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Mechanical Product Disassembly Sequence and Path Planning Based on Knowledge and Geometric Reasoning

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A feature-based assembly model is proposed for disassembly sequence planning, and establishing a correct and practical disassembly path for the part in the product, based on geometric reasoning and knowledge. The fundamental assembly modelling strategy for a product is based on the mating features of its parts.

An algorithm is introduced which uses the information provided by the mating features of parts in the product to find the candidate parts for disassembly and to carry out disassembly path planning. A complete and accurate interference checking approach is used to ensure no global collision while disassembling a part.

In some cases, it cannot be implemented by geometric reasoning alone, so a set of criteria and heuristic rules based on knowledge, constraints, relationships among parts, and quantitative disassemblability assessment are used. It can also be carried out interactively by the user when necessary.

The proposed method is integrated with the CAD model of the product. The user can visually disassemble the product while planning, so it is easier to carry out the disassembly planning and generate an optimal sequence.

Keywords: Disassembly; Geometric reasoning; Path planing; Recycling; Sequence planning

1. Introduction

In recent years, the concept of green engineering has become popular in the engineering community. Concerns about the environment have spurred designers to consider product life, from initial conceptual design, through normal product use, to the eventual disposal of the product. Disassembling a product is necessary for applications such as recycling or maintenance. Disassembly sequence and path planning is an essential step for product disassembly because it influences the productivity and the costs.

Generally, disassembly planning consists of two major activities: assembly modelling and disassembly sequence planning. The efficiency of a disassembly plan depends on the way in which the assembly is modelled. Thus, the importance of developing a good assembly modelling method as a primary step cannot be ignored. In this study, a good assembly modelling method is judged by its potential in direct integration with CAD models and by its capability to assist the generation of a disassembly sequence effectively.

In assembly modelling, the most commonly used method is graph based. This method represents topological relationships between parts of a design, where the nodes represent the parts and the arcs establish the relationships between the parts. Eastman's "location graph" [1] describes a chain of part location relationships by a set of transformation matrix operations. Homem de Mello and Sanderson's "relational model graph" [2] includes parts, contacts and attachment relationships in a model. Ko and Lee's "virtual link mating graph" [3] captures the mating conditions between two parts in the design. Using the above approaches to establish these graphs requires more information than is available directly from most CAD models.

A valid assembly model should provide the precedence relationships for disassembly sequence planning. To generate this precedence knowledge, "common sense" or "intuition" with human assistance was employed in previous work. The sequence generated by mental analysis guarantees a correct and exact sequence, but becomes more and more complex when the number of parts in a design increases. Other approaches use a geometrical reasoning technique to establish this precedence knowledge. However, there are cases that cannot be solved by geometric reasoning alone. Although the geometric reasoning technique has weaknesses, the approach has the advantage of achieving integration with CAD models.

In the case of disassembling a product completely, the problems in disassembly planning are related to those in assembly planning. The inverse of an assembly plan can yield the disassembly plan. The assembly planning for the parts of a product and the sequence of these operations have been analysed by Wilson and Latombe [4]. They have developed

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the concept of non-directional blocking graphs to analyse assemblies. The assembly planning scheme developed by Liu and Popplestone [5] uses the matching of the models with a library of standard compound features. Ling [6] uses a "kinematic pair liaison diagram (KPLD)" to model an assembly process. Methods to determine the constraints on the transitional and rotational motion of 2D and 3D objects from their contact geometry have also been investigated [7].

However, several differences exist between the assembly and the disassembly of a product. The assembly process is reversible as long as no irreversible operation is carried out. However, in practice, there might be several irreversible operations during an assembly. Another difference is that in assembly it is desired to completely assemble the parts, whereas in disassembly only partial disassembling might be required, especially in the case of product maintenance and parts recycling.

One important task during disassembly sequence planning is to guarantee no global interference between parts when disassembling. Ko and Lee [3], Wilson and Rit [8], and Lin and Chang [9] used the swept volume approach to check global interference. Woo [10], Arai and Iwata [11] and Miller and Hoffman [12] used the ray casting technique to detect interference between non-contacting objects. All these approaches can detect interference directly from the 3D representation of a CAD model. However, the accuracy of the result increases the cost of the computation. A simple approach uses an imaginary rectangular parallelepiped to envelop the object, and therefore simplifies the object geometry for checking interference [12,13]. However, this test does not always provide the correct answer.

In this paper, a feature-based assembly model is proposed for disassembly sequence planning. The fundamental assembly modelling strategy is based on the concept of mating features. The degrees of freedom (DOFs) determined by the mating features can provide a local escape direction of a part which will be used to find the candidate parts for disassembly and carry out disassembly path planning based on geometry reasoning and knowledge. The assembly model is directly integrated with the CAD model of the product. A user can carry out product disassembly visually on computer, so it is easier to generate an optimal disassembly sequence, and establish a correct and practical disassembly path for the part in the product.

During path planning, it must be ensured that there is no global interference when disassembling a part along the path. Here, a complete and accurate interference checking method is used to ensure no global collision during disassembly. It converts 3D interference checking to 2D checking, so much computation is saved and at the same time a correct answer is provided. Problems involved in partially disassembling a product are also discussed.

The remainder of this paper is organised into sections. Assembly modelling is discussed in Section 2, disassembly planning in section 3, and an example and summary are given in sections 4 and 5.

2. Assembly Modelling

2.1 Geometry of Single Parts and their Mating Features

The foundation for modelling assemblies consistently is the mating feature. Mating features are local regions on parts where they join to other parts. Typical mating features are cylinders, planes, cones, toruses, spheres, etc.

The basic idea in mating feature definition is that of the local escape or disassembly direction. This is defined as the direction along which two mating features move from the state of complete assembly until the features no longer touch. The local escape direction or DOFs for a mating feature are represented by a simple 3×4 matrix. The elements of the matrix represent the DOFs on the three major axes in 3D space as shown below:

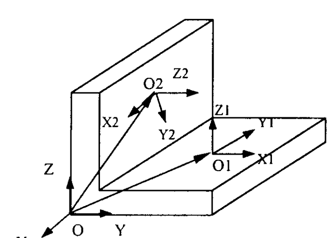
$$\begin{bmatrix} X & -X & \omega X & -\omega X \\ Y & -Y & \omega Y & -\omega Y \\ Z & -Z & \omega Z & -\omega Z \end{bmatrix}$$

where $\pm X$, $\pm Y$, and $\pm Z$ are linear translations, and $\pm\omega X$, $\pm\omega Y$, and ωZ are the rotations about the x-, y- and z-axes. The values of the elements in the feature matrix are either 0 or 1. Integer 1 indicates freedom of motion in the direction along the corresponding principal axis. Integer 0 indicates that the motion is not allowed in the axial direction.

Note that each feature contains a coordinate frame, one axis of which points along the symmetry axis of the feature. This axis by convention is labelled Z. A conventional 4×4 transform relates the coordinate frame of the feature to the base frame of the part (see Fig. 1).

2.2 Escape Direction of a Part

Generally, there are several mating features on a part. If more than one mating feature exists on a part, a single matrix, which can determine the escape direction of the part, will be generated. To accomplish this, intersection iteration is performed on all mating features of the part. This intersection iteration produces the total local DOFs of the part. Figure 1 shows a part having two primary mating feature matrices that are



$$F1_{primary} = F2_{primary} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 \end{bmatrix} \quad F_{total} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$F1_{local} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 \end{bmatrix} \quad F2_{local} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

Fig. 1. An example of a part matrix.

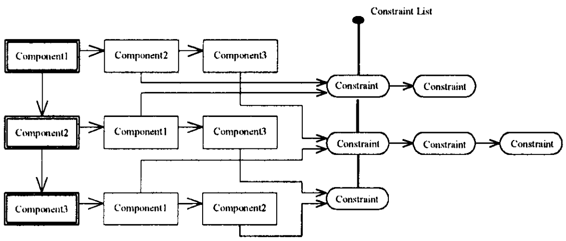


Fig. 2. The constraint relationship in the assembly.

reduced to a single feature matrix through the intersection iteration. Before the intersection iteration, the primary feature matrix should be transformed according to the local coordinate system of the part.

2.3 Connective Model of Assemblies

Typical CAD systems represent assemblies by one of the following methods:

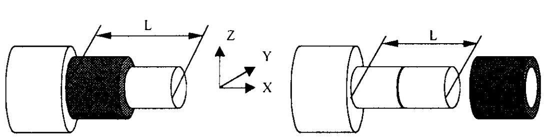
Placing the parts in a world coordinate system in the correct relative position and orientation, but otherwise taking no note of the fact that they are assembled to each other.

Capturing constraints such as "against" or "aligned" that are applied by the designer to various surfaces or axes on parts after they are designed.

The idea of the mating feature to build up assembly is extended and exploited by joining features and simultaneously building up a relational database. Such a model is based on the mating parts defined carefully below as the carriers of dimensional constraint between the parts. The model in Fig. 2 is called a relationship liaison diagram.

The basic information in Fig. 2 is the nominal location of each part, which may be calculated from the location of any other part by well-known methods based on 4×4 transforms. The validity of this calculation is based on the fact that the mates are used to define the connections and support the necessary calculations.

The constraints between two parts are represented by the related mating features, and a constraint matrix is used to describe its attribute (see Fig. 3). In the figure, a simple example is used to illustrate the constraints between two parts with the help of mating features. The shaft has only transitional motion along the $-X$-axis and rotational motion about the $\pm\omega X$-axis, and the ring has only transitional motion along the $+X$-axis and rotational motion about the $\pm\omega X$-axis, because of



$$F_S = \begin{bmatrix} 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad F_S = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

$$F_R = \begin{bmatrix} 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad C_{SR} = \begin{bmatrix} L & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \qquad F_R = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \quad C_{SR} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Fig. 3. A ring assembled on a shaft and the corresponding constraints.

the two mating features. The attribute of the constraint is the length of the shaft (L), which determines the effectiveness of the mating feature. If one of the two parts moves for a distance more than L along the +X- or $-X$-axis, the parts will no longer have any constraint between them.

2.4 The Final Assembly Model

The final assembly model uses a tree structure of "instances" to represent an assembly and subassemblies. It is a recursive definition of assembly. While carrying out disassembly planning on an assembly at a certain level of the model, subassemblies in it are treated as parts. This can greatly simplify the planning.

The final assembly model describes only the spatial locations of the parts in a product; it does not contain information on "how the product is held together", in other words which parts interact and how. So the connective model of assembly described above should be used to hold this information. The detailed structure of the assembly model is given in Fig. 4.

```
Assembly
└─Parts List
   └─Part A
      ├─Name
      ├─Type
      ├─ID number
      ├─Geometry
      ├─Location (4x4)
      ├─Attributions
      │   ......
      ├─Escape direction (3x4)
      ├─Mating Feature List
      │   └─Mating feature
      │       ├─Name
      │       ├─Type
      │       ├─ID number
      │       ├─Feature matrix (3x4)
      │       └─Location (4x4)
      └─Relation Feature List
          └─Part B
              ├─Name
              ├─Type
              ├─ID number
              └─Constraint List
                  └─Constraint
                      ├─Mating feature on Part A
                      ├─Mating feature on Part B
                      └─Constraint matrix (2x3)
```

Fig. 4. The detailed structure of the model.

3. Disassembly Planning

3.1 Preliminary

A mechanical assembly is a cluster of parts constrained by geometric contacts. The basic requirement for a valid disassembly sequence is its geometric feasibility [6].

Definition 1. A disassembly task is said to be geometrically feasible if there is a collision-free path to bring the target subassembly or part out from the assembly.

For example, a geometrically feasible immovable part cannot be disassembled. Similarly, a locally movable but globally infeasible part generates an impractical sequence.

In order to find a valid disassembly sequence, some hypotheses are given below.

Hypothesis 1. The assembly is disassemblable. If the assembly is not disassemblable, some steps should be taken by the user to make the assembly disassemblable.

According to hypothesis 1, two lemmas will be obtained.

Lemma 1. There is at least one part in the assembly having a local escape direction.

Lemma 1 states that at least one part in the assembly has DOFs, that is to say, at least one element of $\pm X$, $\pm Y$, and $\pm Z$ in the part's feature matrix is not zero. These parts will be selected as the candidates for disassembly planning.

Lemma 2. There is at least one candidate part having a global disassembly path.

Lemma 2 guarantees that at least one candidate part in the assembly which has a local escape direction has geometrical feasibility during disassembly.

Hypothesis 2. At every planning step, only one part is disassembled from the assembly.

Hypothesis 3. During the disassembly process, the assembly is stable.

Hypothesis 3 implies that when one part is removed from the assembly, it will not cause the instability of the remaining parts. This can be achieved when the parts are naturally stable or by means of fixtures.

Hypothesis 4. Consider only the nominal model.

Up to now, we have assumed that the assembly model depicts perfectly made and assembled parts. The reality is that parts differ, and this fact should be represented in the assembly model. Two important types of variation should be represented:

1. Variations in the interface constraints between parts.
2. Variations in the geometry or relationships within individual parts.

Variations in interface constraints can arise from many factors. Those considered here involve variation in the location and size of mating features, which are the ones that transmit dimensional constraint from part to part.

Compared to assembly planning, variations in the assembly model have far less influence on disassembly planning. So, hypothesis 4 is allowable.

Hypothesis 5. Consider transitional motion first while disassembling a part. Only in the case of it being impossible to disassemble a part by transitional motion, may the rotation of the part be considered.

Furthermore, there are two types of disassembly, one is disassembly of the product completely, the another is disassembly of the product partially. Although type II disassembly is more difficult than the type I disassembly, it is used frequently in product maintenance and recycling.

Generally, the subassemblies in the assembly model are organised according to the design of the product. In order to partially disassemble the product, it is necessary to reorganise the subassemblies. The following proposition will be used to reorganise the subassemblies.

Proposition. If two parts in an assembly meet the following conditions, the two parts can be grouped into one subassembly.

1. The two parts have constraints with each other.
2. If there is a third part having a constraint with both of the parts, the escape direction set of one part, determined by the third part, should be contained in the escape direction set of the other part, which is determined by the third part.

Proof. $\forall$ assembly, let $\exists$ be two parts which have constraint with each other, and designate them part A and part B, respectively. There are two cases:

Case 1. There is no other part having a constraint with both of them,

$\therefore$ part A and part B can be grouped into a subassembly.

Case 2. Let $\exists$ part (denote part C) connected with both part A and part B. Part A's escape direction set, determined by part C, is D_{CA}, part B's escape direction set, determined by part C, is D_{CB}, and let $D_{CA} \subseteq D_{CB}$, as shown in Fig. 5(*a*).

$\therefore$ Fig. 5(*a*) can be converted into Fig. 5(*b*), and Fig. 5(*b*) meets the condition of Case 1,

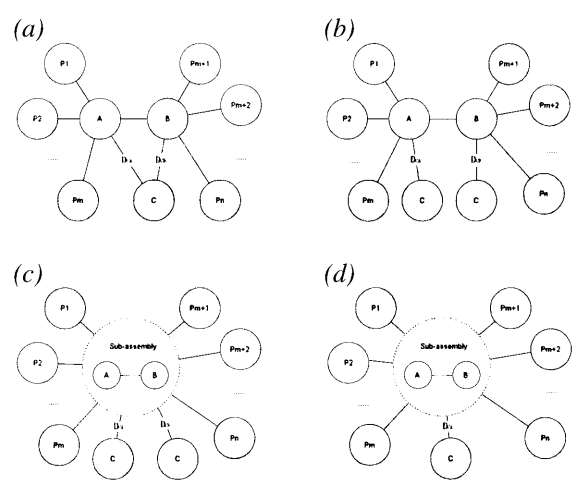


Fig. 5. Parts coalition.

∴ part A and part B can be grouped into a subassembly, see Figs 5(*c*) and 5(*d*).

3.2. Disassembly Planning Process

Based on the assembly model discussed in the previous section, a system for the disassembly sequence and path planning is developed based on the CAD platform Pro/ENGINEER. The algorithm of sequence planning is shown in Fig. 6.

In the algorithm, a group of candidate parts are found according to the feature matrices of the parts in the assembly model. Usually, there exist several candidates. If more than one candidate has been found, some criteria and knowledge must be used to select the best for path planning.

After a single best candidate in the current level is selected, the disassembly path planning of the part begins. If a path is found, the part will be removed from the assembly, and the assembly model will be modified accordingly.

For the next level in the sequence planning, the same analysis procedure as discussed above is repeated, according to the newly modified assembly model, until the corresponding product reaches its disassembly goal.

3.2.1 Select the Best Candidate

The disassembly time is ranked as the most important criterion for selecting the best candidate, because a sequence based on this property requires the minimum disassembly time and hence less disassembly cost can be realised.

Disassembly time is included in this study as a measurement to evaluate the ease of disassembling a part. The disassembly time function is based on several parameters that influence the part's disassemblability. More disassembly time indicates the difficulty in the corresponding disassembling operation. The proposed disassembly time function is defined as follows:

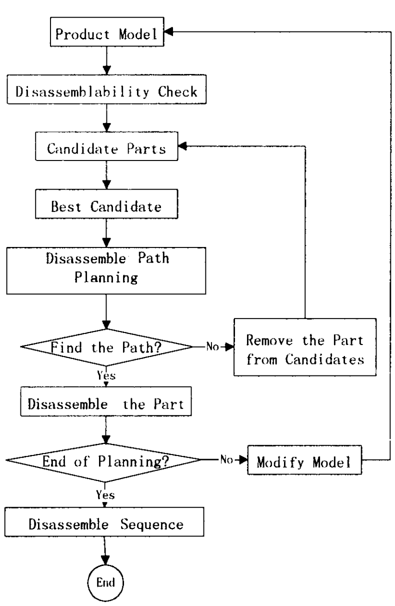


Fig. 6. Disassembly planning process.

$$D_{time} = h_{time} + w_c \times (c_{time} + s_{time}) \tag{1}$$

where,
D_{time} = disassembly time
h_{time} = time for handling part
c_{time} = time for disconnecting fasteners
s_{time} = time for removing part
w_c = weight for accessibility

The handling time, removing time, and disconnecting time, are defined as follows:

$$h_{time} = \left(1 + \sum_{i=1}^{7} zw_i\right) \times sh_{time} \tag{2}$$

$$s_{time} = (1 + sw) \times ss_{time} \tag{3}$$

$$c_{time} = sc_{time} \times n \tag{4}$$

where,
sh_{time} = standard handling time
ss_{time} = standard removing time
sc_{time} = standard disconnecting time
zw_1 = weight for mass
zw_2 = weight for volume
zw_3 = weight for irregularity
zw_4 = weight for fragility
zw_5 = weight for rigidity
zw_6 = weight for symmetry
zw_7 = weight for stability
sw = weight for disassembly resistance
n = number of fasteners

Some other criteria such as first disassemble outside parts, less constrained parts, and/or small parts will also be considered.

During the sequence planning process, the system may postpone the selection of the base part until the end of the planning process. This is because the base part is the reference object in the assembly. According to the knowledge of designers, the base part is assembled first, so it should always be disassembled last.

3.2.2 Path Planning of Part

The part's path planning algorithm is very important for disassembly sequence planning. During path planning, the system will find a disassembly path for the part automatically or through interaction by the user, and also take the global collision-free test. The path planning procedure is shown in Fig. 7.

The detailed algorithm will be illustrated by the simple 2D example shown in Fig. 8. Initially, part P has only one escape direction along the $-X$-axis (see Fig. 8(*a*)), so the movable direction group only contains one direction. Direction $-X$ is selected, and moves part P along this direction a distance D. Distance D equals the diagonal length of the assembly plus the diagonal length of part P. This distance guarantees that part P is moved completely outside the assembly. Because part P interferes with part C, this distance cannot be achieved. Only distance L can be moved. Distance L is the constraint attribute between part P and part A.

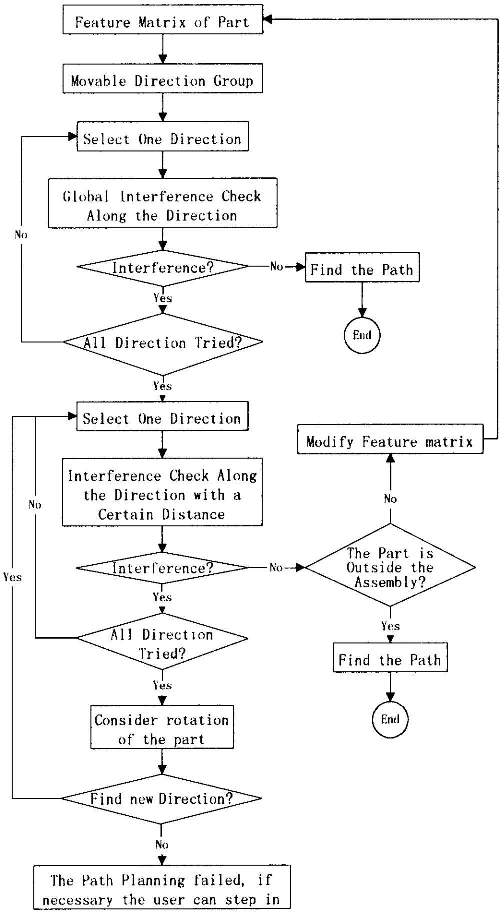


Fig. 7. Disassembly path planning.

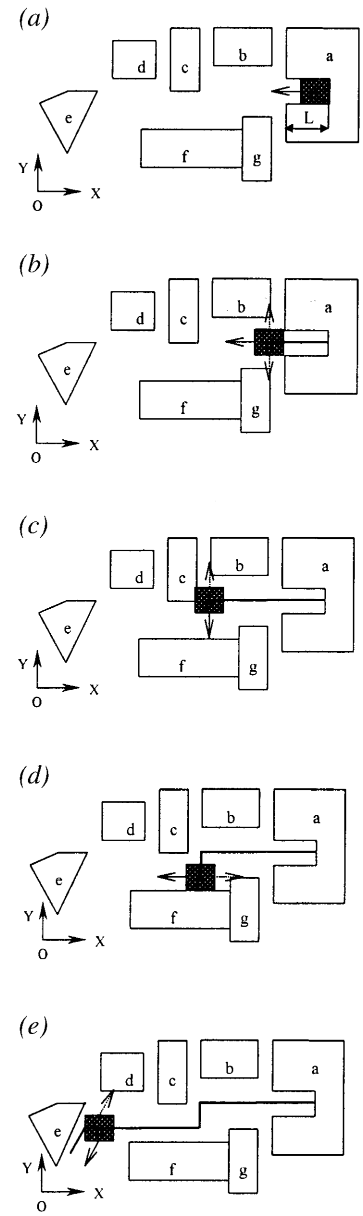


Fig. 8. Automatic disassembly path searching.

After moving (see Fig. 8(*b*)), part P has no constraint with other parts, it has all four escape directions along $\pm X$ and $\pm Y$. Since the last movement was along the $-X$-direction, only three directions, $-X$ and $\pm Y$, are contained in the movable direction group. Direction $-X$ is selected and part P (shaded) is moved to the interference part C (see Fig. 8(*c*)).

Then the moving direction will be determined by the interference of part C combined with the escape direction of part P. According to part C, part P can move along the $\pm Y$ directions. Part P also has escape directions $\pm Y$, so directions $\pm Y$ are included in the movable direction group. Direction $+Y$ is selected. Along this direction, the interference part B will bring part P back and a loop will be constructed, so this direction is not valid, and should be dismissed. Then, direction $-Y$ is selected, and part P is moved to part F (see Fig. 8(*d*)).

This step is repeated until the moving distance from the endpoint to the starting point of part P is greater than the distance *D*. Every moving step of part P forms a feasible disassembly path. As can be seen from the figure, it may not be an optimal path.

3.2.3 Global Interference Check

As described above, a part moves in a linear trajectory along the DOFs direction suggested in its feature matrix, and any subset of the remaining parts may interfere with the part somewhere along the path. Therefore, a global interference check is needed to avoid such an occurrence.

Here, an improved method is used. An algorithm converts 3D interference checking to 2D interference checking, so much computation can be saved and at the same time a correct answer is provided.

In the proposed algorithm, two parallel assistant planes are created to help the interference check. The two planes are normal to the disassembly direction of the part, and the distance between them is the predicted moving length of the part.

After the two planes are created, all the geometry between them is projected onto one of the planes along the disassembly direction. On that plane, a 2D interference check will be carried out to obtain the global interference information.

In the 2D interference check, first the box checking technique is employed to simplify the computation. Three conditions exist between two boxes: non-intersection, partial intersection, and complete enclosure. The non-intersection case indicates the absence of global collision. For the other two conditions, a more precise and complete 2D checking algorithm should be used.

As for the precise interference check, it will be more efficient if a sophisticated feature-recognition module is used for reasoning when the partial intersection and complete enclosure cases occur.

A convex decomposition method called alternating sum of volumes with partitioning (ASVP) is a volumetric representation of solid objects obtained from the boundary information [14]. ASVP decomposition is a hierarchical decomposition of the boundary faces of the given solid, based on extremality where the volumetric expressions abstract the boundary face information. By applying combination operations among the volumes of the ASVP decomposition, based on the hierarchical structure and face-dependency information of the decomposition, the ASVP decomposition is converted into form feature decomposition (FFD) where the volumes correspond to compact and meaningful high-level constituents of the product shape. Being intrinsic to the product shape, FFD is neutral by nature, and can serve as a central feature representation from which an interference check can be carried out through pertinent context-dependent geometric reasoning.

When a partial intersection or complete enclosure case occurs, two scenarios can prove the non-interference between the two parts. One is that the moving part is completely inside the negative features of the resting part. Another is that it is completely outside the positive features of the resting part. Any other case here may be regarded as a case of interference occurring.

2D interference checking technology has been well developed, and it will not discussed here.

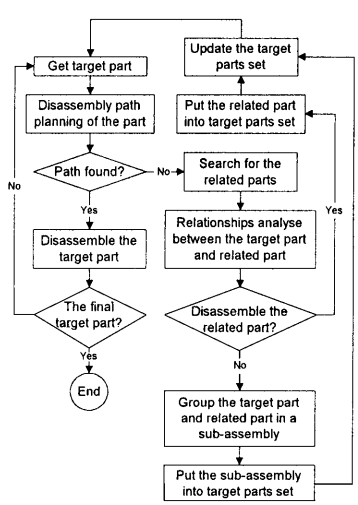


Fig. 9. Process of partially disassembling a part.

The technology of how to project various kinds of features onto a plane is very important. It will affect the validation of the checking result.

Furthermore, the moving part usually interferes with more than one resting part when interference is detected. It is necessary to decide which part first interferes with the moving part. That information is not available from the 2D interference checking. The solution is to calculate the distance between features in the intersecting area, the minimum distance relates to the first interfering part. It is also the distance that is actually moved by the moving part.

The essential aspect of the global interference check algorithm discussed above is using a projection method instead of solid extrusion. This reduces the necessary 3D interference checking to 2D interference checking, and uses a multi-segment lines approach for the actual disassembly path.

3.2.4 Rotation Consideration

During path planning, there may exist situations in which none of the movable directions of the part can fulfil the requirement for disassembly. That is, all movable directions have been tried but none could provide a feasible disassembly path for the part. In that case, a rotational motion of the part must be considered.

It is very difficult to consider rotation in disassembly path planning. In this work the part can only rotate discretely by a certain angle selected by the computer or input by the user, and only non-accurate box checking is implemented.

As soon as a feasible moving direction is found after rotating the part through a certain angle, the algorithm of path planning described in Section 3.2.2 will continue.

3.2.5 Disassembly Visualisation

It is desirable to use virtual prototyping technology to aid the assessment of product disassembly. By virtual prototyping, the designer can visually disassemble the product. A virtual prototype is a model of a product and the process that the product undergoes. Virtual prototyping is defined as the generation of a virtual prototype and its simulation or assessment. Factors involved in generating a product disassembly processes include: determining the disassembly sequence of a product; the disassembly paths of parts; and tool change sequences.

Here, it is used to visualise the product disassembly sequence and path, so the designer can more easily determine the best disassembly sequence and establish a feasible disassembly path.

3.3 Partial Disassembly of the Parts

Compared with complete disassembly of a product, partial disassembly of a few parts or subassemblies from a product is more usual in product maintenance and recycling.

The suggested method is shown in Fig. 9. It contains the path planning algorithm of the part described in Section 3.2.2. The part that the user aims to disassemble is called the final target part. The parts or subassemblies that may be disassembled before the final target part can be disassembled are stored in the target parts set. The difficulty is how to organise the target parts set and how to find the best disassembly sequence to disassemble the final target part effectively. In order to construct the target parts set, the proposition presented in Section 3.1 should be used, and the user should also make more interventions. The target parts set will directly influence how well the disassembly sequence can be generated.

4. Example

The assembly considered for the disassembly sequence and path planning illustration is an actual industrial part, which is an active bevel gear assembly for a heavy off-road vehicle differential. It consists of 13 main parts connected together. They are gear shaft, bearing1, seat, sleeve1, adjustor1, adjustor2, bearing2, sleeve2, block, connector, seal, washer, and nut.

The system shows the disassembly sequence and path visually during the planning. This facility will help the planner in the disassembly planning and assessment of the product. The disassembly planning result of the assembly is shown in Table 1.

Figure 10 is another example, this time the disassembly planning is of a whole driving-axle. The active bevel gear assembly mentioned above is included in the driving-axle. As shown in the figure, the main part of the active bevel gear assembly is disassembled as a single part.

5. Summary

In this paper, a method for disassembly sequence and path planning has been proposed. The concept of DOFs is used to characterise the feasibility of the disassembly process. In particular, the mating feature matrix of two contacting parts is established, which can represent the DOFs. These are used to construct a feature matrix and constraint relationship liaison diagram. Intersection iteration among all the mating features in a part generates the disassembly escape direction. By using features in planning a disassembly sequence, better integration of disassembly planning with CAD models can be realised. The aforementioned procedure constitutes the geometric reasoning. Although geometric reasoning has been proved to satisfy many disassembly precedent relationships, it is insufficient in certain cases. To always guarantee a correct and feasible sequence, the knowledge and help from the user are required.

For disassembly sequence generation, several heuristic rules are introduced to narrow down the search space for the "best" or "approximately optimum" sequence. The problem of partially disassembling a product is also discussed.

Finally, disassembly sequence and path planning examples are provided to illustrate the practicality and effectiveness of the system.

Table 1. Disassembly sequence of the assembly.

Number	Parts	Disassembly time (s)	%
1	Nut	50.3	0.162
2	Washer	2.2	0.007
3	Seal	4.4	0.014
4	Connector	5.7	0.018
5	Block	2.2	0.007
6	Sleeve2	5.3	0.017
7	Bearing2	67.6	0.218
8	Seat	46.8	0.150
9	Adjustor2	2.3	0.007
10	Adjustor1	2.3	0.007
11	Sleeve1	5.4	0.017
12	Bearing1	106.4	0.342
13	Gear Shaft	10.4	0.034
	Total	311.3	

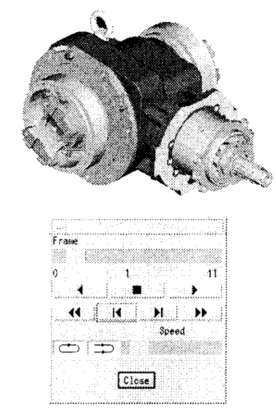


Fig. 10. Driving-axle disassembly planning.

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