3-2015

Disassembly Sequence Evaluation: A User Study Leveraging Immersive Computing Technologies

Leif P. Berg
Iowa State University, lpberg@iastate.edu

Sara Behdad
SUNY University at Buffalo

Judy M. Vance
Iowa State University, jmvance@iastate.edu

Deborah Thurston
University of Illinois at Urbana-Champaign

Disassembly Sequence Evaluation: A User Study Leveraging Immersive Computing Technologies

Abstract

As interest in product recovery, reuse, and recycling rises, planning and evaluating disassembly sequences are becoming increasingly important. The manner in which a product can be taken apart strongly influences end-of-life (EOL) operations and costs. Early disassembly planning can also inform non-EOL processes including repair and routine maintenance. Recently, research has concentrated on creating optimization algorithms which automatically generate disassembly sequences. These algorithms often require data that are unavailable or estimated with high uncertainty. Furthermore, industries often employ CAD modeling software to evaluate disassembly sequences during the design stage. The combination of these methods result in mathematically generated solutions, however, the solutions may not account for attributes that are difficult to quantify (human interaction). To help designers better explore and understand disassembly sequence opportunities, the research presented in this paper combines the value of mathematical modeling with the benefits of immersive computing technologies (ICT) to aid in early design decision making. For the purposes of this research, an ICT application was developed. The application displays both 3D geometry of a product and an interactive graph visualization of existing disassembly sequences. The user can naturally interact with the geometric models and explore sequences outlined in the graph visualization. The calculated optimal path can be highlighted allowing the user to quickly compare the optimal sequence against alternatives. The application has been implemented in a three wall immersive projection environment. A user study involving a hydraulic pump assembly was conducted. The results suggest that this approach may be a viable method of evaluating disassembly sequences early in design.

Disciplines

Computer-Aided Engineering and Design | Manufacturing

Comments

This article is from *Journal of Computing and Information Science in Engineering* 15 (2015): 1, doi:10.1115/1.4028857. Posted with permission.

Leif P. Berg
Mechanical Engineering Department,
Iowa State University,
Ames, IA 50011
e-mail: lpberg@iastate.edu

Sara Behdad
Assistant Professor
Mechanical and Aerospace
Engineering Department,
Industrial and Systems
Engineering Department,
University at Buffalo, SUNY,
Buffalo, NY 14260
e-mail: sarabehd@buffalo.edu

Judy M. Vance[1]
Professor
Fellow ASME
Mechanical Engineering Department,
Iowa State University,
Ames, IA 50011
e-mail: jmvance@iastate.edu

Deborah Thurston
Professor
Fellow ASME
Industrial and Enterprise Systems
Engineering Department,
University of Illinois at Urbana-Champaign,
Urbana, IL 61820
e-mail: thurston@illinois.edu

Disassembly Sequence Evaluation: A User Study Leveraging Immersive Computing Technologies

As interest in product recovery, reuse, and recycling rises, planning and evaluating disassembly sequences are becoming increasingly important. The manner in which a product can be taken apart strongly influences end-of-life (EOL) operations and costs. Early disassembly planning can also inform non-EOL processes including repair and routine maintenance. Recently, research has concentrated on creating optimization algorithms which automatically generate disassembly sequences. These algorithms often require data that are unavailable or estimated with high uncertainty. Furthermore, industries often employ CAD modeling software to evaluate disassembly sequences during the design stage. The combination of these methods result in mathematically generated solutions, however, the solutions may not account for attributes that are difficult to quantify (human interaction). To help designers better explore and understand disassembly sequence opportunities, the research presented in this paper combines the value of mathematical modeling with the benefits of immersive computing technologies (ICT) to aid in early design decision making. For the purposes of this research, an ICT application was developed. The application displays both 3D geometry of a product and an interactive graph visualization of existing disassembly sequences. The user can naturally interact with the geometric models and explore sequences outlined in the graph visualization. The calculated optimal path can be highlighted allowing the user to quickly compare the optimal sequence against alternatives. The application has been implemented in a three wall immersive projection environment. A user study involving a hydraulic pump assembly was conducted. The results suggest that this approach may be a viable method of evaluating disassembly sequences early in design. [DOI: 10.1115/1.4028857]

1 Introduction

In the course of executing routine maintenance or repair, a product may need to be partially or fully disassembled. When products approach EOL, a variety of challenges arise. In many cases, components can be reused or recycled, so a product disassembly process is required. Additionally, some components may have inherent value such that the primary objective of disassembly is the extraction of such a component.

Disassembly sequences are defined as a set of subsequent disassembly operations for the separation of an assembly into its subassemblies [1]. Disassembly and assembly are strictly disparate processes. Assembly operations are not always reversible, and the value added in the disassembly process is typically lower than the obtained value in assembly; therefore, there are situations when partial disassembly is preferred to complete disassembly, especially when disassembly is performed for maintenance or component recovery. In addition, in disassembly planning, significant uncertainty exists with regard to the quality of the parts. Further, compared to assembly planning, there tend to be more sequence alternatives when performing disassembly. Even a small assembly with only a few parts may have many different possible disassembly sequences.

Disassembly planning often involves multiple objectives and considerations including: disassembly time, cost, and potential for damage. For products that require disassembly, EOL disassembly may account for significant product take-back costs. Considering disassembly processes early in the product design process provides opportunities to evaluate and explore multiple methods of disassembly leading to improved designs.

The generation and evaluation of disassembly sequences can be explored using optimization methods, CAD tools, or physical prototypes. Optimization methods seek to arrive at an optimum disassembly sequence based on input and the formulation and solution of the optimization problem. The solution is only as valid as the accuracy of the system modeling and the suitability of the optimization method with the particular use case. CAD software allows designers to examine geometric constraints that dictate disassembly paths but neglect to account for the physical interaction of the disassembly operator. Physical prototypes can be used to produce experience-guided disassembly sequences; however, they are often not available in the early design phase.

This research explores the use of ICT in disassembly sequence planning. ICT supports user interaction with virtual design configurations in increasingly natural ways to achieve an immersive lifelike design experience. The ICT approach differs from traditional mouse and keyboard techniques in that it supports testing of virtual design alternatives through natural and context-based human interactions. Visual feedback is presented to a designer through stereoscopic viewing, resulting in the perception of a three dimensional workspace. Real-time position tracking coupled with haptic (force feedback) devices enable the designer to interact with the virtual products using natural human motions. Localized audio feedback increases the realism of the simulated environment. These technologies can be leveraged to simulate assembly and disassembly operations without the need for physical prototypes. Additionally, they support exploration of potential alternatives and evaluation of multiple cost-effective approaches.

[1]Corresponding author.

Contributed by the Design Engineering Division of ASME for publication in the Journal of Computing and Information Science in Engineering. Manuscript received April 2, 2014; final manuscript received October 16, 2014; published online November 7, 2014. Assoc. Editor: Joshua D. Summers.

Previous work has only begun to examine the coupling of traditional disassembly sequence planning methods with the real-time potential of ICT [2–5]. In attempts to further investigate this area the authors have designed, implemented, and evaluated an ICT application in a large-scale projection screen-based immersive environment.

The paper is outlined as follows: Section 2 will present related background research. The ICT application is described in Sec. 3. A user study is presented in Sec. 4, with results in Sec. 5. Discussion and conclusions are presented in Secs. 6 and 7.

2 Background and Motivation

Interest in disassembly sequence planning is rapidly increasing due to its critical role in green product design. Various algorithms, methods, and software tools have been introduced to help designers and remanufacturers determine the disassembly sequence while considering cost-based criteria. The methods include graphical methods [6–8], mathematical models [1,9–11], heuristics [12–14], and multicriteria analysis [11,15] techniques. These methods generally fail to leverage the knowledge of designers, maintenance, or remanufacturing experts in the process of generating disassembly sequences. Disassembly planning research has frequently employed graph models to represent product architecture, collect and record relevant product information, and illustrate feasible disassembly sequences [16–18]. Several implementations of these graphs include adjacency graphs, Petri Net, AND/OR graphs, and precedence graphs [19–21]. Graphical representations of feasible disassembly operations are commonly used as input parameters to mathematical models to generate optimum disassembly sequences. A complete disassembly graph is presented in Fig. 1 showing all possible disassembly sequences for a six piece assembly. Individual components are labeled with capital letters: B, G, P, R, T, and Y. The research presented here will explore the use of graph models to guide experts in disassembly sequence planning.

The use of ICT environments for the simulation of manual assembly tasks, a critical functionality for disassembly simulation, has been the concentration of a significant amount of research. In order to better understand the ease of part handling and part insertion tasks, Gupta et al. [22] designed and implemented a virtual environment with the ability to simulate physical part interaction. They discovered that tasks performed by users in the virtual environment took about twice as long as when performed using physical models. Angster and Jayaram [23] described the system requirements of a virtual reality (VR) system which allowed users to grasp virtual parts with an instrumented glove. Assembly constraints and object interference checking were among the virtual assembly features. The design of the system was initially implemented into an application called VEDAM. In a similar effort, Jayaram et al. [24] developed a virtual assembly application called VADE which allowed users to perform manual virtual assembly. In 2001, Jayaram et al. [25] describe the hardware and software challenges involved in employing ICT systems to real world engineering problems, specifically the challenges that exist in creating accurate graphical representations of product assemblies and the resulting clearance-checking issues that arise. Seth et al. [26] described the design and implementation of a dual-hand assembly system which included the use of haptic devices. Their application implemented an assembly feature called subassembly; the ability to manipulate more than one part simultaneously. Tching et al. [27] presented a two-part virtual assembly method combining kinematic constraints and virtual guiding fixtures. Geometry is first aligned with the aid of virtual fixtures followed by a kinematic constraint to assist in the assembly task. Initial evaluations were completed using a peg and hole insertion task. More recently, Seth et al. [28] suggested the promise of a hybrid part interaction algorithm combing physics and constraint-based modeling.

The use of ICT for assembly training has also been the topic of notable research. Boud et al. [29] emphasized the potential of ICT environments in a water pump assembly task. Participants either trained with traditional engineering and assembly drawings or various VR apparatuses. Both the VR and AR (augmented reality) conditions out-performed the use of traditional engineering drawings. Later in 2009, Sung et al. [30] describe a system that automatically modeled design processes through data logging. An expert user's tasks are tracked and analyzed. Design knowledge extracted during an expert task execution can be presented to novice designers performing similar design tasks.

Past research has focused on the use of ICT for assembly planning and training. The research presented here focuses on the specific process of disassembly. It seeks to explore the benefit of combining a visual representation of the geometry, coupled with natural interaction, with a representation of the abstract precedence information contained in a disassembly graph.

3 Application Implementation

This section describes the design and implementation of an ICT application that combines geometric representation of product components with natural human interactions in an immersive

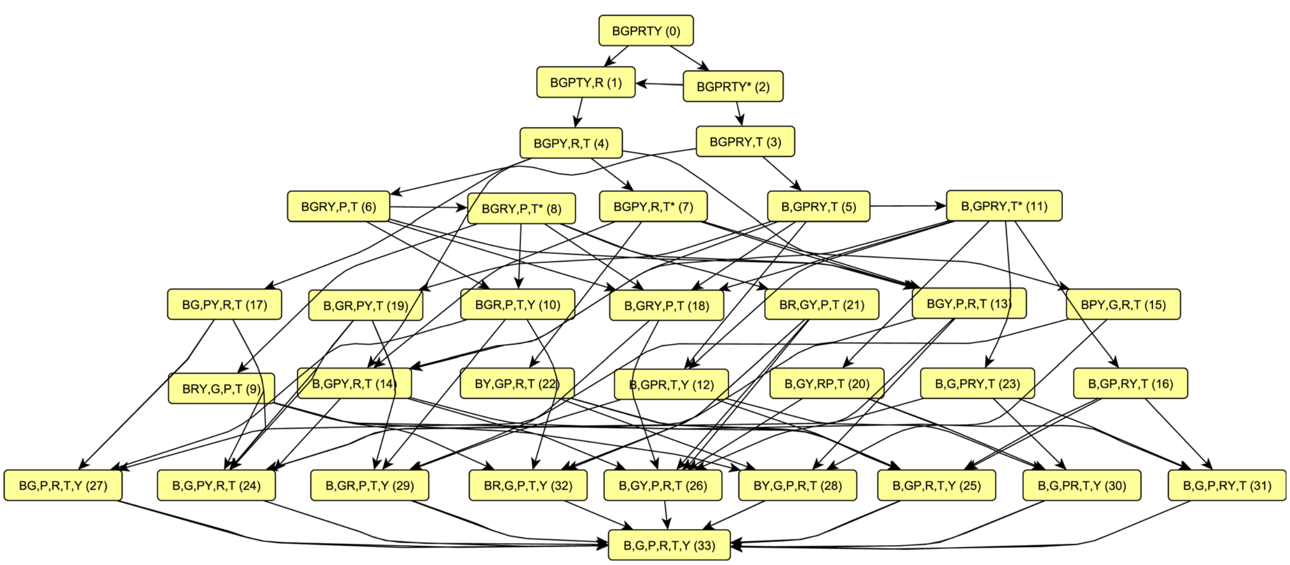

Fig. 1 Disassembly graph of a six piece wooden puzzle [2]

projection screen environment. A graph representation of the potential disassembly sequences is rendered in the same space as the virtual product geometry. This combination of abstract representation (disassembly graph) with the 3D immersive representation and natural interaction with the actual part geometry ties the theoretical approach to the intuitive approach in a method that supports free exploration of multiple disassembly paths.

3.1 Facility and Supporting Hardware. This application was designed and implemented in an immersive projection environment with three viewing screens. The viewing area consists of a wall and a floor both measuring 12 in. by 9 in. and an additional wall measuring 9 in. by 9 in. providing over nine hundred cubic feet of physical workspace. Digital projectors permit the display of active stereographic imagery at 120 Hz. Computational resources are provided through two rack-mounted servers. Images are rendered to all three walls using 2 NVIDIA Quadro Plex 2200-D2. The position and orientation of the user's head and hand are tracked using an optical tracking system equipped with four infrared cameras. A 5.1 surround sound speaker system provides audio stimuli within the workspace.

3.2 Supporting Software. Graphical and audio representations are generated by a VR JUGGLER-based [31] application called VR JUGGLUA [32]. This software interface encapsulates the functionality of VR JUGGLER, OPEN SCENE GRAPH (OSG) [33], and the LUA scripting language [34]. VR JUGGLER is a scalable, open source software platform that enables the abstraction and integration of multiple ICT technologies into a single software interface. OSG is a popular graphics toolkit for VR and other visualization applications. LUA, a lightweight scripting language, allows for simple yet concise syntax.

The manipulation of virtual objects and physics-based calculations are managed by a program called SPARTA: Scriptable Platform for Advanced Research and Teaching in Assembly [35]. Through SPARTA, physically modeled virtual objects may interact within the workspace. At its core, SPARTA uses the VPS voxel-based collision detection and force calculating physics engine [36]. While the application of this work was implemented in an immersive projection environment, the supporting software allows the application to be effortlessly scaled to other ICT environments.

3.3 Application. When the application starts, the user is placed within the walls of a simple virtual factory. Next, the user loads any set of 3D models representing a physical product. The virtual product is displayed directly in front of the user. From this position, the user may move naturally to view the virtual product from a variety of angles. Walking around the product enables the user to see a complete view of a product's physical geometry. By employing a tracked Nintendo Wii Remote®, as a metaphor for a hand or tool, the user can manipulate the components of the assembly. This combination of positioning and tools immerses the user in a manufacturing setting where they have the physical freedom to explore and manipulate the virtual assembly. Part collisions are accompanied by a representative sound rendered through the surround system audio speakers. A graph visualization is presented to aid the user in disassembly sequence planning. Figure 2 shows a person interacting in the immersive application.

Graph visualizations used in this application consist of disassembly states (nodes) and disassembly operations (edges) (Fig. 3). A disassembly state is a discrete set of components that make up a product assembly or subassembly. Disassembly operations are physical tasks that the operator must execute in the course of disassembly. While disassembly operations may include component removals (removing the component from the assembly) as well as component reconfigurations (reorienting but not removing the component), this research focuses primarily on the former. For this work, the disassembly graphs were generated manually. The authors disassembled each product by hand to identify

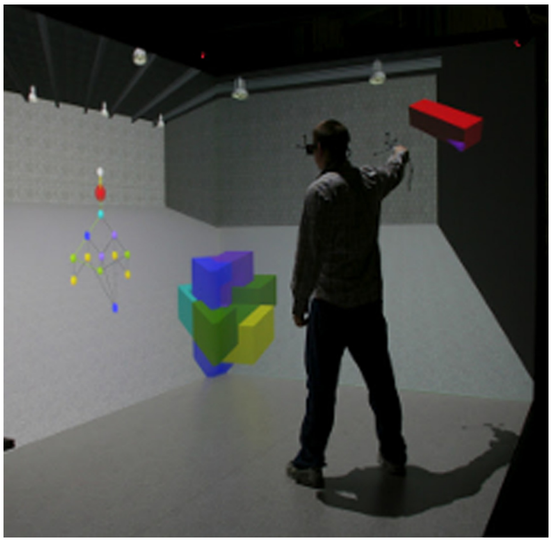

Fig. 2 Disassembly sequence planning of a block puzzle using ICT [2]

disassembly states and operations. Disassembly states are represented by simple geometric glyphs: spheres. Disassembly operations, on the other hand, are represented as line-based geometry (thin cylindrical geometry) connecting one disassembly state to another. A user progresses from one disassembly state to another in the graph by executing specific predefined disassembly operations. In efforts to increase the readability of the graph, it has been arranged in a top down orientation. A user starts the disassembly at the top of the graph (white node in Fig. 3) and completes the disassembly process at any of the bottom-most nodes.

To help the user better understand how their actions relate to positions in the disassembly graph, a red glyph (larger transparent sphere) is used to draw the user's attention to the current disassembly state. The color red was chosen for its stark contrast with respect to other visual elements in the scene. As the user progresses through the disassembly sequence, the position of the red glyph is updated in real-time, resulting in the user's path through the disassembly process being recorded and visualized in real-time. A larger yellow cylinder linking two disassembly states indicates a path that has already been traversed (a single disassembly operation completed) (Fig. 4(*a*)). The combination of these visual indicators help the user understand where they are, where they have and have not been, and what disassembly alternatives lie ahead.

As a user interacts with the virtual geometry, the graph visualization changes. The colors of the nodes are updated according to the possible disassembly transition alternatives at a given decision juncture. While feasible, the visualization of all paths results in large complex graphs (Fig. 1). Moreover, the issue of visual complexity becomes exacerbated as the number of components

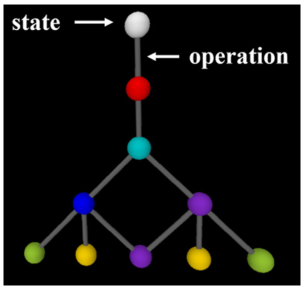

Fig. 3 Virtual disassembly graph

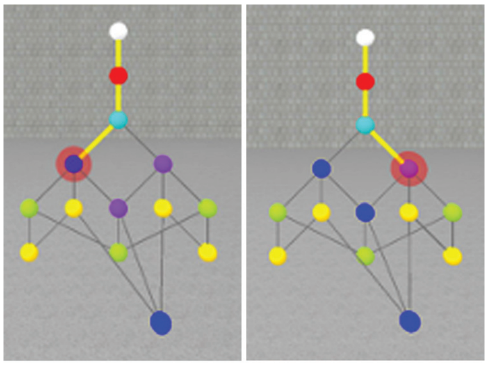

Fig. 4 Graph visualization changes dynamically with user interaction. The top white node represents the starting, fully assembled state and the bottom nodes represent possible end states. (*a*) red, teal, and blue pieces removed and (*b*) red, teal, and purple pieces removed

increases. This work investigates a state-centric graph in which each node represents a configuration of geometry (set of components). The color of a node may change depending on which path is traversed. To illustrate, consider Figs. 4(*a*) and 4(*b*). Figure 4(*a*) shows a partial disassembly sequence for a block puzzle. The red, teal, and blue pieces have been removed, and the operator has the choice of removing the green, yellow, or purple piece. Figure 4(*b*) also shows a partial disassembly sequence but for a different sequence (red, teal, and purple removed). From this state, the operator can remove the blue, yellow, or green piece. In Figs. 4(*a*) and 4(*b*) note that the center-most node changes color based on the path traversed, representing the current options for the next step in the disassembly sequence.

While the most common interaction is to remove pieces from an assembly during the disassembly process, the application also enables the user to reassemble a virtual product. Adding components to the assembly effectively allows the user to step back up the disassembly graph (reverse disassembly). The graph visualization always highlights the current state regardless of whether the user is disassembling or assembling the product. To encourage the exploration of multiple disassembly sequences, two features have been implemented to help the user step "back in time." First, in the event the user wants to start completely from the beginning they can simply press a button on the Wii Remote and the virtual product will be displayed in its fully assembled configuration. However, if a user wishes to only undo their last transition (removal of a component), pressing another button on the Wii Remote will place the previously removed component back in the assembly. Pressing this button multiple times can be used to step back through the graph (go back in time) one transition at a time.

While the virtual product may be disassembled without a graph visualization, two unique graph visualization features are available. First, a preexisting graph may be loaded to help the operator visualize known disassembly alternatives. With this method, an operator can easily compare and evaluate multiple disassembly sequences simultaneously. This visualization may also be useful in training operators to disassemble products in a certain sequence. Second, in the spirit of exploring unknown disassembly sequences, extensions to the preexisting graph visualization may be generated interactively or ad-hoc. As the user interacts and manipulates components new nodes and edges are added to the graph dynamically and the graphics are updated.

4 User Study

In order to evaluate the potential benefits of the application, it has been evaluated in two stages. First, a pilot study of five participants was completed. The application was then improved based on feedback from the pilot study, and a more formal user study was conducted.

4.1 Pilot Study Results. Five members of the research center were invited to participate in the initial evaluation of the application. For the purposes of the pilot study, a wooden interlocking puzzle was selected as the product of interest. The puzzle was chosen because it represents common products with multiple components. Although it only consists of six pieces, the puzzle contains significant complexity; affording numerous disassembly sequences (Fig. 1); several of which are not intuitive. Complete details on the pilot study can be found in Ref. [2].

The pilot study provided valuable feedback regarding the application. Several modifications were made to increase the readability of the disassembly graph. The overall size of graph visualization was increased. The space between the nodes was also increased making it easier to distinguish nodes from one another. Arrows were added to the ends of graph edges to show transition directionality. With respect to physical interaction, the algorithm that detected disassembly transitions was altered to be more precise and offer faster feedback.

4.2 Study Participants. Fifteen graduate and undergraduate students were invited, through word of mouth and email, to take part in the user study. All participants had some prior experience in large-scale virtual environments; however, none were involved with the development of the application. Participants had backgrounds across numerous fields and were 18 yr of age or older.

4.3 Study Procedure. While the pilot study employed a block puzzle as the sample geometry, a hydraulic pump assembly was chosen for the user study. Through discussions with the pump manufacturer, a set of disassembly sequences were identified and modeled in the virtual environment. Although there were numerous paths for disassembly, for the purpose of this research a subset of the potential disassembly paths were displayed in the immersive environment. For the sake of simplicity, the components of the pump were combined into nine subassemblies. Participants were able to interact with the individual subassemblies as if each subassembly was a single object. Only those operations that required complete removal of a subassembly from the assembly were represented in the graph.

The user study consisted of three tasks. Every participant experienced the tasks in the same order. This was done to understand the additive benefit at each stage.

Task 1. In task one, the participant was asked to explore disassembly sequences while only being able to interact the pump geometry (Fig. 5). The disassembly graph visualization was not present for this task.

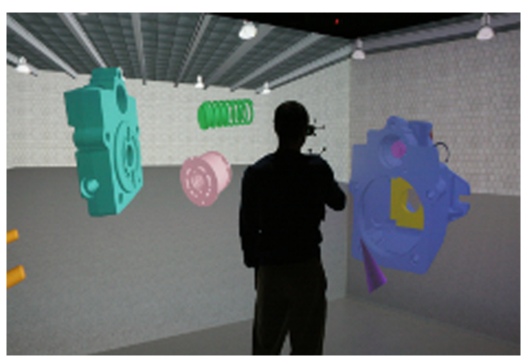

Fig. 5 A user interacting with the pump geometry (task 1)

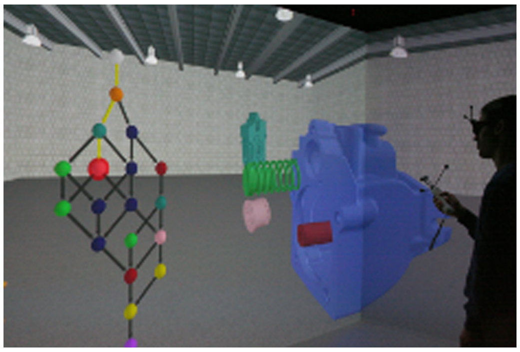

Fig. 6 A user interacting with the geometry and the disassembly graph (task 2)

Table 2 In the course of the three tasks unsolicited comments were recorded. The six most common are listed here.

Categories	Participants
Color makes parts more distinguishable	33% (5/15)
Participant noticed physical constraints before interacting with geometry	73% (11/15)
Graph helped confirm or dismiss potential disassembly sequences	53% (8/15)
Being able to rotate the entire assembly is desirable	73% (11/15)
Desired a richer virtual environment - more geometry	46% (7/15)
Following highlighted disassembly path was easy (task 3)	46% (7/15)

Task 2. For task two, in addition to the pump geometry, the participant was provided with a virtual disassembly graph (Fig. 6). The participant was instructed to explore disassembly sequences using the disassembly graph visualization.

Task 3. For the third and final task, the user was instructed to disassemble the virtual pump as indicated by the highlighted path on the disassembly graph.

After each task, the participant stepped out of the immersive environment and discussed their most recent experience with the researcher. After each task, participants were asked a variety of questions about their experiences (Table 1). Upon completion of all three tasks, the study was closed with a final interview conducted by the researcher.

5 Results

This section will present the results of the users interacting in the three tasks: Geometry-only disassembly, disassembly with graph visualization, and disassembly with graph visualization and highlighted sequence. Unsolicited comments from participants were recorded. Similar comments were grouped into categories. Table 2 lists frequent comments. This section concludes with general observations from the study.

5.1 Task 1: Geometry-Only. Even without the graph visualization to assist the user, interacting in the ICT environment provided several benefits. All of the participants indicated that the ability to physically walk around the geometry of the pump was crucial for contemplating disassembly opportunities. Walking around the geometry, a natural interaction, provided participants a unique perspective from which to gain valuable understanding of the geometry. Viewing multiple perspectives of geometry is often difficult in traditional CAD packages. Several participants mentioned that this resulted in a stronger understanding of the interconnectedness and physical constraints of the geometry. However, there were situations in which it was challenging to view the geometry from a specific perspective. As users moved naturally about the space, the virtual geometry would disappear as it moved off the projection screens. While this effect is unavoidable in three-walled immersive projection systems, 12 out of 15 participants reported being mildly annoyed when the geometry left the viewing space. In efforts of working around the limitation, the majority of participants, 11 of 15, indicated a desire to rotate the entire assembly; a capability not present in this simulation.

Table 1 Subset of post task questionnaire

Post task questions
Tell me about your (most recent) experience.
What do you think about using an application like this to think about disassembly?
Is there anything in particular you liked or disliked about the ICT application? Why?
Did the graph visualization alter your exploration process? If so, how?

Participants quickly inferred how components were physically related to one another. Before interacting with the assembly, 11 out of 15 participants mentioned finding several precedence relationships based on visual display alone. For example, a common finding was that the retaining ring must be extracted before the shaft component could be removed. Several participants mentioned that the coloring of the components helped differentiate subassemblies from one another; reducing the mental task of determining how parts will move with respect to one another.

For the majority of participants, executing disassembly operations in the ICT environment required little effort and time. The interaction of removing components was straightforward compared to assembling components, which requires components to be positioned and orientated with respect to other components within an assembly.

Participants indicated that comparing multiple disassembly sequences was difficult. This resulted in participants forgetting which sequences they had already evaluated.

5.2 Task 2: Disassembly With Graph Visualization. Task 2 consisted of a disassembly graph along with the virtual geometry presented in the same space. Participants indicated an appreciation for the disassembly graph visualization as it added a discrete structure to their evaluation process. Eight of fifteen participants noted that the graph visualization helped confirm or dismiss questions regarding potential disassembly operations. Interaction between the graph and geometry tended to be an influential factor in learning to use and understand the graph visualization. While the majority of participants learned how the graph could be utilized, 8 of the 15 participants mentioned wanting a stronger relationship between the graph and geometry. Some mentioned it would be beneficial to have more information in the graph beyond which sequences were possible. The simple geometric glyphs in the graph visualization resulted in participants being able to quickly learn how disassembly states and transitions were related. Because sequences were presented visually, participants were not forced to remember what sequences they had already explored and were often able to refer to specific paths verbally (i.e., "right-most path"). Moreover, glancing at the graph provided participants with a visual and spatial cue for remembering previous actions or considerations. Being able to view the entire graph enabled participants to think about the disassembly processes as a cohesive experience rather than a sequential set of unrelated operations.

A few participants suggested that the graph visualization provided information complementary to the geometry. Participants noted that while the product geometry provided insight as to how the components were physically related and constrained, the graph permitted the extraction of component removal opportunities required to disassemble the product. Many mentioned that the color organization connecting the pump with the graph was effective. However, in assemblies with a large number of components, color alone may not be sufficient for distinguishing components visually. Overall, the graph appeared to encourage participants to explore more disassembly sequences compared to the geometry-only case in task 1.

5.3 Task 3: Disassembly With Graph Visualization and Path. The third and final task presented the participant with a similar graph visualization from task 2, however, one of the disassembly sequences was highlighted with a different color. The participant was asked to disassemble the pump in the sequence highlighted on the graph.

By this point in the exercise, participants were acclimated to the graph and how to interact with it through manipulating the virtual geometry. Users quickly traversed the highlighted path and completed the task.

5.4 Observations. While the visual layout and structure of the graph was a welcomed organization tool, it also led participants to anchor on the predefined sequences. More than half of the participants only explored paths that were represented by the prescribed path. This suggests a possible fixation on predefined paths, potentially limiting the participant's overall experience and ability to accomplish objectives. Participants suggested that the visualization of the graph be limited to only show the current state and current component removal opportunities. As this suggestion would appear to reduce the complexity of the graph, it may also result in the presentation of less information hindering the user's ability to evaluate multiple sequences.

Overall, the participants concluded that this application was beneficial in evaluating and exploring disassembly sequences. The graph visualization afforded users the ability to quickly gain insight as to potential opportunities for disassembly. The use of color and dynamic interaction appeared to be successful methods of tying disassembly operations to abstract graph representations.

Participants learned to use the application at different rates. Individuals with substantive VR experience quickly learned how to interact with the virtual pump geometry and tended to progress through disassembly sequences faster compared to participants with less experience. Those with less experience in VR environments spent slightly more time in the geometry-only task (task 1) exploring the capabilities of the application. By the beginning of the second trial, regardless of prior experience, participants appeared equally confident in using the application.

6 Discussion

Results from the user study suggest that large-scale ICT environments enhanced with visual representations of the underlying mathematical models hold strong potential for aiding in early design decision making. It was clear that the ICT provided a means for participants to naturally interact with virtual product geometry. Both inexperienced and experienced participants were able to manipulate the geometric models easily after just a little exposure to the virtual environment. It was also clear that participants made use of the additional information contained in the abstract representation of the disassembly graph to direct them in deciding what operation to perform in the next step of the disassembly. Connecting the geometry display and graph visualization in an interactive way, where each is updated based on user interaction, was helpful in decision making.

The ICT environment allowed participants to evaluate the physical interaction of disassembly operations. Through interacting with the virtual geometry, two disassembly operations were reported as being ergonomically challenging. First, several participants indicated struggling to manipulate and remove a snap ring component in the ICT environment. As the snap ring is one of the smallest components, this is a notable challenge. In reality, removing the snap ring requires meticulous operations involving both hands. In a second case, 9 of 15 participants recognized the challenge in removing the swash plate component. Compared to the removal of other components, the swash plate requires various manipulations through multiple axes. Interacting with virtual geometry can help steer the design direction early in design.

Expanding beyond disassembly methods planning, this study suggests that large-scale projection ICT environments may be valuable during the course of cross domain design evaluations, where team members with diverse technical expertise come together in a product review session to make design decisions. Each discipline has its own method of data representation. Often the interpretation of domain-specific data by nondomain experts is difficult. For example, for people without a mathematical background, simple two-dimensional graphs might be difficult to interpret and, additionally, understanding trends based on relationships presented in graphs might be nonintuitive. A full understanding of the data could be critical to the team discussion and decision making process. Coupling abstract data representation with geometry in an immersive computing environment that supports natural interaction could bridge the understanding gap between team members from widely differing backgrounds, resulting in increased depth of understanding and subsequent better individual participation in team decision making.

7 Conclusions and Future Work

This paper describes the design, implementation, and evaluation of an ICT application to aid in the exploration of product disassembly sequences through the use of interactive graph visualizations. This application presents three primary modes of use. First, a user is able to explore the virtual geometry within the ICT environment. Interacting with the virtual geometry provides natural human-centric information and can help inform early ergonomic decisions. Second, a user may utilize a graph visualization to better understand existing disassembly sequences. The graph adds a visual structure to help guide exploration. In the third and final mode, a highlighted path is offered to present the user with an opportunity to learn specific sequences and compare it to previously experienced sequences. A user study, involving 15 participants and a hydraulic pump assembly, was conducted. Results from the study suggest that the coupling of natural human-centric 3D interaction with abstract data visualization holds strong potential for aiding early design decision making.

From the study several promising areas for future work emerged. It would be of interest to explore further methods to increase the interplay between geometric models and the graph visualization. As this research focused on component removals, future work may concentrate on the inclusion of fasteners, snap-fits, and other common disassembly operations.

Acknowledgment

This material is based upon work supported by the National Science Foundation under Grant Nos. CMMI-1068926 and CMMI–1100177. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

[1] Lambert, F. J., 2001, "Optimum Disassembly Sequence Generation," Proc. SPIE 4193, Environmentally Conscious Manufacturing, Vol. 4193.
[2] Berg, L. P., Behdad, S., Vance, J. M., and Thurston, D., 2012, "Disassembly Sequence Evaluation Using Graph Visualization and Immersive Computing Technologies," ASME Paper No. DETC2012-70388.

[3] Behdad, S., Berg, L. P., Thurston, D., and Vance, J., 2014, "Leveraging Virtual Reality Experiences With Mixed-Integer Nonlinear Programming Visualization of Disassembly Sequence Planning Under Uncertainty," ASME J. Mech. Des., **136**(4), p. 041005.
[4] Behdad, S., Berg, L. P., Vance, J., and Thurston, D., 2014, "Immersive Computing Technology to Investigate Tradeoffs Under Uncertainty in Disassembly Sequence Planning," ASME J. Mech. Des., **136**(7), p. 071001.
[5] Behdad, S., Berg, L. P., Thurston, D., and Vance, J. M., 2013, "Synergy Between Normative and Descriptive Design Theory and Methodology," ASME Paper No. DETC2013-13035.
[6] O'Shea, B., Kaebernick, H., Grewal, S., Perlewitz, H., Muller, K., and Seliger, G., 1999, "Method for Automatic Tool Selection for Disassembly Planning," Assembly Autom., **19**(1), pp. 47–54.
[7] Moore, K. E., Güngör, A., and Gupta, S. M., 2001, "Petri Net Approach to Disassembly Process Planning for Products With Complex AND/OR Precedence Relationships," Eur. J. Oper. Res., **135**(2), pp. 428–449.
[8] Singh, A., Tiwari, M., and Mukhopadhyay, S. K., 2003, "Modeling and Planning of the Disassembly Processes Using an Enhanced Expert Petri Net," Int. J. Prod. Res., **41**(16), pp. 3761–3792.
[9] Kongar, E., and Gupta, S. M., 2002, "A Multi-Criteria Decision Making Approach for Disassembly-to-Order Systems," J. Electron. Manuf., **11**(02), pp. 171–183.
[10] Menye, J.-B., Ait-Kadi, D., Coulibaly, A., and Caillaud, E., 2009, "Mathematical Model for the Minimization of the Mean Disassembly Time of a Mechanical System at Design Stage," IEEE International Conference on Computers and Industrial Engineering, Troyes, France, July 6–8, pp. 1198–1203.
[11] Behdad, S., and Thurston, D., 2010, "Disassembly Process Planning Tradeoffs for Product Maintenance," Proceedings of the ASME Design Engineering Technical Conference, Montreal, Quebec, Canada, Aug. 15–18, pp. 427–434.
[12] Pomares Baeza, J., Torres Medina, F., and Puente Mendez, S., 2002, "Disassembly Movements for Geometrical Objects Through Heuristic Methods," Proc. SPIE 4569, Environmentally Conscious Manufacturing II, Vol. 71.
[13] Seo, K. K., Park, J. H., and Jang, D. S., 2001, "Optimal Disassembly Sequence Using Genetic Algorithms Considering Economic and Environmental Aspects," Int. J. Adv. Manuf. Technol., **18**(5), pp. 371–380.
[14] Giudice, F., and Fargione, G., 2007, "Disassembly Planning of Mechanical Systems for Service and Recovery: A Genetic Algorithms Based Approach," J. Intell. Manuf., **18**(3), pp. 313–329.
[15] Lee, S., Lye, S., and Khoo, M., 2001, "A Multi-Objective Methodology for Evaluating Product End-of-Life Options and Disassembly," Int. J. Adv. Manuf. Technol., **18**(2), pp. 148–156.
[16] Hui, W., Dong, X., and Guanghong, D., 2008, "A Genetic Algorithm for Product Disassembly Sequence Planning," Neurocomputing, **71**(13–15), pp. 2720–2726.
[17] Henrioud, J., Relange, L., and Perrard, C., 2003, "Assembly Sequences, Assembly Constraints, Precedence Graphs," IEEE International Symposium on Assembly and Task Planning, Besancon, France, July 10–11, pp. 90–95.
[18] Dini, G., Failli, F., and Santochi, M., 2001, "A Disassembly Planning Software System for the Optimization of Recycling Processes," Prod. Plann. Control: Manage. Oper., **12**(1), pp. 2–12.
[19] Tang, Y., Zhou, M., Zussman, E., and Caudill, R., 2000, "Disassembly Modeling, Planning and Application: A Review," IEEE International Conference on Robotics and Automation, San Francisco, CA, Vol. 3, pp. 2197–2202.
[20] Jiménez, P., and Torras, C., 2000, "An Efficient Algorithm for Searching Implicit AND/OR Graphs With Cycles," Artif. Intell., **124**(1), pp. 1–30.
[21] Jiangang, G. A. O., Dong, X., Haifeng, C., Guanghong, D., and Jinsong, W., 2003, "Disassembly AND/OR Graph Model for Disassembly for Recycling," IEEE International Symposium on Electronics and the Environment, Boston, MA, May 19–22, pp. 54–59.
[22] Gupta, R., Whitney, D., and Zeltzer, D., 1997, "Prototyping and Design for Assembly Analysis Using Multimodal Virtual Environments," Comput.-Aided Des., **29**(8), pp. 585–597.
[23] Angster, S. R., and Jayaram, S., 1996. "VEDAM: Virtual Environments for Design and Manufacturing," Ph.D. thesis, Washington State University, Pullman, WA.
[24] Jayaram, S., Connacher, H. I., and Lyons, K. W., 1997, "Virtual Assembly Using Virtual Reality Techniques," Comput.-Aided Des., **29**(8), pp. 575–584.
[25] Jayaram, S., Vance, J., Gadh, R., Jayaram, U., and Srinivasan, H., 2001, "Assessment of VR Technology and its Applications to Engineering Problems," ASME J. Comput. Inf. Sci. Eng., **1**(1), pp. 72–83.
[26] Seth, A., Su, H.-J., and Vance, J. M., 2008, "Development of a Dual-Handed Haptic Assembly System: SHARP," ASME J. Comput. Inf. Sci. Eng., **8**(4), p. 44502.
[27] Tching, L., Dumont, G., and Perret, J., 2010, "Haptic Assembly of CAD Models Using Virtual Constraint Guidance," ASME Paper No. WINVR2010-3707.
[28] Seth, A., Vance, J. M., and Oliver, J. H., 2010, "Virtual Reality for Assembly Methods Prototyping: A Review," Virtual Reality, **15**(1), pp. 5–20.
[29] Boud, A. C., Haniff, D. J., Baber, C., and Steiner, S. J., 1999, "Virtual Reality and Augmented Reality as a Training Tool for Assembly Tasks," IEEE International Conference on Information Visualization, London, England, July 14–16, pp. 32–36.
[30] Sung, R. C., Ritchie, J. M., Robinson, G., Day, P. N., Corney, J., and Lim, T., 2009, "Automated Design Process Modeling and Analysis Using Immersive Virtual Reality," Comput.-Aided Des., **41**(12), pp. 1082–1094.
[31] Bierbaum, A., Just, C., Hartling, P., Meinert, K., Baker, A., and Cruz-Neira, C., 2001, "VR Juggler: A Virtual Platform for Virtual Reality Application Development," IEEE Virtual Reality Conference, Yokohama, Japan, Mar. 13–17, pp. 89–96.
[32] Pavlik, R. A., and Vance, J. M., 2012, "VR JuggLua: A Framework for VR Applications Combining Lua, OpenSceneGraph, and VR Juggler," IEEE 5th Workshop on Software Engineering and Architectures for Realtime Interactive Systems (SEARIS), Costa Mesa, CA, Mar. 5, pp. 29–35.
[33] Wang, R., and Qian, X., 2010, *OpenSceneGraph 3.0: Beginner's Guide*, Packt Publishing, Olton, UK.
[34] Ierusalimschy, R., de Figueiredo, L. H., Henrique, L., Waldemar, F., and Filho, W. C., 1995, "Lua—An Extensible Extension Language," Softw. Pract. Experience, **26**(6), pp. 635–652.
[35] Pavlik, R. A., and Vance, J. M., 2011, "Expanding Haptic Workspace for Coupled-Object Manipulation," ASME Paper No. WINVR2011-5585.
[36] McNeely, W. A., Puterbaugh, K. D., and Troy, J. J., 1999, "Six Degree-of-Freedom Haptic Rendering Using Voxel Sampling," SIGGRAPH'99: Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques, ACM, Los Angeles, CA, Aug. 8–13, pp. 401–408.