Title:
Streamlining Educational Product Teardown through Affordable Reverse Engineering

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Introduction:
Product teardown is a critical component of engineering design education, offering students invaluable insights into the functionality and composition of various electromechanical products such as power tools and small household appliances [1]. These exercises are traditionally performed through the physical disassembly of products, typically at the end of their lifecycle. As such, product teardown demands significant resources, including a dedicated workshop space, tools, supervision, and the physical products themselves. The financial burden, coupled with the inherent limitation of a one-time use of products that often become unusable post-disassembly, emphasizes the inefficiency of this traditional method. Another significant challenge of the conventional approach is the lack of repeatability and sustainability. Each academic year, educators face the daunting task of replicating the teardown exercises for new cohorts of students, which is both resource-intensive and environmentally taxing (see, e.g., [2] for an extensive overview of challenges). These challenges raise questions about the long-term viability of physical product teardowns in educational settings.

In response to these challenges, this paper proposes a shift towards a virtual teardown, leveraging the advancements in digital technology. The virtual teardown, facilitated through the disassembly of detailed 3D models, offers a sustainable, repeatable, and flexible approach. It is argued that the teardown of virtual products reduces the logistical constraints and costs associated with physical teardowns, enabling a more inclusive and accessible learning experience for students. Virtual approaches to the analysis of physical artifacts have already been tested in various domains [3-4], including engineering design [5]. However, despite their advantages, virtual teardowns hinge on the availability of high-quality, detailed 3D models that accurately represent real-world products, both in geometry and texture. The main challenge lies in the scarcity of models that exhibit the right amount of complexity required for understanding product functionality. For example, the existing online 3D model libraries normally provide merely superficial models of products' exteriors without the necessary textures or internal components. Additionally, the available 3D models are often not directly compatible with standard CAD software used by the students, meaning that they would have to either learn new software or convert the models into formats that can be opened using CAD systems, which, in return, may result in errors and wrong representations.

Addressing this gap, the presented research focuses on the development of an affordable and accessible reverse engineering methodology to create comprehensive 3D CAD models that can be used for virtual product teardowns. The methodology is intended for both educators and students, who can apply it to digitalize product assemblies for sustainable, scalable, and effective execution of product teardown and function analysis.

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Methodology

Previous experience in both physical and virtual product teardown was instrumental in identifying and formulating the main requirements necessary for developing the reverse engineering methodology. The following requirements must, therefore, be met to enable satisfactory and accessible replication of product teardown in the virtual environment:

- The methodology should be feasible using affordable and easy-to-use hardware and software.
- The final models must be structured as assemblies with separable components and allow for error-free import and manipulation in 3D CAD software.
- The methodology should be applicable to products of different shapes, sizes, and materials.
- The virtual components in the final model should closely resemble their real counterparts in form and color/texture, ensuring overall visual similarity rather than prioritizing geometrical precision and accuracy.
- Local geometrical precision is critical for interfaces between components and should clearly reflect their degrees of freedom in relation to the rest of the product assembly.

The core idea of the proposed methodology is to engage students in creating a 3D CAD assembly model of a product through a combination of reverse engineering techniques. This includes the use of affordable 3D scanning devices (both handheld and tabletop), photography, and 3D CAD modeling. The modeling involves three primary steps: (1) obtaining the components' geometrical models, (2) the application of color and/or texture, and (3) assembly of components into the final model. The simplified overview of the methodology in the form of a workflow is shown in Fig. 1.

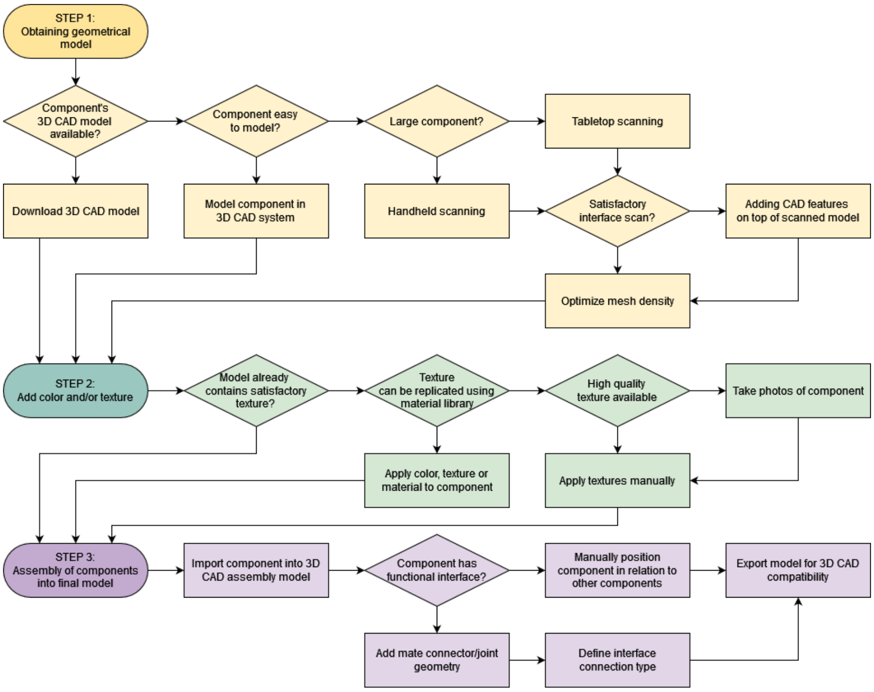

Fig. 1: Overview of the proposed reverse engineering methodology.

For some components, it must first be checked whether their 3D CAD model is already available. This is typically the case for some standard and off-the-shelf components. If such a model exists, it is downloaded for use. When no model is available, the complexity of the component is assessed. For components that are simple and easily modeled, direct modeling in a 3D CAD system is conducted.

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3D scanning (or photogrammetry as an alternative) must be employed for all components that do not match the abovementioned criteria, meaning that their geometry is too complex to be modelled directly. Handheld scanning is suitable for large components, and different scanners may be used for capturing various geometrical aspects. Tabletop scanners with a rotary table are ideal for smaller components and can sometimes scan multiple parts simultaneously for later separation into individual models. While this paper cannot delve deeper into the specifics and best practices of 3D scanning, the process is already sufficiently studied and documented across various other sources.

If the initial scan does not effectively capture certain features, such as holes or ribs, additional manually modeled CAD features are added on top of the scanned model to refine the representation. Finally, the geometric model, which is ultimately a mesh, can be optimized for better performance, without significantly affecting the component's appearance.

The texturing of the final model is contingent on the capabilities of the scanning equipment. Scanners that can capture color information directly integrate this into the model, closely replicating the original texture. When color capture is not possible, or if the component has been treated with matting spray (if they have dark, transparent, or shiny surfaces), textures are manually applied after scanning. If the component has a uniform color or texture which is available in the CAD system's library, it can be applied directly to the model. If this does not provide satisfactory results, one must acquire or take photographs of the component and manually apply them as textures (i.e., as decals).

The final step involves assembling the individual components into a comprehensive assembly model, ensuring that the components are correctly positioned, and mate connections or joint geometry are defined for components with functional interfaces and specific degrees of freedom. This creates a final model that is ready for virtual manipulation and teardown.

<u>Case Study</u>

The product selected to demonstrate the practical application of the proposed reverse engineering methodology was a leaf blower (Fig. 2, left), a relatively complex electromechanical device comprising multiple components that would provide a comprehensive challenge for the methodology.

The case study involved an engineering design student who undertook the task of modeling the product using a combination of 3D scanning and CAD modeling techniques. The student utilized various scanning devices available at the Design Laboratory – CADLab of the Faculty of Mechanical Engineering and Naval Architecture, including the Scan Dimension SOL PRO, Creality CR-Scan 01, Revopoint POP 2, and Tupel 3D Dental. These devices were chosen based on the size and complexity of the components to be scanned, employing structured light technology and laser triangulation for capturing the geometrical data of the product's components.

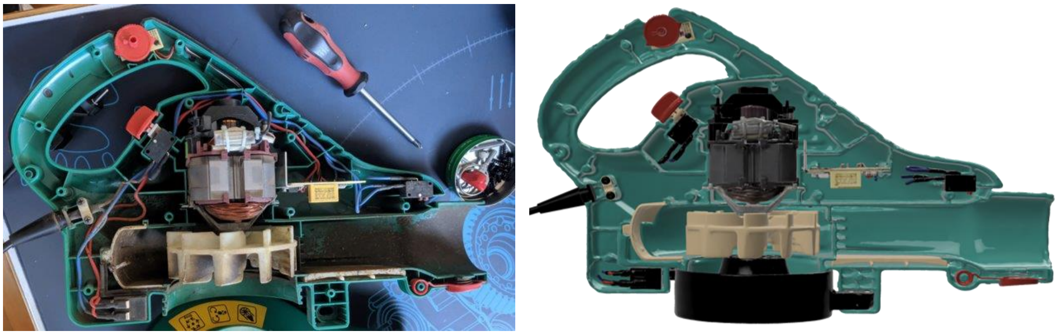

Fig. 2: Partially disassembled physical product on the left and its virtual replica on the right.

In addition to the scanning equipment, the student utilized standard computing hardware to handle the demands of the 3D scanning and modeling processes. For processing the point cloud data, surface

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reconstruction, and texturing, the student used Meshlab software, while for assembly creation, mesh optimization, and sharing of the final model, they employed Autodesk Fusion 360. The cross-section of the final model is shown in Fig. 2, right. Examples of components and how they were reverse-engineered for the purpose of product teardown are shown in Tab. 1.

Physical component	Specification	Process	Virtual component
	50 x 55 x 60 mm, matte surface	Scanned on a rotary table, groove added in CAD system, material color applied from the CAD system's library	
	Ø50 x 155 mm, reflective surfaces, different materials	Pretreated with matte spray, scanned on a rotary table, photographed, and manually textured	
	460 x 110 x 300 mm deep grooves and ribs, combination of dark and reflective surfaces	Pretreated with matte spray, hand scanned with two scanners (faster for global geometry and slower for detail features), photographed and manually textured	
	40 x 30 x 25 mm, reflective surface	Pretreated with matte spray, scanned on a rotary table, original mesh density retained for textured labels, material color applied from the CAD system's library	
	90 x 35 x 35 mm, flexible component, dark and reflective surface	Pretreated with matte spray, scanned on a rotary table, pins and cable modelled in CAD system, material color applied from the CAD system's library	

Tab. 1: Examples of components and associated reverse engineering processes.

The leaf blower assembly was divided into four main subassemblies: housing, switch, filter, and drive assembly. Each subassembly was created by importing individual components into Fusion 360 and defining their spatial relationships and connections. These were not only visually represented but also functionally structured to reflect the actual product's operation. The components were positioned correctly within each assembly, and connections were made using mate features in the CAD software to replicate the physical interfaces and interactions between parts (see Fig. 3).

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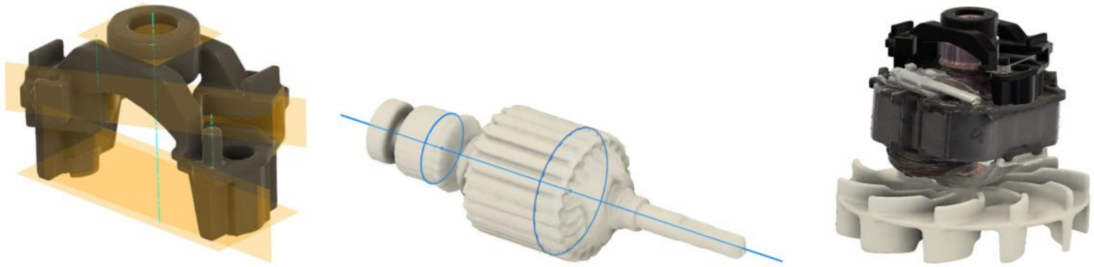

Fig. 3: Construction geometry and mates are used to define component interfaces and interactions.

For example, where components interfaced with each other, construction geometry was used to define the precise location of contact and the degrees of freedom necessary for realistic movement within the assembly. The student ensured that each component was fixed in space and derived other subassemblies to achieve the desired component tree structure within the assembly model.

Conclusions

The described example demonstrates how the proposed methodology for creating virtual assembly models for design education enables comprehensive virtual product teardowns and functional analysis. The reverse engineering approach encourages the decomposition of both physical products (in order to digitalize individual components and their interfaces) and virtual products (to perform functional, structural, and other types of analyses). These types of activities are essential in addressing the need for new practices that will motivate engineering students and provide them with skills necessary for the adaption to the ever-changing field [6]. Additionally, the proposed methodology is aligned with the trends of incorporating virtual activities in engineering education and addresses the calls for modernizing education through digital technologies (such as digital twins and virtual reality) and digital skills [7].

Looking ahead, the potential expansion into virtual reality promises to enhance this methodology by offering a more immersive learning experience. Virtual reality's inherited compatibility with visualization and CAD tools could significantly elevate students' engagement and foster a deeper understanding, which can ultimately lead to more independent and efficient problem-solving skills [8].

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