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Research Method of Assembly Sequence Planning Based on Assembly Constraint Relationship Analysis

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Abstract. In order to effectively reduce the human-computer interaction (HCI) workload before the assembly process simulation in the digital assembly environment, and to enhance the intelligence of assembly sequence planning, we introduce the assembly constraint relationship into the automatic generation of assembly sequences and propose a practical assembly sequence planning method for intelligent assembly. Firstly, starting from the assembly geometry model, an assembly model liaison graph is constructed by combining the analysis of assembly constraint relationship and the definition of disassembly direction rules. Then, according to the liaison graph, disassembly priority constraint matrix based on constraint relationship is constructed, and the automatic generation and dynamic update of the disassembly priority diagram can be realized by the definition of disassembly doubly linked list. According to the diagram, the rationality of the disassembly sequence is determined through the interference check analysis, and then the assembly sequence is automatically generated from the reversed disassembly sequence. Finally, the method in the text is verified by an example case study.

1 Introduction

In recent years, with the wide application of model-based definition (MBD) technology, three-dimensional (3D) digital assembly technology as a further extension and deepening of virtual assembly technology has become a hot topic in the field of manufacturing. The product process design based on the 3D model is the bridge to connect product design and manufacturing based on MBD. The 3D digital assembly is an important part of the product process design. Among them, assembly sequence planning (ASP) is the core of the 3D digital assembly process design, and is also one of the focuses of the current assembly process automation and intelligence.

Currently, many scholars have conducted extensive research on the methods and techniques of ASP. Some typical ASP methods have been proposed, which can be summarized as "graph model + solving & search method" and "product disassembly model + optimization algorithm for disassembly solution" [1]. Combined with the application of ASP in practical engineering, we believe that all the current ASP methods have limitations. The method based on priority relationship [2] is simple and intuitive and easy to operate, but the priority relationships of assembly constraint relationship are

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provided by HCI rather than automatic recognition. The method based on cut-set [3-4], with the sharp increase of the number of parts and the solution space, is easy to encounter the assembly sequence explosion problem. For the proposed knowledge-based ASP method [5], it is difficult to ensure the matching degree between actual assembly models and standard knowledge bases in terms of knowledge acquisition and expression. The method based on GCA [6-7] solves the problem of generating a complete assembly sequence in a 3D environment, however, the further promotion of the method is hampered due to the amount of calculation quantities and results. The methods based on heuristic intelligence algorithm [8-9] usually need to establish complete assembly constraints relationship and are restricted by search space and time, which leads to sacrifice algorithm efficiency largely to obtain optimal or sub-optimal solution.

2 An overview of this paper

An assembly sequence planning method based on assembly constraint relationship analysis for intelligent assembly was proposed in this paper. Firstly, in order to identify and acquire the assembly constraint relationship between parts, and to derive a set of feasible disassembly directions, the geometric information of product assembly model is extracted. Then, the assembly model liaison graph (AMLG) is constructed, and the disassembly priority constraint matrix is generated by the assembly priority constraint relationship. The disassembly priority relationship diagram is inferred by interference check in the feasible disassembly directions. Finally, the assembly sequence can be generated by reversing the generated disassembly order. When constructing the liaison graph of product assembly model, a product hierarchy connection diagram with a hierarchical structure can be established according to product hierarchy tree, and a layered disassembly is performed in a bottom-up order. In addition, according to the principle of "can be removable and can be assembled, can be reassembled after being disassembled", product assembly is disassembled layer-by-layer from the original assembly state of product. In this way, the disassembly sequence of the entire product is generated finally, and the product assembly sequence can be obtained by reversing the acquired disassembly sequence.

The overall flow diagram of the method in this paper is shown in Fig. 1. The diagram takes a given 3D assembly model as input, and finally generates a feasible assembly sequence, in which n denotes the number of product assembly layer.

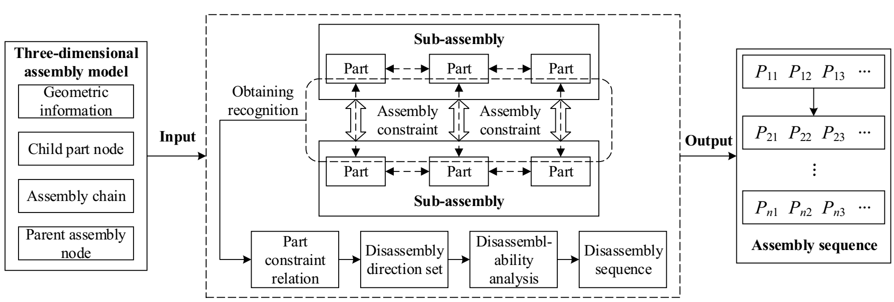


Figure 1. Overall flow diagram of the method in this paper.

3 Analysis of the assembly constraint relationship

3.1 Assembly constraint relationship

Product assembly modeling is the process of creating assembly by defining assembly constraint relationship on several parts. The constraint relationship is mainly a collection of areas with engineering significance on parts that match each other by cooperative actions such as coaxial, coplanar, align, offset, etc., which can be used to fix the position and orientation in the assembly and limit its corresponding the degree of freedom. Since these relationships between parts directly affects the assembly direction, movement form, assembly sequence, etc., they significantly determine the difficulty degree of product assembly. Therefore, the modeling, expression, and identification of assembly constraint relationship are prerequisites for product intelligent assembly process planning and evaluation.

These parts in the product assembly are associated with each other through point, line, and face. The association can form assembly pairs and the corresponding associated point/line/face are termed as assembly auxiliary elements. From a topological viewpoint, there are 6 basic forms of assembly pairs: vertex-vertex, vertex-edge, vertex-face, edge-edge, edge-face, and face-face. However, since most of parts are connected by face-face constraint in the assembly, only the condition of face-face constraint is considered in this paper. The surface type elements are restricted to plane, cylinder, conical surface, sphere and torus. The CAD models with complex shape (e.g. thread surface, involute gear surface, etc.) generally are processed with simple surfaces (e.g. cylinder).

The mating relations of geometric surface of assembly constraint can be classified as against, coplanar, fit and align. The mating relations between geometric surfaces is shown in reference [10].

3.2 Disassembly direction reasoning

In the process of 3D digital assembly sequence planning, a general adopted method to obtain assembly sequence is to analyze the disassembly feasibility with product assembly what have been assembled. Therefore, the initial assembly position and orientation of the parts in the assembly have been determined by assembly constraint relationship. Assume that all parts of the assembly are rigid bodies, and there are not irreversible operations during product disassembly process. The analysis of disassembly feasibility is based on the product assembly, and the assembly sequence is generated by the reverse order of feasible disassembly sequence. Among them, the determination of the disassembly direction is a very key step in the process.

According to the definition of assembly constraint relationship, it can be seen that mating between parts is mainly realized by face-face constraint. The contact mating relation determines the disassembly direction of part, which is called surface contact characteristics. First of all, based on the mating relations, the basic form of surface contact is divided into two types: contact between planes and contact between rotary surfaces. Then, the disassembly direction set (DDS) is inferred and generated automatically using the surface contact characteristics and the automatic identification of the mating relations based on the surface contact. The specific algorithm flow is shown in references [11-12].

4 Assembly sequence planning based on Assembly Constraint Relationship Analysis

4.1 Assembly model liaison graph (AMLG)

The reasonable representation of assembly information (topological information, geometric information, and constraint information) in product assembly is the basis of ASP. The rationality of assembly information expression will seriously affect the efficiency of ASP. Therefore, in the process of ASP, it is necessary to identify and extract the relevant geometric constraint information from the product assembly model, and establish the liaison graph model of product assembly.

Product assembly model can be represented as a liaison graph connected by a group of part nodes in term of geometric constraint relationship. The expression formula is as follows:

$$G=<N, E> \tag{1}$$

where G represents the assembly model, and $N=\{v_1, v_2, ... ,v_n\}$ represents a collection set of part nodes attribute, n is the number of part node, and E represents a collection set of edges attribute connected part nodes, E=e_{ij}={E_1, E_2, ... ,E_m}, $(i, j \in n)$, m is the number of connected edges, and e_{ij} represents connection constraint information between v_i and v_j .

A simplified assembly of pulley mechanism and the corresponding assembly model liaison graph are shown in Fig. 2. Among them, these circles represent the nodes of liaison graph, and these connected edges between nodes represent the constraint relationship between two parts. The dashed line represents the fastening connection relation, and the solid line represents the mating contact relation.

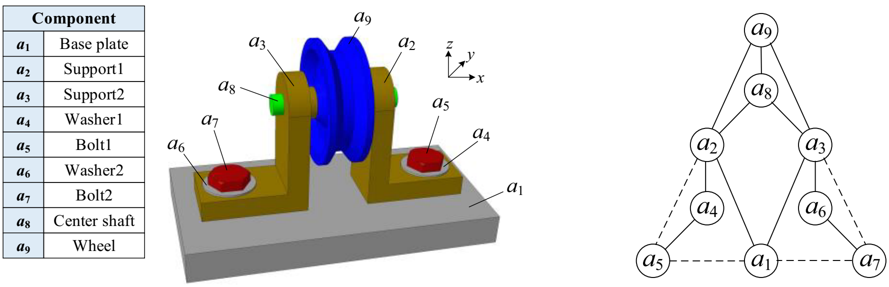


Figure 2. Simplified assembly of pulley mechanism and the corresponding AMLG.

4.2 Generation method of assembly sequence planning

The process of ASP can be seen as the reverse of disassembly sequence. In the 3D digital assembly environment, the main task of interactive disassembly is to generate information about priority constraint relationship, disassembly direction, etc. For the disassembly sequence planning of product assembly, the interference information of parts can be inferred by using the breadth-first search algorithm of AMLG and assembly constraint relationship between parts, and then the disassembly priority constraint matrix can be established to automatically calculate and generate the disassembly priority relationship diagram.

In order to obtain the interference information between parts, the disassembly direction in the initial state of product assembly can be determined according to the assembly constraint relationship. Then the benchmark part is selected by the selection principle of reference part and it is regarded as the starting point of searching. Based on them, the undirected liaison graph of product assembly is traversed by using the breadth-first search algorithm. The searching program can exit until all of nodes in AMLG have been accessed and the interference information between parts is generated. The interference information of disassembly pulley mechanism is shown in Table 1, and the symbol "#" represents no interference information between parts.

Table 1. Part interference information of disassembly pulley mechanism.

disassembly part	interference part	disassembly part	interference part
a_1	#	a_6	a_7
a_2	a_4, a_5	a_7	#
a_3	a_6, a_7, a_8	a_8	#
a_4	a_5	a_9	a_2, a_3, a_8
a_5	#		

The disassembly priority constraint matrix is derived from the interference information of AMLG and the matrix can be represented as a two-dimensional table with n-1 rows and n-1 columns. Excluding the reference part of assembly, the matrix $[a_{ij}]_{n-1,n-1}$ can be built. Each element a_{ij} represents the priority constraint relationship at the row ai and the column a_j , and the element a_{ij} can be defined as follows:

$$a_{ij} = \begin{cases} -1, P_i \Leftarrow P_j \\ 0, P_i \neq P_j \\ 1, P_i \Rightarrow P_j \end{cases} \tag{2}$$

In Eq. (2), $P_i \Leftarrow P_j$ indicates that the part P_i must be disassembled after the part P_j , and $P_i \neq P_j$ indicates that there is no explicit constraint relationship between the parts P_i and P_j , and $P_i \Rightarrow P_j$ indicates that the part P_i must be disassembled before the part P_j . According to the Eq. (2), the disassembly priority constraint matrix of pulley mechanism assembly (Fig. 2) can be inferred as shown in Table 2, and the part a_1 is benchmark part.

Table 2. The disassembly priority constraint matrix of pulley mechanism assembly.

a_i \ a_j	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
a_2	0	0	-1	-1	0	0	0	1
a_3	0	0	0	0	-1	-1	-1	1
a_4	1	0	0	-1	0	0	0	0
a_5	1	0	1	0	0	0	0	0
a_6	0	1	0	0	0	-1	0	0
a_7	0	1	0	0	1	0	0	0
a_8	0	1	0	0	0	0	0	1
a_9	-1	-1	0	0	0	0	-1	0

According to the disassembly priority constraint matrix, it can be seen that multiple parts may be disassembled before one part, or it may appear that multiple parts are disassembled simultaneously after one part. In order to realize the dynamic adjustment of disassembly priority relationship, using the double linked list of disassembly parts can realize the dynamic update of *previous* pointer and *next* pointer in the process of disassembly priority relationship reasoning. The algorithm flow of constructing product disassembly priority relationship diagram is shown in Fig. 3.

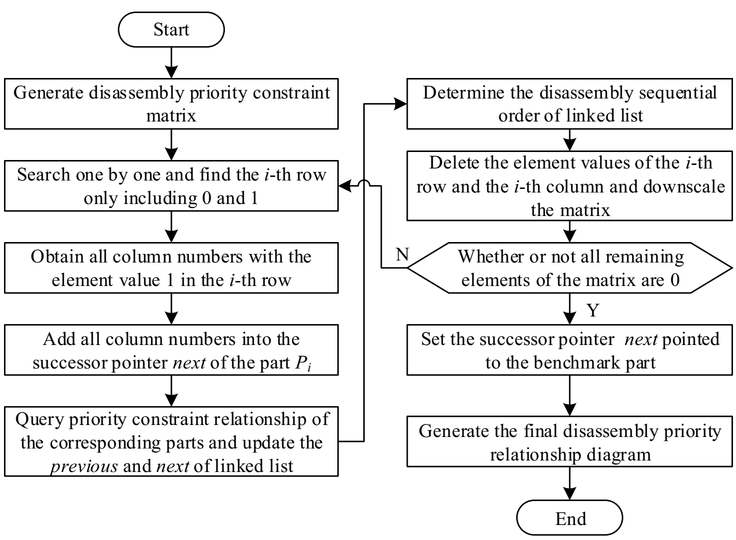


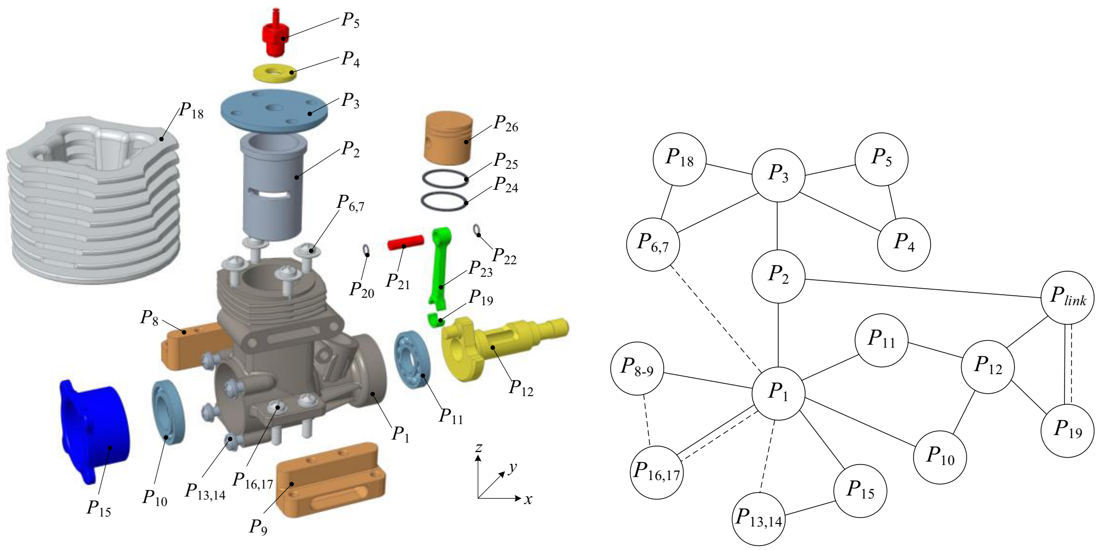
Figure 3. Generation algorithm flow of disassembly priority relationship diagram.

According to the algorithm flow of the above, the priority constraint relationship of pulley mechanism assembly is $a_5 \Rightarrow a_4 \Rightarrow a_2 \Rightarrow a_7 \Rightarrow a_6 \Rightarrow a_3 \Rightarrow a_8 \Rightarrow a_9 \Rightarrow a_1$. The disassembly sequence also accords with the practical engineering application. Finally, the assembly sequence of pulley mechanism is generated in the reverse order of disassembly sequence. It needs to point out that, due to the symmetry of the pulley mechanism assembly, the disassembly sequence of $a_5 \Rightarrow a_4 \Rightarrow a_2$ and $a_7 \Rightarrow a_6 \Rightarrow a_3$ can exchange the sequence or be executed in parallel.

5 Case study

Based on the above-mentioned methods and key techniques, the assembly sequence planning of product assembly is implemented in a prototype computer-aided assembly process planning (CAAPP) system named AMTProcesser in our laboratory [13], which is developed based on ACIS and HOOPS using VC 2008. The following is a detailed description of concrete example case.

The explosion diagram of 3D assembly model of engine body and the liaison graph are shown in Fig. 4. The 3D assembly model of engine body is built in Pro/E and imported into 3D digital assembly process design system environment named AMTProcesser. Using the disassembly method in this paper, the disassembly priority constraint matrix can be generated, which is similar to Table 2. P_{20}-P_{26} represent parts of a piston rod sub-assembly and they can be viewed as a part named P_{link} . At the same time, to be easy for analysis, engine body1 and engine body2 can also be viewed as a part named $P_{8\text{-}9}$, and fasteners (e.g. bolt-washer) can be grouped as three part named $P_{6,7}$, $P_{13,14}$ and $P_{16,17}$, respectively.



(a) Explosion diagram of 3D assembly model (b) Assembly model liaison graph

P_1-Engine body, P_2-Cylinder sleeve, P_3-Cylinder sleeve, P_4-Copper backing, P_5-Ignition plug, P_6-Washer 4×M3, P_7-Bolt 4×M3×12, P_8-Engine base1, P_9-Engine base2, P_{10}-Bearing1, P_{11}-Bearing2, P_{12}-Crankshaft, P_{13}-Washer 4×M3, P_{14}-Bolt 4×M3×8, P_{15}-End cover, P_{16}-Washer 4×M3, P_{17}-Bolt 4×M3×12, P_{18}-Radiator, P_{19}-Rod head, P_{20}-Ring1, P_{21}-Axis pin, P_{22}-Ring2, P_{23}-Rod body, P_{24}-Piston ring1, P_{25}-Piston ring2, P_{26}-Piston

Figure 4. Explosion diagram of engine body and the corresponding liaison graph.

According to the analysis of the assembly constraint relationship between parts of engine body, the disassembly direction of each part can be obtained. Then, using the generated disassembly priority constraint matrix, the disassembly priority relationship diagram is inferred. Finally, the feasible disassembly sequence is generated by implementing the detection of disassembly feasibility. The generating disassembly priority relationship diagram is shown in Fig. 5.

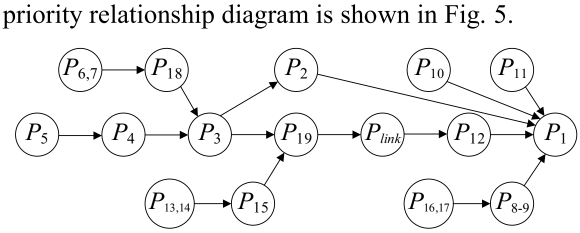


Figure 5. Generating disassembly priority relationship diagram of engine body.

Since dismantling engine body is a more complicated process, other than satisfying the disassembly geometric feasibility, many factors such as disassembly cost, disassembly time, tool operability, disassembly difficulty, etc. should also be taken into consideration. Therefore, a more practical disassembly sequence can be obtained from the above example about the disassembly of engine body and the dismantling scheme is $P_5 \Rightarrow P_4 \Rightarrow P_{6,7} \Rightarrow P_{18} \Rightarrow P_3 \Rightarrow P_{13,14} \Rightarrow P_{15} \Rightarrow P_{19} \Rightarrow P_{link} \Rightarrow P_{12} \Rightarrow (P_2 \cap P_{10} \cap P_{11}) \Rightarrow P_{16,17} \Rightarrow P_{8\text{-}9} \Rightarrow P_1$, where there is no sequential relationship between P_2, P_{10} and P_{11}. Finally, the assembly sequence of engine body is obtained by reversing the above disassembly sequence.

6 Conclusions

Assembly sequence planning has always been a very concerned issue in the field of manufacturing. The efficient, convenient and practical assembly sequence generation strategy is one of the key technologies for improving the efficiency of 3D digital assembly process design. In consideration of the shortages of automatic and human-computer interactive assembly planning in the three-dimensional environment, an assembly sequence planning method based on assembly constraint relationship analysis for intelligent assembly is proposed in this paper. The results of case study clearly show the capability of generating assembly sequence simply and reasonably. The automatic generation method of assembly sequence based on the identification and acquisition of assembly constraint relationships can be used in 3D digital assembly process design for assembly sequence planning in a more convenient and practical way.

However, further research questions arise. Since the complexity and diversity of the product assembly process design, the computational volume and search efficiency will be one of the major issues affecting intelligent assembly or disassembly planning. How to properly mix different methods to obtain the optimal assembly sequence from several geometrical feasible assembly sequences by combining the advantages of precise calculation method and various heuristic intelligence algorithms will be the next step in our study. At the same time, more detailed research is required to validate and apply these ideas using more complex case-studies.

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