASF(s), and ACSF(s).

6 CONCLUSION

In this paper, the introduction of ACSFs to handle sketches of chains, springs, and screws is explained, and a new method, SFBCM with ACSFs, is proposed. The results of this study can be summarized as follows.

- Five types of ACSFs can be defined, and one SF and three ASFs can be defined in sketches of chains, springs, and screws. The handling of ACSFs can be explained by three examples.
- Two advanced examples are presented to demonstrate the effectiveness of the method. Although many issues were identified, solutions can be obtained from these examples.
- The issues and effectiveness of this method are discussed in detail.

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