Advanced Engineering Informatics 26 (2012) 306–316

Contents lists available at SciVerse ScienceDirect

Advanced Engineering Informatics

journal homepage: www.elsevier.com/locate/aei

# Disassembly sequence structure graphs: An optimal approach for multiple-target selective disassembly sequence planning

Shana Smith *, Greg Smith, Wei-Han Chen

*Department of Mechanical Engineering, National Taiwan University, Taiwan, ROC*

ARTICLE INFO

*Article history:*
Received 16 February 2011
Received in revised form 24 November 2011
Accepted 30 November 2011
Available online 29 December 2011

*Keywords:*
DSSG
Optimal
Multiple target
Selective disassembly sequence planning
Disassembly sequence structure graph

ABSTRACT

Modern green products must be easy to disassemble. Specific target components must be accessed and removed for repair, reuse, recycling, or remanufacturing. Prior studies describe various methods for removing selective targets from a product. However, solution quality, model complexity, and searching time have not been considered thoroughly. The goal of this study is to improve solution quality, minimize model complexity, and reduce searching time. To achieve the goal, this study introduces a new 'disassembly sequence structure graph' (DSSG) model for multiple-target selective disassembly sequence planning, an approach for creating DSSGs, and methods for searching DSSGs. The DSSG model contains a minimum set of parts that must be removed to remove selected targets, with an order and direction for removing each part. The approach uses expert rules to choose parts, part order, and part disassembly directions, based upon physical constraints. The searching methods use rules to remove all parts, in order, from the DSSG. The DSSG approach is an optimal approach. The approach creates a high quality minimum-size model, in minimum time. The approach finds high quality, practical, realistic, physically feasible solutions, in minimum time. The solutions are optimized for number of removed parts, part order, part disassembly directions, and reorientations. The solutions remove parts in practical order. The solutions remove parts in realistic directions. The solutions consider contact, motion, and fastener constraints. The study also presents eight new design rules. The study results can be used to improve the product design process, increase product life-cycle quality, and reduce product environmental impact.



## 1. Introduction

Modern green products must meet economic, environmental, and social design constraints. To meet the constraints, products must be easy to disassemble. During their life cycle, products may be selectively disassembled to repair or replace parts. At end of life, products must be fully, partially, or selectively disassembled to recover, reuse, or recycle parts and materials [1,2]. Therefore, disassembly planning is an important part of the product design process.

During the design process, many different design options and disassembly plans must be considered. For even simple structures, the process can be computationally complex. Therefore, designers need effective, efficient disassembly planning methods, to solve the problem. Prior studies describe various methods for selective disassembly planning. However, solution quality, model complexity, and searching time have not been considered thoroughly.

In general, the goal of any disassembly planning method is to find an optimal solution, in minimum time. Most methods use disassembly graph (DG) models. Due to model complexity, they cannot guarantee that they will find an optimal solution (the overall best solution). They can only guarantee that they will find an optimized solution (the best solution found). Therefore, methods must be compared by solution quality, model complexity, and searching time.

The goal of this study is to improve solution quality, minimize model complexity, and reduce searching time. In this study, high quality solutions are optimized for number of removed parts, part order, part disassembly directions, and reorientations. Practical solutions remove parts in practical order. Realistic solutions remove parts in realistic directions. Physically feasible solutions consider contact, motion, and fastener constraints.

This study introduces a new DSSG model for selective disassembly planning, an approach for creating DSSGs, and methods for searching DSSGs. The DSSG model contains a minimum set of parts, with an order and direction for removing each part. The approach uses expert rules to choose parts, part order, and part disassembly directions, based upon physical constraints. The searching methods use rules to remove all parts, in order, from the DSSG.

* Corresponding author. Address: No. 1, Sec. 4, Roosevelt Road, Taipei, Taiwan, ROC. Tel.: +886 2 33662692; fax: +886 2 23631755.

*E-mail address:* ssmith@ntu.edu.tw (S. Smith).

1474-0346/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.aei.2011.11.003

The DSSG approach is an optimal approach. The approach improves solution quality, minimizes model complexity, and minimizes searching time. The approach creates a high quality minimum-size model, in minimum time. The approach finds high quality, practical, realistic, physically feasible solutions, in minimum time. The solutions are optimized for number of removed parts, part order, part disassembly directions, and reorientations.

This paper describes disassembly planning, prior studies, the goal of this study, the DSSG model, approach, and methods, time complexity, case studies, and eight new design rules.

## 2. Disassembly planning

Disassembly planning consists of two major steps, creating a disassembly model and generating disassembly sequences (disassembly sequence planning) [3]. Disassembly models are usually graphs. Graph nodes represent parts. Graph links represent constraints between the parts [4–10]. Parts may be components, which have specific design functions, or fasteners [8]. Graphs are generally converted into matrices for computer processing [4].

Disassembly sequence planning consists of searching a graph (moving from node to node along individual links in the graph) to find optimal paths [5–8]. Optimal paths have maximum quality and minimum length. Therefore, model quality and complexity affect solution quality and searching time. Graphs that contain more information improve solution quality. Graphs that contain less information reduce searching time.

### *2.1. Prior models*

Prior studies describe two graph models for disassembly planning, disassembly graphs and disassembly constraint graphs. This study shows that a new graph model is needed.

#### *2.1.1. Disassembly graphs*

Disassembly graphs (DGs), such as non-directional blocking graphs (NDBGs), contain $n_d$ graphs, one for each disassembly direction [4–10]. Each graph contains $n_p$ nodes and $O(n_p^2)$ links. Nodes represent all parts, links represent all physical constraints, graphs represent all disassembly directions, and directions are determined by all part surfaces. Therefore, DGs can be used to find high quality solutions.

However, DG model complexity and searching time are high. DG model complexity is $O((n_d \cdot n_p)! \cdot n_o)$ paths, for $n_o$ optimization criteria. Minimum time complexity for creating a DG is $O(n_d \cdot n_p^2)$ [4]. Time complexity for searching all paths is $O((n_d \cdot n_p)! \cdot n_o)$. Time complexity for searching all paths, from $n_t$ targets to $n_b$ boundary parts, is $O(n_t \cdot (n_d \cdot n_p)^{n_p} \cdot n_o)$.

In Fig. 1, with a DG, components 5, 1, 2, 8, and 9 can be removed, in order. The disassembly directions for all fasteners and components are realistic and feasible. For $n_t = 3$, $n_d = 6$, $n_p = 19$, and $n_o = 2$, model complexity is $O((6 \cdot 19)! \cdot 2) = 5 \cdot 10^{186}$ paths. Time complexity for searching all paths, from targets to boundary parts, is over $2 \cdot 10^{26}$ years, at 1 µs per path.

#### *2.1.2. Disassembly constraint graphs*

Disassembly constraint graphs (DCGs), such as removal influence graphs (RIGs), contain one graph [5,11]. The graph contains $n_p$ nodes and $O(n_p^2)$ links. Nodes represent all parts, links represent all disassembly constraints, and the graph does not contain disassembly directions. Therefore, DCGs cannot be used to find high quality solutions.

However, DCGs reduce model complexity and searching time. DCG model complexity is $O(n_p! \cdot n_o)$. Time complexity for extracting a DCG from a DG is $O(n_d \cdot n_p^2)$. Time complexity for searching all paths, between $n_b$ boundary parts and $n_t$ targets, is $O(max(n_b, n_t) \cdot n_p^3 \cdot n_o)$.

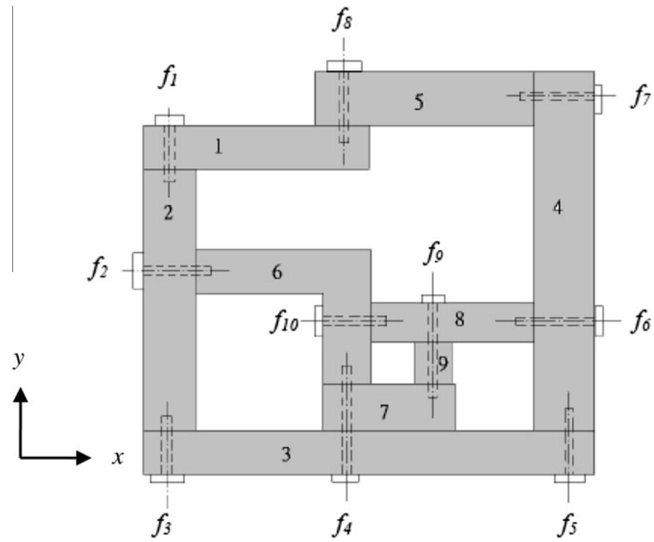

**Fig. 1.** Example assembly.

In Fig. 1, with a DCG, components 2, 8, and 9 can be removed, in order. The disassembly directions for $f_9$, 8, and 9 are unrealistic and infeasible. However, for $n_t = 3$, $n_d = 6$, $n_b = 13$, $n_p = 19$, and $n_o = 2$, model complexity is $O(19! \cdot 2) = 2.4 \cdot 10^{17}$ paths. Time complexity for searching all paths, between boundary parts and targets, is 178 ms, at 1 µs per path.

### *2.2. Prior methods*

Prior studies describe three rule-based graph searching methods for selective disassembly sequence planning. This study shows that a new rule-based graph searching method is needed.

#### *2.2.1. Smith et al.'s approach*

Smith et al.'s approach [8] creates a DG. The approach uses rules to search the DG, from targets to boundary parts, along all paths that have higher qualities than other complete paths. The approach calculates qualities with a multi-criteria function, to reduce $n_o$ to one.

The approach finds high quality solutions for general 3D structures. The approach reduces model complexity to $O((n_d \cdot n_p)!)$ paths. The approach reduces time complexity for searching a disassembly graph to $O(n_t \cdot (n_d \cdot n_p)^{n_p})$. However, searching time is still high.

For 3D structures, minimum time complexity for creating and searching a DG is $O(n_d \cdot n_p^2)$. Minimum time complexity for searching a DG is $O(n_t \cdot (n_d \cdot n_p)^{np})$, for Smith et al.'s approach. Therefore, Smith et al.'s approach does not search a disassembly graph in minimum time.

#### *2.2.2. The wave propagation approach*

The wave propagation approach [12] extracts a DCG (RIG) from a DG (NDBG). The approach uses rules to search the DCG, in waves, from both boundary parts and targets, to create a partial DCG, and searches the partial DCG to find solutions.

The approach finds solutions for 3D structures. However, the solutions may be unrealistic or infeasible. DCG model complexity is $O(n_p! \cdot n_o)$ paths. Time complexity for creating a partial DCG is not given. Time complexity for searching the partial DCG is $O(2^{n_t} \cdot n_p^2)$