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Illustrating the disassembly of 3D models

Jianwei Guo [a], Dong-Ming Yan [a,b,*], Er Li [d], Weiming Dong [a], Peter Wonka [b,c], Xiaopeng Zhang [a]

[a] NLPR-LIAMA, Institute of Automation, Chinese Academy of Sciences, China
[b] GMSV Center, King Abdullah University of Science and Technology, Saudi Arabia
[c] Department of Computer Science and Engineering, Arizona State University, USA
[d] State Key Laboratory of Computer Science, Institute of Software, Chinese Academy of Sciences, China

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ABSTRACT

We present a framework for the automatic disassembly of 3D man-made models and the illustration of the disassembly process. Given an assembled 3D model, we first analyze the individual parts using sharp edge loops and extract the contact faces between each pair of neighboring parts. The contact faces are then used to compute the possible moving directions of each part. We then present a simple algorithm for clustering the sets of the individual parts into meaningful sub-assemblies, which can be used for a hierarchical decomposition. We take the stability of sub-assemblies into account during the decomposition process by considering the upright orientation of the input models. Our framework also provides a user-friendly interface to enable the superimposition of the constraints for the decomposition. Finally, we visualize the disassembly process by generating an animated sequence. The experiments demonstrate that our framework works well for a variety of complex models.

1. Introduction

The disassembly of 3D models is a process that involves the decomposition of a given assembled model into individual parts, without breaking any part. Designing a disassembly is also an important concept of Green Design. As discussed by Knoth et al. [1], for a product, “almost all end-of-life possibilities – upgrade, reuse, recycling of materials – require some form of disassembly.” Disassembly can provide an optimal solution for repair and maintenance, such as for the replacement of a model's damaged parts or performing equipment maintenance. Furthermore, product design for assembly can be facilitated by performing disassembly analysis. Disassembly analysis either leads to a feasible assembly sequence (by reversing the disassembly steps) or alerts the designers of an assembly problem in the product design that has to be fixed [2].

As mentioned above, disassembly has numerous applications in the domain of industrial engineering. However, currently disassembly remains mainly a manual process [3]. Complex 3D objects are typically composed of numerous components, and understanding the spatial relationships of parts within the assembly is difficult. Thus, skilled humans are needed to generate disassembly sequences with specific tools.

To the best of our knowledge, research on disassembly in computer graphics is just at the beginning. Existing works focus on designing assembly sequences [4] and generating exploded view diagrams [5,6]. In these papers, the authors use blocking constraints to derive moving directions and the ordering of individual parts. We build on these initial works and improve them for our purposes. First, we noticed that solving the disassembly problem based only on blocking constraints is insufficient. Stability and the needs of illustration must also be considered. Second, previous works also exhibit a number of limitations, for example, the moving directions of one part contain only six directions, and the creation of part hierarchies for an assembly is performed manually.

In this paper, we present a framework for the automatic disassembly of 3D models and provide several visualization tools to illustrate the process. In our approach, we use the geometric properties of individual parts to retrieve their motion parameters (e.g., translational axis, separation direction and distance) and compute the hierarchical structure of the model. We observed that using the blocking constraint to determine the disassembly order for sub-assemblies might be unstable. To overcome this issue, we provide an interface that enables users to specify some fixed parts (e.g., bottom grey parts in Fig. 1). We then use this information to perform a top-down and constrained disassembly. Finally, we develop visualization methods to illustrate the disassembly process automatically.

The contributions of our work include: (1) an improved method for the calculation of the blocking relationships between parts based on their geometric properties; (2) an automatic

* Corresponding author at: NLPR-LIAMA, Institute of Automation, Chinese Academy of Sciences, China.
E-mail addresses: jianwei.guo@nlpr.ia.ac.cn (J. Guo), yandongming@gmail.com (D.-M. Yan), lier@ios.ac.cn (E. Li), weiming.dong@ia.ac.cn (W. Dong), pwonka@gmail.com (P. Wonka), xiaopeng.zhang@ia.ac.cn (X. Zhang).

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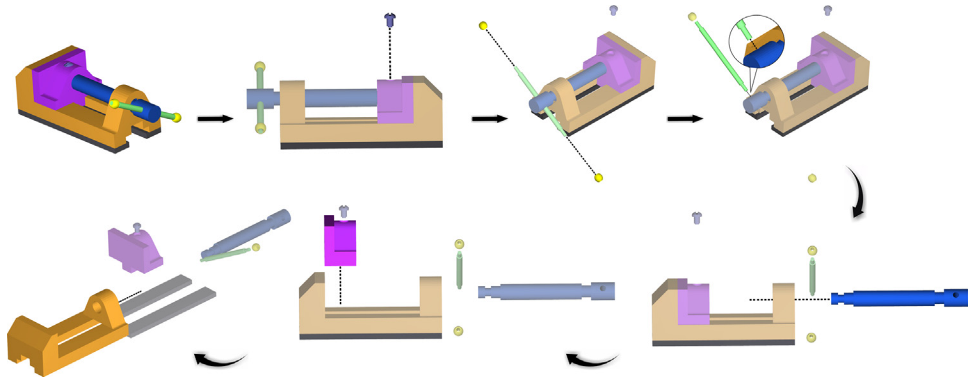

Fig. 1. Disassembly sequence of the bench vice model generated by our framework.

technique that clusters individual parts into groups; and (3) new constraints for stable disassembly.

1.1. Related work

Although assembly planning has been a classic problem for a long time, studies on disassembly only became popular in recent decades and in the area of robotics [1–3]. The input of their system includes the geometrical models of products and the different features of parts stored in a database (e.g., the type of each part and the style of contacts between parts). Based on such information, a disassembly theory is applied to compute the optimal disassembly sequence from all possible candidate solutions. However, these plans are only used by robotic machines and do not present any ways to depict disassembly operations for humans.

Assembly/disassembly planning. In the field of computer graphics, many works have focused on assembly planning and visualization for 3D models [7,4,8,9]. For example, Agrawala et al. [4] combine the planning with presentation techniques to design effective step-by-step assembly instructions by automatically determining the separation order and directions. The limitation of their work is that the direction to which one part can move only contains six principal directions (consider the green oblique cylinder in Fig. 1). The work of Xin et al. [9] illustrates the puzzle assembly or disassembly process, in which they aim to design and create burr puzzles from 3D models. Song et al. [8] develop a constructive approach for generating recursive interlocking puzzles. However, only one specific sequence of assembly and disassembly exists for such an interlocking puzzle, making it unsuitable for general mechanical assemblies.

Exploded views. The exploded view diagram is a powerful tool used to convey the spatial relationships between components within complex objects. To generate such diagrams, illustrators design many methods to explode one part from others with the proper direction and distance. Agrawala et al. [4] and Li et al. [6] use blocking information to infer the exploded directions. The latter also includes an interface that enables users to view the parts of interest. However, the parts of their input models are organized into a hierarchy manually beforehand. Li et al. [5] present a system to allow interactive cutaway illustrations for complex 3D models. Tatzgern et al. [10] generate compact explosion diagrams by finding similar sub-assemblies and only rendering the representatives. Most of these works generate traditional static diagrams or provide an interactive way that requires user's participation.

Shape analysis. Shape analysis has been demonstrated to help deduce the characteristic properties of man-made objects. Recently, understanding the higher-level representations of 3D models has received considerable interest (see survey [11]), including symmetry detection [12–14], upright orientation inference [15] and shape abstractions [16]. Benefitting from these techniques, a wide spectrum of applications are spawned, such as shape manipulation [17–19], shape synthesis [20], motion analysis [21–24] and computational furniture design [25]. In addition, many works focus on the analysis of individual parts within an input model, which are similar to our framework. Mitra et al. [22] analyze the interactions and motions of mechanical parts based on recent advances in geometric shape analysis. Jain et al. [20] present a system to interpolate new shapes from two database shapes by decomposing input shapes and recombining individual parts according to constraints deduced through shape analysis.

2. Principles for disassembly

We extend the conventions from traditional illustrations [26,27,6] for mechanical assemblies to principles that are suitable for the disassembly process. Although disassembly is distinct from assembly, we can still obtain some heuristics from the assembly process [4], because the sequence of assembly is usually the reverse of that of disassembly.

Hierarchy of parts. Generally, a mechanical assembly can be divided into several sub-assemblies. During the disassembly process, if a sub-assembly can be removed entirely, people prefer that the parts within this sub-assembly are disassembled later after the sub-assembly is separated.

Stability. In actual disassembly studies, stability analysis is used to investigate whether sub-assemblies can be collapsed by gravity. Some parts usually perform a supporting function in an assembly. Such holding parts should be fixed, and unstable sub-assemblies should be pruned out early in the disassembly process.

Step-by-step operations. Disassembly sequences are listings of subsequent disassembly operations. Showing all these disassembly operations in a single static diagram hinders users from identifying the order in which parts are removed. On the other hand, depicting the disassembly process step-by-step using animation is easy to understand and follow.

Visibility. Visibility serves an important function in visualization. The sub-assembly being removed must be visible to users. A notable exception is that not all the parts in a symmetry group can be seen simultaneously.

Non-destructive disassembly. Depending on the goals, disassembly has two main types [28]. One is "destructive disassembly", in which a part is removed from a previously assembled product by destroying or damaging some other parts of the product. The other is "non-destructive disassembly", in which each of the parts can be removed without affecting any of the others. Our work focuses on non-destructive disassembly for the purpose of reuse, such as equipment maintenance and recycling of materials.