A Virtual Disassembly Tool to support Environmentally Conscious Product Design

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Abstract - This paper presents a disassembly tool to support environmentally conscious product design. The disassembly tool consists of a software program that gives recommendations to product design based on disassembly analysis. The disassembly analysis consists of Product analysis, Disassemblability analysis, Computing an optimal disassembly sequence and Design rating. These considerations make a product easier to disassemble and therefore are beneficial to the environment.

I. INTRODUCTION

Today, both consumer demand and government legislation require that manufacturers reduce the quantities of manufacturing waste generated. Both environmental concerns and rising product disposal costs have triggered customer pressure for more environmentally friendly products. Governmental action encompasses both legislation and purchasing programs. As a result of these economic and legislative restrictions, a firm's competitiveness in future world markets depends upon making environmental issues a central concern.

Design for Environment (DFE) follows the engineering concepts of concurrent engineering. Design for Manufacturing and Design for Disassembly (DFD). In DFE initiatives, environmental considerations are the main focus of product design. However, before products can be developed in an environmentally sound way, designers must understand the relationship between a product and the environment. They also need to use recycled materials and make recyclable products. A designer can increase the chances of a product being reused/recycled by initially designing the product for disassembly.

Disassembly is defined as the process of removing components from the products. De-manufacturing is the process of disassembling products and then reusing, recycling or refurbishing them. Figure 1 shows the block diagram of virtual de-manufacturing analysis. In this case, the virtual prototype -- the CAD model of the product -- is analyzed for disassembly before production. This analysis could result both in the reduction of the disassembly cost/time for the product maintenance and its recyclability at the end of its life.

Figure 1. De-manufacturing analysis

Virtual disassembly allows designers to evaluate design options in a virtual environment without building an actual prototype. Therefore, a geometric disassembly software tool needs to be developed to support product design which takes into account ease of disassembly to effectively reuse and recycle materials.

II. RELATED WORK

The work to-date has focused on disassembly sequencing, disassembly path planning and the evaluation tools development. Boothroyd [2], Gupta [5], Peney [13] and Jovane [8] provide an overview of the ongoing research in product disassembly and also present the topics and trends for future activities. Hrinyak [7] examines the existing disassembly software tools available to the designers for inclusion in their design processes.

At present, there exists extensive research on disassembly sequence analysis. Disassembly sequence is defined as the order in which the components are disassembled. Researchers have suggested several approaches. However, key differences such as irreversible operations including welding, riveting or breakage of components [10], and selective disassembly, which requires only a portion of an assembly to be disassembled [17], suggests that the most economical assembly sequence need not be the most economical disassembly sequence. Moreover, the differences between assembly and disassembly analysis make a separate study of product disassemblability essential.

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Several approaches have been developed to determine the disassemblability of product geometry and generation of disassembly sequence. Disassemblability refers to whether a selected component is removable from an assembly. Woo [19] has developed an algorithm to determine the disassemblability of a 1-disassemblable component by considering the faces of the component which mate with the rest of the assembly. A later disassembly study, [4] describes identifying a sub-assembly to initiate the disassembly process for a 2.5D parallel assembly. Beasley [1] considers the generation of disassembly motion for voxelized models of objects. Other disassemblability and disassembly sequence techniques include [11], [15] and [16]. These approaches aim to minimize the disassembly cost by optimizing the disassembly sequence. Xu [20] addresses the problem of geometric path determination by generating the partial medial axis of the free space within the assembly.

Some of the existing evaluation schemes are listed below. Kroll [9] has developed a rating scheme for disassembly evaluation based on the difficulty scores of each task in order to determine the overall design effectiveness of a product. Bras [3] estimates the cost incurred by different designs based on Activity-Based-Costing (ABC). The suitability of ABC is explored in the context of design for product retirement. Other evaluation techniques include [12] and [18]. These evaluation techniques are useful to the designer in identifying weaknesses in the design and comparing alternative designs.

While DFD is a strong and growing field, the existing research still has several important limitations. Researchers have focused on the development of DFD research without significantly analyzing the three dimensional geometric disassembly of products. Furthermore, the design steps and the problem areas in building an automated geometry based disassembly tool have yet to be analyzed. This paper presents a disassembly tool and analyzes the design modules needed to build a geometric virtual disassembly tool.

III. DFD FRAMEWORK

The DFD framework, shown in Figure 2, identifies the abstract design modules that need to be developed to build a geometric virtual disassembly tool. The modules are software programs that are executed as part of various design steps. The design steps are: (1) Product analysis. (2) Disassemblability analysis. (3) Optimal disassembly sequence generation and (4) Design rating.

![DFD Diagram](image)

**Figure 2. DFD Framework**

IV. PRODUCT ANALYSIS

The first design step needed to build a virtual disassembly tool is the product analysis. This step involves: (1) Selection of components that need to be disassembled and the appropriate de-manufacturing application. (2) Formulating disassembly constraints. (3) Identifying the objective variables.

The information regarding the components to be disassembled, the objective variables and disassembly constraints are available from: (1) the knowledge-base, which consists of material, environment and application domain databases and (2) the user requirements.

The material, environment and application domain factors impose requirements/constraints on the disassembly process. The material database includes information such as material cost and material properties. The environmental database includes information concerning the hazardous components; environmental impact of such components; information pertaining to whether the component can be either recycled, reused or refurbished; and the components needing frequent maintenance. The application domain, such as electronics and automotive database, includes the components that need grouping (the collection of components to form the sub-assembly) while disassembling; the specific hierarchy of the components (for example, disassembling the cover of the gear casing before disassembling the gear); and the joint or fastener information (fasteners and the components disassemblability and the type of disassembly). The user requirements include minimal cost and time.
V. DISASSEMBLABILITY ANALYSIS

This design module consists of several steps: (1) Determining the disassemblability of components and (2) Analyzing all possible disassembly methods and the selection of an appropriate disassembly that best fits the user requirements.

A. Disassemblability

A component is disassemblable if it can be removed from the rest of the assembly. For example, in the assembly shown in Figure 3, the component A can be easily removed from the assembly, whereas component B is not disassemblable. Component B can be disassembled only after disassembling either component A or C.

![Figure 3. Example: disassemblability](image)

The geometrical information, such as mating faces and visibility maps are used to determine the disassemblability of a component. The disassembly directions for a component with respect to its mating faces are mapped onto a Gaussian sphere for 3D assemblies. The disassembly directions intersect to get the resultant disassembly direction for a 1-disassemblable component. Figure 4 shows the disassembly directions of component C₂ from the mating faces M₁ and M₂ of component C₁. When considering only the mating face M₁, the disassembly direction for component C₂ is d₁. When considering the mating face M₂, the direction is d₂. The resultant disassembly direction for the component C₂ is the intersection of d₁ and d₂. This is shown as dᵣ. If dᵣ is null then the component is not disassemblable. In the test assembly shown in Figure 3, the disassembly directions of component B, considering only M₁, M₂, M₃ and M₄ are d₁, d₂, d₃ and d₄ respectively, are shown in Figure 5a. The dᵣ is null, showing that the component B is not disassemblable. Similar analysis for component A is shown in Figure 5b. As dᵣ is not null, component A is disassemblable.

![Figure 4. Finding the disassembly directions](image)

![Figure 5a. Disassemblability of B in Figure 3.](image)

![Figure 5b. Disassemblability of A in Figure 3.](image)

B. Disassembly method selection

There are several possible disassembly methods for removing a component from a given assembly. Figure 6 shows the classification of disassembly methods into different classes.

**Disassembly Classification**

- based on number of linear motions
  - required
  - m-disassembly
  - 1-disassembly
- based on number of components that need to be disassembled
  - Direct disassembly
  - Indirect disassembly
- based on number of components disassembled at a time
  - Sequential disassembly
  - Parallel disassembly
- based on disassembling a component
  - Monotonic disassembly
  - Non-monotonic disassembly
  - is partial or full
- based on disassembling a component disassembled from an assembly
  - Complete disassembly
  - Selective disassembly
- based on disassembling a component is by destructive means or not
  - Destructive disassembly
  - Non-destructive disassembly

**Figure 6. Disassembly classification**

**m-disassembly:** A component motion is m disassemblable if the component requires m continuous motions to be removed from the assembly.

**Direct and indirect disassembly:** A component is directly disassemblable if the component can be removed from the assembly without removing other components. Otherwise the component is indirectly disassemblable.

**Sequential and parallel disassembly:** In sequential disassembly, only one component is removed from the assembly at a time. But in parallel disassembly, several components or a sub-assembly are removed from the assembly at a time.
**Monotonic and non-monotonic disassembly:** In monotonic disassembly the component is completely removed from the assembly. Conversely, non-monotonic disassembly requires partial disassembly of one or more components.

**Selective and Complete disassembly:** Complete disassembly occurs when all components are separated from one another. Selective disassembly occurs only when some components are removed.

**Non-Destructive and Destructive disassembly:** In non-destructive disassembly, none of the components of an assembly are destroyed. However, if one or more components are destroyed then the disassembly method is destructive disassembly.

Disassembly method selection is carried out by analyzing all the possible disassembly methods for the given assembly. And then the disassembly method that best fits the user’s requirements is selected for disassembly analysis.

**VI. OPTIMAL DISASSEMBLY SEQUENCE**

Disassembly analysis consists of: (1) generating an optimal disassembly sequence and (2) disassembly directions generation for the components to be disassembled.

Disassembling a component from an assembly can be done in several sequences and paths, one of which is better, faster and less complicated. Finding the best possible sequence which satisfies both the specified user and environmental requirements involves the use of metrics. A metric is a non-dimensional parameter constructed for every objective variable. An objective function is formulated from the metrics and the relative importance between the objective variables. The objective variables and their relative importance are available from the knowledge-base. This objective function is used as a means of comparison in order to evaluate different design solutions for disassembly.

\[ \text{Metric } M_1 = f_1 * \frac{A_e}{T_e} \]
\[ \text{Metric } M_2 = f_2 * \frac{(W_t - W_c)}{W_t} \]
\[ F = f_1 * M_1 + f_2 * M_2 \]

where,
- \( A_e \) = Accessibility of the component of interest
- \( T_e \) = Maximum possible accessibility
- \( W_c \) = Weight of the component of interest
- \( W_t \) = Total weight of the assembly or sub-assembly
- \( f_1 \) = Relative importance (accessibility)
- \( f_2 \) = Relative importance (weight)

As an example, Figure 7 shows a test assembly for complete disassembly sequence generation. As different disassembly sequences are possible to disassemble all the components in the test assembly, the formulation of an objective function is necessary. A component with maximum \( M_1 \) value shows that the component’s accessibility is maximum compared to other components. Similarly, a component with maximum \( M_2 \) value shows that the component’s weight is minimum. The disassembly sequence is selected based on \( F \) value (equation 3). The component with the maximum \( F \) value is always selected at any given instant. The disassembly sequence for the test assembly shown in Figure 7 (with \( f_1 \) and \( f_2 \) being 0.8 and 0.2) is \( \{ C_1, C_2, C_3, C_4 \} \). The disassembly path generation is already discussed in section VA.

**VII. DESIGN RATING**

This design step involves: (1) Disassembly evaluation (2) Disassembly rating and (3) Design recommendations.

The disassembly evaluation involves evaluating the design for parameters such as cost and time in disassembling the components. Disassembly evaluation value allow designers to establish how well the product is designed with respect to parameters like cost and time.

The product design is rated based on how well the product is designed for disassembly operations and for comparison with identical designs. A typical rating index calculated is the Disassemblability Index (\( D_I \)).

\[ D_I = F_1 ( D_0, E_0, C_0, T_0, ...) \]  

where,
- \( D_0 \) : Number of components disassembled
- \( E_0 \) : Ease of disassembly
- \( C_0 \) : Complexity of path
- \( T_0 \) : Time taken for disassembly

The design recommendations are given to modify the product at the design stage. The design recommendations is based on design rating and attempts to recycle the product. Also it focuses on enhance the product design to minimize the disassembly cost and time involved in the overall product cycle.

**VIII. EXAMPLE**

This section presents the design steps involved in the disassembly analysis with an example. The example assembly taken for analysis is flange coupling assembly, which is shown in Figure 8a.
### A. Design step 1

**Product information**

1. No component should be destroyed.
2. Disassembly path should not be complicated.
3. The heavier component should be clamped.
4. Disassembly cost should be minimum.
5. Assembly will be clamped to the table.
6. No hazardous or chemically reactive material.
7. Rubber material will wear faster than other materials.
8. The assembly consists of steel, CI and rubber material.
9. No components need to be grouped.

The product information in 1 and 2 are for disassembly method selection. The information in 3 and 4 are modeled as objective variables. The information in 5 and 6 are modeled as geometric constraints for disassembly process. The information in 7, 8 and 9 are for component selection for disassembly operation.

**Component and application selection**

1. Disassembly of all components for reuse and refurbishing applications.
2. Disassembly of washer components for recycling and maintenance applications.

**Geometric constraints**

1. As there are no hazardous components, special precautions are not required.
2. As assembly is clamped to the table, downward disassembly direction is restricted.
3. The components need not be grouped as subassemblies.

**Objective variables**

1. Weight/Volume of components.
2. Accessibility of components.
3. Cost of disassembly.

### B. Design step 2

**Disassemble method**

1. Complete, non-destructive, non-monotonic disassembly for reuse and refurbishing.
2. Selective, non-destructive, non-monotonic disassembly for recycling and maintenance.

### C. Design step 3

**Objective function for complete disassembly**

Metric 1: Heavier components should be removed last. Metric 2: Accessibility should be maximized

**Objective function for selective disassembly**

Metric 1: The accessibility should be maximized
Metric 2: The number of components disassembled should be minimum
Metric 3: The volume of the component disassembled should be minimum

**Optimal disassembly sequence**

Complete disassembly sequence: \{C_6,C_5,C_7,C_6,C_5,C_3,C_4,C_2,C_1\}
Selective disassembly sequence: \{C_5,C_7,C_6,C_8\}

### D. Design step 4

The design of the flange coupling (design A) shown in Figure 8a is evaluated for disassembly cost and time for the identified disassembly sequence (both complete disassembly and selective disassembly sequence). The parameter $\mathcal{D}$ is computed to compare the design with alternatives. As an example, four possible alternative designs are shown in Figure 8b. Design A is better than design B, as the washers and nuts in design A can be more easily disassembled (accessibility is more) than design B. However, the fastener connections in design A are easily removable compared to design C and hence are rated as better design compared to design C. The $\mathcal{D}$ value for design A is better compared to design D as the number of components that need to be disassembled to remove each washer is two in design D, but in design A it is only one. Rating design A and design E for selective disassembly, one will conclude that the design E is better for selective disassembly as the nuts in design E need not be fully removed (non-monotonic disassembly) compared to design A. Hence design E is preferred for selective disassembly and rated as the better design compared to design A.
**Figure 8b. Design modifications**

**SUMMARY**

This paper presents a framework for a geometric virtual disassembly tool. The design modules in the virtual disassembly tool were discussed with an example of flange coupling assembly. This analysis is applicable for all electronic and mechanical products.

**REFERENCES**


