

CAD Assembly Retrieval by Searching Kinematic Relation Isomorphic Sub-graph

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Abstract: *Effective reuse of existing models, which can shorten the cycle of the product design, can be achieved by assembly retrieval. In this paper, an assembly retrieval approach is proposed by searching kinematic relation isomorphic sub-graph. First, the assembly constraints among parts in the assembly are gotten by CAD software API, and the degrees of freedom of parts are reasoned according to their constraints to generate the kinematic relation adjacency graph. Then, the graph is divided into several sub-graphs to screen assemblies according to the number of matched sub-graphs. And VF2 algorithm is used to search the maximum kinematic relation isomorphic sub-graph between assemblies, so as to obtain the mapping between parts. Subsequently, point sampling is carried out on surfaces for all parts in the assembly. The distances of arbitrary point-pairs are calculated to generate the histograms of part shape distribution. And the histograms of part-pairs in the maximum isomorphic sub-graph are compared to obtain the dissimilarity of part shape. Eventually, the assembly model retrieval is realized by considering the maximum kinematic relation isomorphic sub-graph and part shape information comprehensively. Experiments show that the approach has high accuracy.*

Keywords: Assembly retrieval; Isomorphic sub-graph; Assembly constraint; Kinematic relation adjacency graph

1. Introduction

With the widespread use of CAD system, enterprises have accumulated a large number of 3D CAD models. These existing models have significant reference value for the design of new products, and some of them can even be directly reused to new products after appropriate modifications. Therefore, how to retrieve models that can be referred to or reused from the massive assemblies is of great significance for accelerating the progress of product development and avoiding design mistakes.

Compared with the part model, the assembly model contains abundant topological information such as assembly constraint information between parts, which is a more sophisticated research object. Therefore, the assembly information extraction and retrieval approaches are more complex. In recent years, a variety of assembly retrieval approaches have emerged. There are mainly three kinds: semantics-based [1], graph-based [2] and part-information-based [3]. The semantic-based approaches divide the assembly into several meaningful parts, each of which is a separate functional unit. The graph-based approaches transform the assembly into an attribute adjacency graph, which is composed of nodes and edges, and attach specific information to the nodes and edges. And assembly retrieval is converted into the matching problem of the graph. The part-information-based approaches ignore the constraints between parts, treat the assembly as a bag of parts, and match the parts according to their shape distribution or attribute information. However, the above methods do not make full use of different information in the assembly, so the retrieval result is not satisfactory [4].

In order to obtain better retrieval effect, this paper synthesizes topology information and part shape information of assembly. First, the assembly constraints between parts are obtained, and the DOFs (degrees of freedom) of parts are deduced to generate the kinematic relation adjacency graph.

Then adjacency graph is divided into several sub-graphs, and the sub-graphs of the two assemblies are matched to screen out the candidate assembly models according to the count of matched sub-graphs. VF2 is used to search the maximum kinematic relation isomorphic sub-graph between assemblies, so we can obtain the mapping of nodes in the isomorphic sub-graph. Second, point sampling is conducted on all part surfaces of assemblies. Afterwards, the distances between all points on the same part are calculated to obtain the histograms of the shape distribution. Subsequently, the distances of histograms of the corresponding parts in the two assemblies are calculated to work out the shape dissimilarity of the parts. Retrieval is realized by integrating kinematic relation maximum isomorphic sub-graph and shape dissimilarity of parts. The overall framework of the approach in this paper is shown in Figure 1.

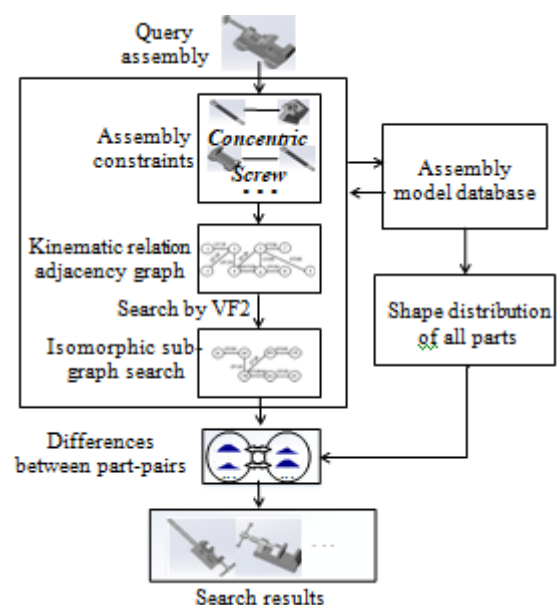


Figure 1: Overall framework of our approach

2. Generation of kinematic relation adjacency graph

Assembly constraints are imposed in the assembly process of parts, which restrict the relative movement and relative position between parts. For the CAD models generated by 3D feature modeling software, with the API function provided by the software, the assembly constraints between any two parts as well as the constrained objects (namely the entities of points, lines and surfaces) can be obtained. In the shaft-sleeve assembly model shown in Figure 2, if the **Concentric** constraint is applied between the inner surface *a* of the sleeve and the surface *b* of the shaft, so there is a constraint: $R = \{(a, b, Concentric)\}$.

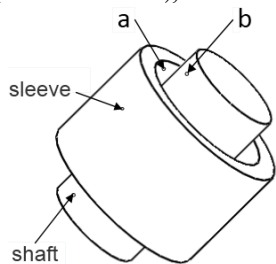


Figure 2: shaft - sleeve assembly model

The DOFs of parts can be deduced by the assembly constraints and the constrained objects, including translational DOF *T* and rotational DOF *R*.

Translational DOF: In this paper, according to the count of translational DOF, it is expressed as follows:

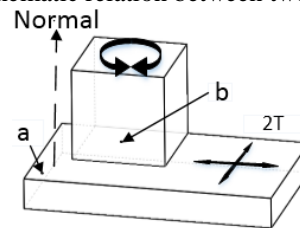
- Completely free translation, such as a point in space without constraints, is denoted as $3T$;
- The translation in a plane is denoted as $2T$. The slider in Figure 3(a) has the translational DOF along the plane *a*;
- The translation along a certain direction is denoted as $1T$. The shaft in Figure 3(b) has the translational DOF along the axis;
- Translation is not allowed. This kind of translational DOF is denoted as $0T$. The handle in Figure 3(c) cannot be translated due to the constraints.

Rotational DOF: According to different rotation axes or points. The rotational DOF is divided into the following categories:

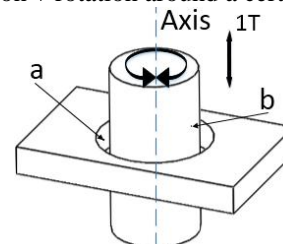
- Rotational DOF around a certain direction is denoted as $1R_d$. In Figure 3(a), the slider has the rotational DOF around normal direction of plane *a*;
- Rotational DOF around a fixed axis is denoted as $1R_a$. In Figure 3(b), the shaft has rotational DOF around the fixed axis;
- Rotational DOF around the fixed point is denoted as $1R_p$. The handle in Figure 3(c) has the rotational DOF around the fixed point.
- Rotation is not allowed. This kind of rotational DOF is denoted as $0R$.

By combining rotational DOF and translational DOF, the kinematic relation between two parts can be obtained. The DOF between two parts in Figure 3(a) is $2T1R_d$, namely,

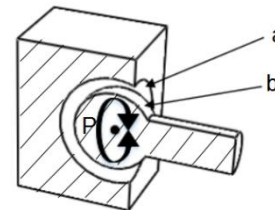
translational DOF in a plane and rotational DOF around a certain direction. And in Figure 3(b), it is $1T1R_a$. Figure 3(c) is $0T1R_p$. Thus, it can be concluded that the type of assembly constraints and the type of constrained objects determine the kinematic relation between two parts.



(a) Translation + rotation around a certain direction R_d



(b) Translation + rotation around a fixed axis R_a



(c) Rotation around a fixed point R_p

Figure 3: Schematic diagram of translational and rotational degrees of freedom

However, the kinematic relation is not always defined by single assembly constraint. Under the effect of multiple assembly constraints, the DOFs will be reduced. Translational DOFs are reduced only by translational DOFs, and so are rotational DOFs. Reduction rules are summarized as follows [5].

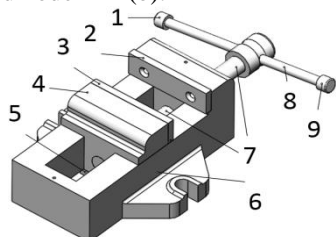
- 1) $3T$ and nT : The reduced translation DOF is same with nT , where $n = 0, 1, 2, 3$.
- 2) $2T$ and $2T$: If the two planes are parallel, the reduced translational DOF is $2T$; If the two planes are at an angle, the reduced translational DOF is $1T$, which is along the intersection line of the two planes.
- 3) $1T$ and $2T$: If the direction of $1T$ and the plane of $2T$ are parallel, the reduced translational DOF is $1T$, the direction is the same as the $1T$; or else it is $0T$.
- 4) $1T$ and $1T$: If the two directions are parallel, the reduced translational DOF is $1T$; otherwise it is $0T$.
- 5) $0R$ and other rotational DOFs: The reduced rotational DOF is $0R$.
- 6) $1R_a$ and $1R_a$: If two rotation axes are collinear, then the result is $1R_a$; if else, it is $0R$.
- 7) $1R_a$ and $1R_d$: If the direction of the rotation axis of $1R_a$ is the same as the rotation direction of $1R_d$, the result is $1R_a$; otherwise, it is $1R_d$.
- 8) $1R_d$ and $1R_d$: If the directions of the two rotation axes are parallel, then the result is $1R_d$; if else, it is $0R$.

- 9) $1R_d$ and $1R_p$: The result is $1R_a$ and its rotation axis is along the rotation direction of $1R_d$ and passes the rotation point of $1R_p$.
- 10) $1R_p$ and $1R_p$: If the two rotation points are coincide, the result is $1R_p$; if not, it is $0R$.

The reduction of DOF conforms to the law of commutation, that is, there are i assembly constraints $C_1, C_2, C_3, \dots, C_i$, and the reduction can be carried out in any order. After the reduction is completed, the kinematic relation between the two parts can be obtained. There are three different types of rotational DOF, for the sake of simplicity, we ignore types and only record whether rotational DOF exists, and denote the kinematic relation with $nTmR$, where $n = 0, 1, 2, 3, m = 0, 1$.

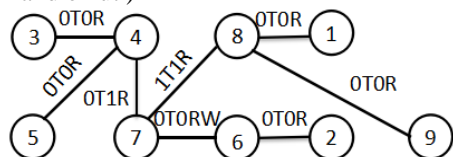
In the 3D modeling software SolidWorks, 25 kinds of assembly constraints are defined, among which 8 kinds of constraints such as *Coincidence*, *Concentric*, *Vertical*, *Distance*, *Tangent*, *Angle*, *Width* and *Parallel* can be converted into translational DOF and rotational DOF using the above rules. For the other 17 kinds of assembly constraints, such as pinion and rack constraint, gear constraint, screw constraint, etc., above rules cannot be used to reason the DOF, which should be separately recorded. For example, the DOF between parts is $2T1R$, and there is also a screw constraint, we denote the screw constraint with W , then the kinematic relation of the part-pair is $2T1RW$. Moreover, pinion and rack constraint is represented with P , gear constraint is G , and other assembly constraints also have corresponding symbols.

After the above processing, the kinematic relation adjacency graph of the assembly can be generated. As shown in Figure 4, for the vise assembly model (a), its kinematic relation adjacency graph is (b). We take lead screw 7 and movable clamp 4 as an example. There is only rotational DOF between them, so there is an edge with attribute of $0T1R$ between node 7 and node 4 in (b).



(a) Vice assembly

(1 handle nut 2 base pad iron 3 movable pliers mouth iron 4 movable jaw 5 positioning pad 6 base 7 lead screw 8 handle 9 handle nut)



(b) Adjacency graph of kinematic relation

Figure 4: Assembly model and its kinematic relation adjacency graph

3. Screening assembly with Kinematic Relation Sub-Graphs

There are massive assembly models in the database. In order to improve the retrieval efficiency, a screening mechanism is proposed to find out the candidate assemblies with local similarity to the query before searching the maximum kinematic relation isomorphic sub-graph.

First, the assembly kinematic relation adjacency graph should be divided into several sub-graphs. The sub-graph with 3 nodes has a simple topological structure and can well reflect the sub-structure of whole graph. Therefore, the sub-graphs with 3 nodes are generated in this paper. Figure 5 is the 9 sub-graphs divided from Figure 4(b).

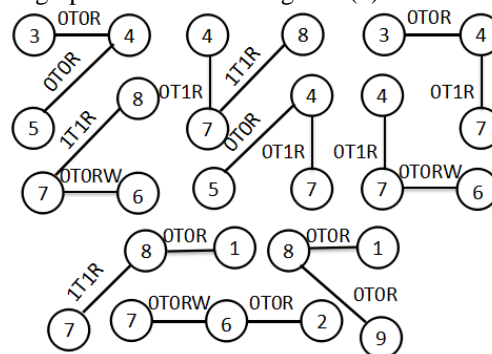


Figure 5: Sub-graphs of kinematic relation graph

The next step is to calculate the number of identical sub-graphs between the assemblies in database and query. In order to speed up the calculation, all sub-graphs are coded [6], and the matching of sub-graphs is converted into the query of codes. The coding process is divided into two steps, namely kinematic relation coding and sub-graph coding.

(1) Coding of kinematic relation: According to section 2, kinematic relations can be divided into translational DOF and rotational DOF, as well as gear constraint G , screw constraint W , pinion and rack constraint R and so on. 1 and 0 of binary can be used to represent the presence or absence of each complex assembly constraint and the rotational DOF, while two bits are used to represent different translational DOFs. Thus, for the $2T1RW$, its kinematic relation code of 20 bits can be generated, as shown in Figure 6.

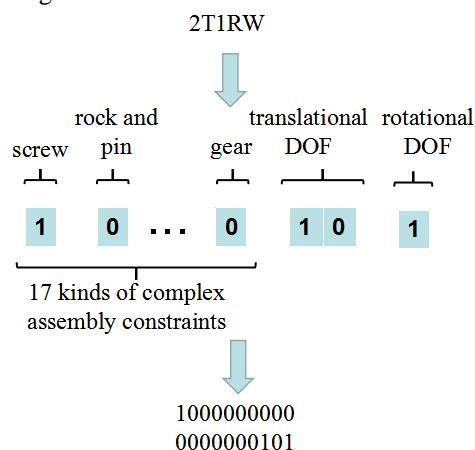


Figure 6: Example of kinematic relation coding

(2) Coding of sub-graph: The topological structure of the sub-graph with 3 nodes has two types (a) and (b) as shown in Figure 7, and the (b) can be converted into (a) by adding a virtual edge. And we encode virtual edge with 20 bits of 1 to avoid the repetition with the codes of the existing kinematic relations.

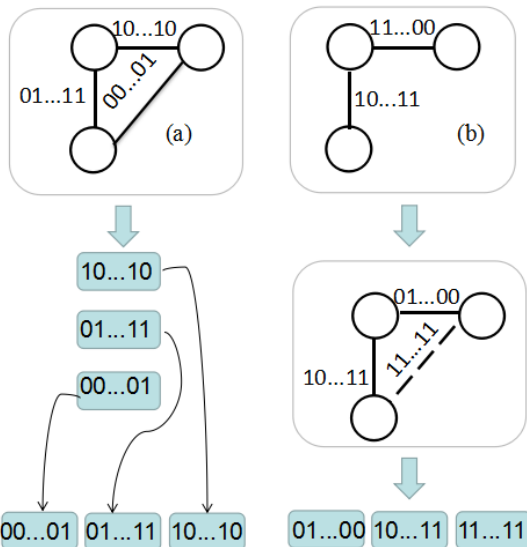


Figure 7: Example of kinematic relation sub-graph coding

After completing the sub-graphs coding, we can conveniently calculate the number of the same sub-graphs between the assemblies in the database and the query, then we sort the assemblies in the database according to the number and select assemblies with more same sub-graphs. In this paper, we select the top 15 in consideration of efficiency and accuracy.

4. Searching maximum isomorphic sub-graph by VF2 algorithm

4.1. VF2 algorithm

VF2 is an efficient sub-graph isomorphic algorithm [7]. It can make full use of the connection relation between nodes and the additional information on the edges to quickly judge whether the query graph is isomorphic with the sub-graph of the target and obtain the mapping of nodes between two graphs. The algorithm has several validity criteria, which can perform pruning effectively and avoid redundant search.

As shown in Figure 8, nodes in the query graph can arbitrarily match nodes that have not been matched in the target, but the following two validity criteria should be met: (1) Two nodes have the same adjacency edge. For example, node 1 can match with node A, both of them have an adjacency edge with the attribute of OT1R, but cannot match with B, because they do not have any same adjacency edge. (2) If there are edges between the nodes of current matching node-pair and the nodes in the matched node-pair, the attributes of the two edges should be same. If the matched node-pair is (1, A), and the current matching node-pair is (2, C), the attribute of edge 1-2 should be same with edge A-C. Each node is matched in turn according to the criteria. If the reliability criteria are not satisfied, it goes

back to the previous node and tries again.

It should be noted that the VF2 algorithm is designed to solve the problem of whether the query graph is isomorphic to the sub-graph of target. However, when retrieving the assembly model, if the target assembly and the query share the same sub-structure, they will also be considered similar. At this point, the problem needs to be solved is to determine whether the query graph and the target share isomorphic sub-graph. Therefore, during the matching process of VF2 algorithm, we record the maximum isomorphic graph obtained as the final result, which has the most part-pairs among all isomorphic sub-graphs as shown in Figure 8(b).

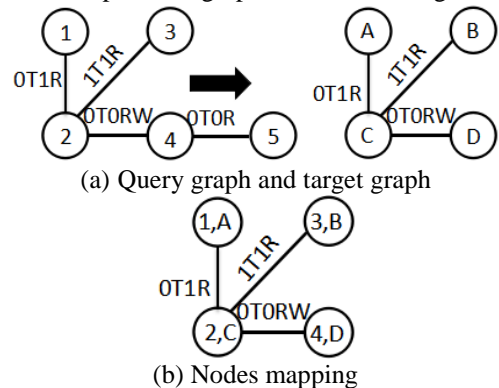
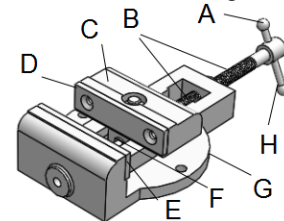


Figure 8: Searching with VF2 algorithm

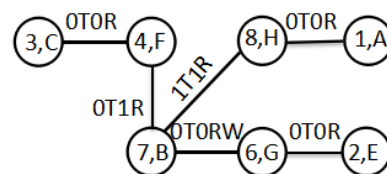
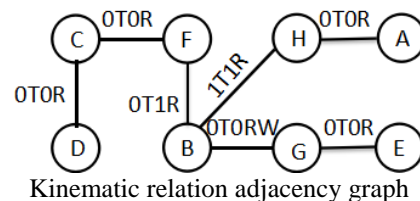
4.2. Searching maximum kinematic relation isomorphic sub-graph

We employ vice assembly in Figure 4 as the query and the vise assembly in Figure 9 as target, and search for the maximum isomorphic sub-graph of them using VF2 algorithm. The maximum kinematic relation isomorphic sub-graph can be obtained as shown in Figure 9.



(a) Vice assembly

(A handle nut B lead screw C movable jaw D movable jaw pad iron E base pad iron F guide pad G base H handle)



(b) Maximum kinematic relation isomorphic sub-graph

Figure 9: Schematic diagram of maximum isomorphic sub-graph search

The isomorphic sub-graph between two assemblies indicates that two assemblies own the sub-structure with same kinematic relation. On this basis, the differences of matched part-pairs can be calculated to describe the similarity between the assemblies. In Figure 9, the mapping of parts can be generated from the maximum isomorphic sub-graph: $S = \{(1, A), (2, E), (3, C), (4, F), (6, G), (7, B), (8, H)\}$.

The next section describes the shape of the parts and compares the differences between mapping parts.

5. Shape dissimilarity calculation according to the maximum isomorphic sub-graph

In this paper, shape distribution histograms are used to describe the shape of parts in assemblies. Specifically, the algorithm in literature [8] is adopted to conduct point sampling on the surfaces of all parts.

In this paper, the number of sampling points is 1024. And we calculate the distances of all point-pairs. Then the $C_{1024}^2 = 523776$ distances are evenly divided into 512 bins to construct the part shape distribution histogram. The specific process is shown in Figure 10.

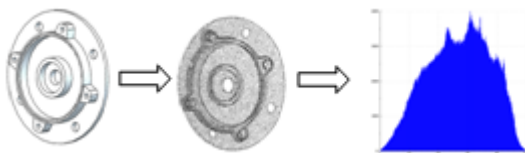


Figure 10: Generation of part shape distribution histogram

After obtaining shape distribution histograms of the parts, the following formula can be used to calculate the shape dissimilarity between the mapping parts in the maximum isomorphic sub-graph:

$$Dissim_{AB} = \left(\sum_{i=1}^N \sum_{j=1}^{512} |a_{ij} - b_{ij}| \right) / \left(C_{1024}^2 \cdot N \right) \quad (1)$$

where a_{ij} and b_{ij} are values of the j th bin in the histograms of i th part-pairs in maximum isomorphic sub-graph for assemblies A and B respectively; N is number of part-pairs in the maximum isomorphic sub-graph. The function of the denominator is to normalize the value of dissimilarity, so the comparison and analysis will be convenient.

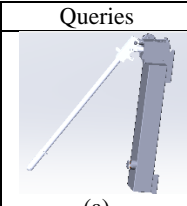
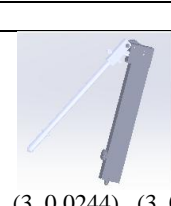
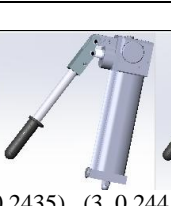
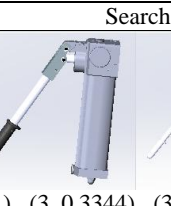
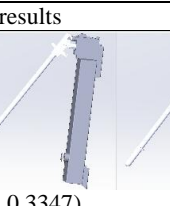
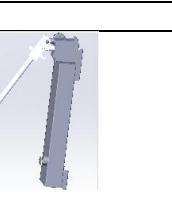
6. Retrieval experiments and analysis

In order to conduct the experiment, a retrieval system is developed under VS2015 environment with C++ and SolidWorks 2016 API. The experimental computer is equipped with Intel Core i5-4460 CPU and 4G memory. And assembly database contains 102 assemblies. Most of them are downloaded from the Internet, while a few are modeled by us.

The assembly model can be retrieved by integrating the maximum kinematic relation isomorphic sub-graph and shape dissimilarity. We can analyse the number of part-pairs N in the maximum isomorphic sub-graph, the larger N is, the larger the scale of sub-structure with the same kinematic relation between two assemblies is, and the more similar two assemblies are in topological structure. Therefore, N is a metric of the similarity of topological structure. So we define the similarity vector $V = \{N, Dissim\}$ to fully describe the similarity between two assemblies. After the similarity vectors between the query and assemblies in the database are obtained, we sort the similarity vectors according to N in ascend order. If N is same, then we sort the vectors according to $Dissim$ in descend order. In order to verify the accuracy of the approach, experiments are carried out on 7 series of assemblies, including hand pump, vise, chuck, motor, rotating slider mechanism, sub-assembly of rotating slider mechanism, and mechanical arm. The results are shown in Figure 11.

For each query, we show the six most similar search models. The number of mapped part-pairs and the dissimilarity are shown under the snapshots. For the query (a), we can see the vector (3, 0.0244) of the first retrieved model, where 3 denotes the number of part-pairs in the sub-structure with the same kinematic relation, and 0.0244 indicates the shape dissimilarity. Only 5 retrieved assemblies are listed for query (a), because there are only 5 assemblies left after screening. For rotating slider mechanism query (e), two models are failed to retrieve. The main reason is that the two assemblies own few parts, so the number of part-pairs in sub-structure with same kinematic relation is less, and other assemblies which share the larger sub-structure with query are in the front. If the sub-assembly of the rotating slider mechanism is used as the query, all relevant assemblies can be retrieved successfully as shown in query (f).

Experiments show that our approach can retrieve assemblies similar to the query. The more similar the assembly is, the better the order is. The satisfactory retrieval accuracy is achieved.

Queries	Search results				
					
(a)	(3, 0.0244)	(3, 0.2435)	(3, 0.2441)	(3, 0.3344)	(3, 0.3347)

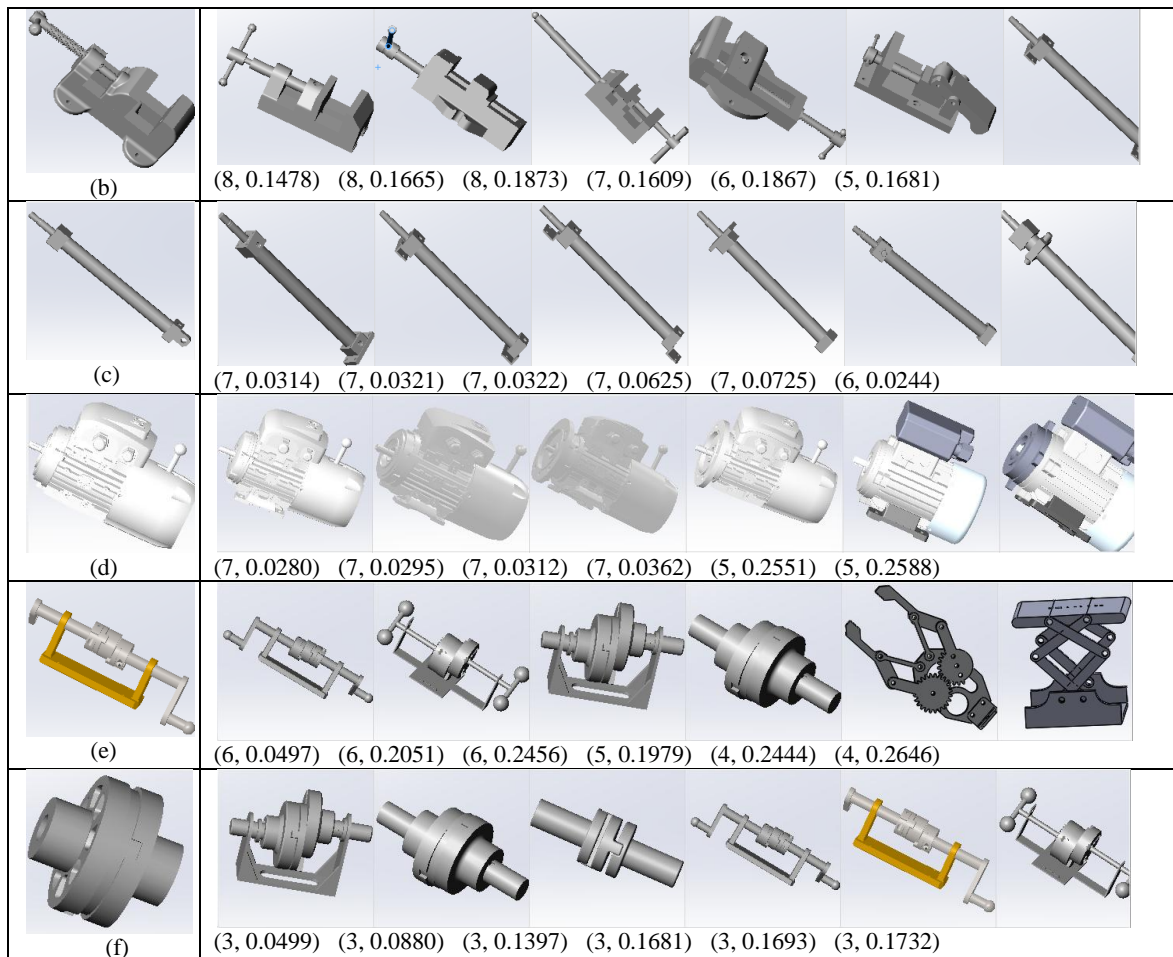


Figure 11: Examples of assembly model retrieval

7. Conclusion

- 1) In this paper, we utilize assembly constraints and part shape information for the assembly retrieval. So as to support the reuse of existing assemblies.
- 2) The kinematic relation adjacency graph is constructed according to the assembly constraints. And the sub-graph of the adjacency graph can be used for screening to accelerate the assembly retrieval.
- 3) VF2 algorithm is used to search the maximum kinematic relation isomorphic sub-graph. The larger the isomorphic sub-graph is, the more similar the topological structure of the two assemblies will be.
- 4) We calculate the distances between the shape distribution histograms corresponding parts in the isomorphic sub-graph, and take the difference as the shape dissimilarity of parts, which can efficiently and concisely search the similar assemblies.

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