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Disassembly Sequence Evaluation Using Graph Visualization and Immersive Computing Technologies

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Abstract

With the goal of making product recovery economically viable, disassembly sequence planning and evaluation can be used to influence product design features early in the product design process. Several researchers have investigated using optimization methods to determine disassembly sequences. One of the difficulties with using this approach is that because of the unique aspects of product disassembly at the end of life, input parameters for the optimization algorithms are commonly unavailable or estimated under high uncertainty. In practice, design engineers explore disassembly sequencing using either CAD software or manipulation of physical prototypes. These approaches produce solutions, but only intuitive solutions are explored and more optimal solutions may exist. To support decision making early in the design process, the research presented in this paper combines these two approaches within an immersive computing technology (ICT) application to aid in early product design with the goal of designing products with consideration of product recovery, reuse and recycle.

The ICT application displays both 3D geometry of the product to be disassembled and an interactive graph visualization of the potential disassembly paths. The user can naturally interact with the geometric models and explore the potential paths indicated by the graph visualization. The optimal path can be indicated and the user can explore other potential paths. The result is an application that combines the strength of mathematical modeling with visualization and human interaction to provide an experience where the user can explore potential effects of design decisions. The initial application has been implemented in a 3 wall immersive projection environment and preliminary results show this approach proves to be an efficient method of evaluating and training potential disassembly sequences.

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1 INTRODUCTION
Disassembly may be required for a number of different reasons. During a product's life, it may need to be partially disassembled while executing routine maintenance or repair tasks during the product use phase. When products approach end-of-life (EOL) a variety of challenges arise. Often, components or sub-components may be reused or recycled, so disassembly is required. Additionally, some components may have inherent value such that the primary objective in 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 sub-assemblies (Lambert, 2003). Disassembly and assembly are strictly disparate for several reasons. Assembly operations are not completely 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. Unlike assembly planning, there are typically many more alternative ways to perform 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 the optimum disassembly sequence based on input parameters 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 tools allow the designer to examine geometric constraints that define disassembly paths but fail to bring into account the physical interaction of the disassembly worker. Physical prototypes can be used to produce experience-guided disassembly sequences but are often not available in the early product design phase.

This research explores the use of immersive computing technologies (ICT) in disassembly sequence planning. ICT supports user interaction with virtual design configurations in increasingly natural ways to achieve an immersive life-like experience. Visual feedback is presented to a user through stereo viewing, resulting in the perception of a three dimensional workspace. Real-time position tracking coupled with haptic (force feedback) devices allows 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 used to simulate assembly and disassembly tasks without the need for physical prototypes, supporting wide exploration of potential alternatives and evaluation of multiple cost effective approaches. A combination of various stimuli creates an environment where a user can interact with a virtual product earlier in the design process; evaluating and modifying the design prior to costly physical prototyping. The ICT approach differs from traditional mouse and keyboard methods as it supports virtual testing of design alternatives for their impact on cost effective disassembly.

Previous work has yet to fully examine the coupling of traditional disassembly sequence planning methods with the real-time potential of ICT. In attempts to bridge this gap the authors have designed and implemented an ICT application in a projection screen-based immersive environment. Providing expert operators with a simulation and visualization tool may assist in the evaluation of product disassembly sequences, potentially providing new input for the redesign of products. The paper is outlined as follows: Section 2 will present related background research. The ICT application is described in section 3. A case study is presented in section 4, with results and discussion in section 5. Section 6 presents conclusions and provides insight to potential future research opportunities.

2 BACKGROUND AND MOTIVATION

This research draws on several distinct areas of expertise. An overview of current work in disassembly sequence planning and visualization/virtual assembly will be presented in this section.

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 (O'Shea et al., 1999, Moore et al., 2001, Singh et al., 2003), mathematical models (Lambert, 2001, Kongar and Gupta, 2002, Menye et al., 2009, Behdad et. al., 2010), heuristics (Kuo et al., 2000, Pomares et. al., 2001, Seo et al., 2001, Giudice and Fargione, 2007), and multi-criteria analysis (Lee et al., 2001, Behdad and Thurston, 2010). These methods generally do not 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 (Hui et al., 2008, Henrioud et al., 2003, Dini et al., 2001). Several implementations of these graphs include adjacency graphs, Petri Net, AND/OR graphs and precedence graphs (Tang et al., 2000, Jiménez and Torras, 2000, Gao et al., 2003). Graphical representations of feasible disassembly operations are commonly used as input to mathematical models to generate optimum disassembly sequences. The research presented here will explore the use of graph-models to guide the experts in the disassembly ICT. A full disassembly graph is presented in Fig. 1 showing all possible disassembly sequences for a six piece assembly. Individual parts are labeled B, G, P, R, T and Y. The state number is indicated in parentheses.

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. 1997 designed and implemented a virtual environment with the ability to simulate physical part interaction. They discovered that tasks

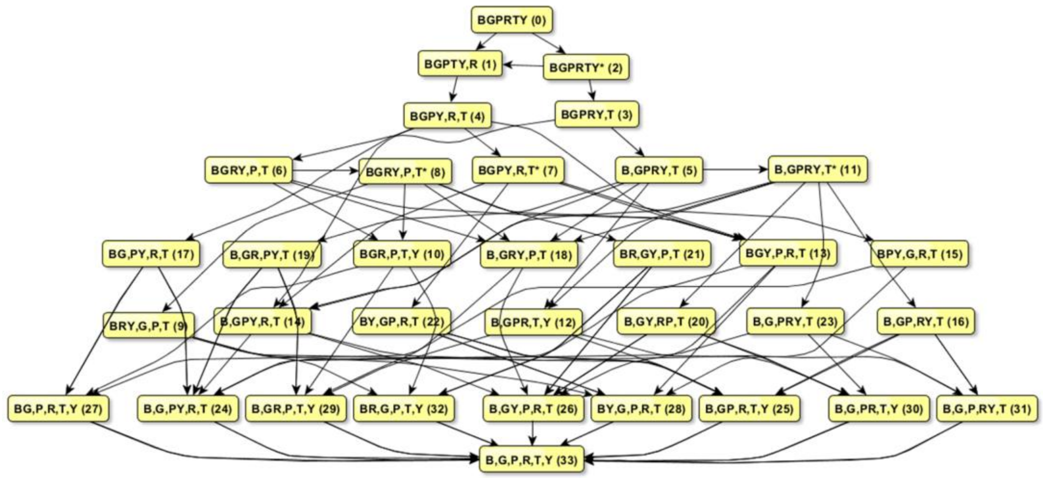

Figure 1. Example disassembly graph of a wooden puzzle

performed by users in the virtual environment took about twice as long as when performed using physical models. Angster and Jayaram (1997) described the system requirements of a virtual reality 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. 1997 developed a virtual assembly application called VADE which allowed users to perform manual virtual assembly. In 2001, Jayaram et al. describe the hardware and software challenges in applying 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 and associates (2008) 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. (2010) 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. 2010, suggest the promise of a hybrid part interaction algorithm combing physics-based and constraint modeling.

The use of ICT for assembly training has also been explored. Boud et al. 1999 emphasized the potential of ICT environments in a water pump assembly task. Participants either trained with traditional engineering and assembly drawings or various virtual reality apparatuses. Both the VR and AR (augmented reality) conditions out-performed the use of traditional engineering drawings. Later in 2009, Sung and associates describe a system that automatically models 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. (Sung et al. 2009)

Past research was focused on the use of ICT for assembly planning and training. The research presented here focuses on disassembly. It seeks to explore the added benefit of combining a visual representation of the geometry, coupled with natural interaction, with a representation of the abstract 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 the parts to be disassembled with natural human interactions in an immersive projection screen environment with a graph representation of the potential disassembly sequences. 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.

Facility & 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' x 9' and an additional wall measuring 9' x 9' providing over 900 cu. ft. of physical workspace. Digital projectors permit the display of active stereographic imagery at 120 frames per second. 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 orientations 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 capabilities within the workspace.

Supporting Software

Graphical and audio representations are handled by a VR-Juggler based application called VRJugglua (Pavlik and Vance 2011a). This software interface encapsulates the functionality of VR-Juggler (Bierbaum et al. 2001), Open Scene Graph (OSG), and the Lua scripting language. VR-Juggler is a scalable, Open Source software platform that enables the abstraction and integration of multiple ICT technologies into a single software testbed. Open Scene Graph is a popular graphics toolkit for virtual reality 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 (Pavlik and Vance 2011b). Through SPARTA, physically modeled virtual objects may interact within the workspace. At its core, SPARTA uses the VPS voxel-based collision detection and force rendering physics engine (McNeely et al. 1999). 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.

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/operator may move his/her head and body to view the virtual product from a variety of angles. Walking around the product provides a complete view of a product's physical geometry providing the user further disassembly information. By employing a tracked Nintendo Wii Remote, as a metaphor for a hand or tool, the user can manipulate the sub-components of the assembly. This combination of positioning and tools immerses the user in a manufacturing setting where he/she has the physical freedom to explore and manipulate the 3D assembly. Part collisions are accompanied by a representative sound heard via the surround system audio speakers. A graph visualization is presented to aid the user in disassembly sequence planning. Fig. 2 shows a person interacting in the immersive application.

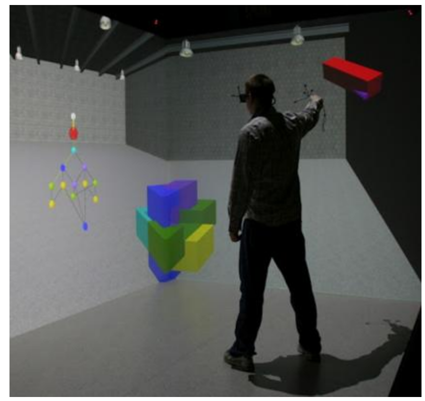

Figure 2. Disassembly sequence planning using immersive computing technologies

Graphs used in this research include representations of disassembly states and disassembly operations. A disassembly state is a specific combination of components currently involved in a product assembly. Disassembly operations are any physical task the operator must execute in the course of disassembly. While disassembly operations may include component removals (removing the part from the assembly) as well as component reconfigurations (reorienting but not removing the component), this research focuses primarily on

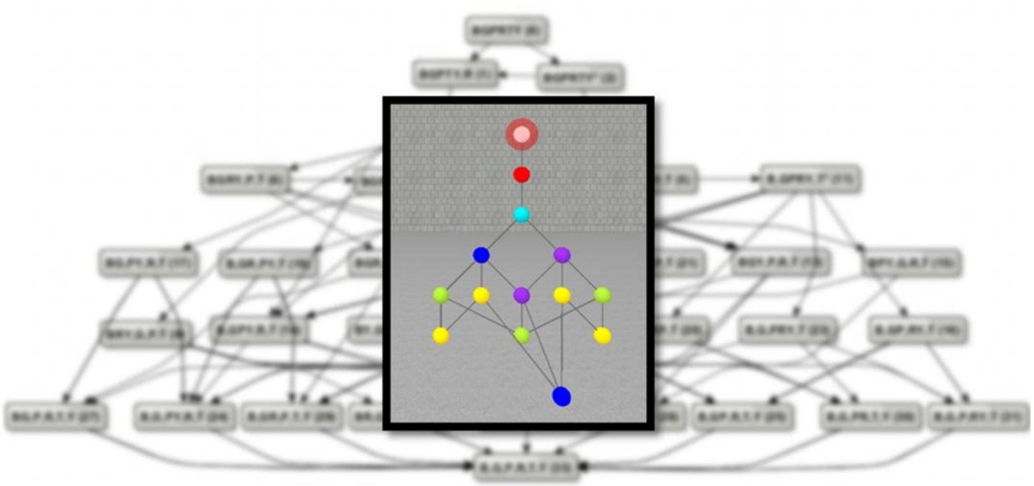

Figure 3. Sample subset disassembly graph taken from the complete Burr Puzzle disassembly graph

the former. Disassembly states are represented by simple geometric glyphs: spheres. Disassembly operations, on the other hand, are represented as line-based geometry (a thin cylinder) connecting one disassembly state to another. An operator travels from one disassembly state to another through the execution of specific disassembly operations. In efforts to increase the readability of the graph, it has been placed in a top down order such that a user starts the disassembly at the top of the graph and finishes the disassembly at the bottom. While the complete disassembly graph for the Burr Puzzle, shown in Fig. 1, contains 33 nodes and 99 edges, a subset of that graph has been implemented in this example for the purpose of illustration and discussion (Fig. 3).

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 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). The combination of these visual indicators help the user maintain where they are, where they have and have not been, and what disassembly alternatives lie ahead.

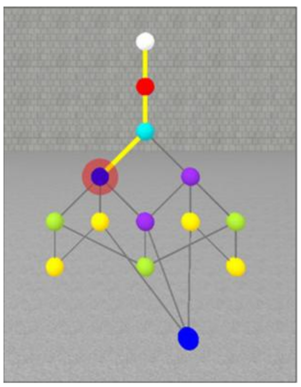

Figure 4a. Disassembly graph with Red, Teal, and Blue pieces removed

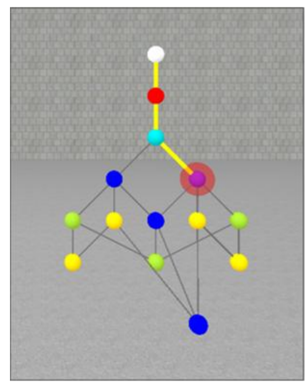

Figure 4b. Disassembly graph with Red, Teal, and Purple pieces removed

The representation of the graph changes based on the user's actions. The colors of the nodes are updated according to the possible disassembly transition alternatives at a given decision juncture. To illustrate, consider Fig. 4a and 4b. Fig. 4a (left) shows a partial disassembly sequence for the Burr Puzzle. The red, teal, and blue pieces have been removed and the operator has the choice of removing the green, yellow or purple piece. Fig. 4b (right) also shows a partial disassembly sequence but for a different path (red, teal, and purple removed). From this state the operator can remove the blue, yellow, or green piece. Note that the centermost node changes color based on the path traversed, representing the most current options for the next step in the disassembly sequence.

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 disassembly alternatives. An operator can easily compare and contrast different sequences of disassembly. This visualization may also be beneficial in training operators to disassemble products in a certain sequence. Alternatively, in the spirit of exploring unknown disassembly sequences, extensions to the preexisting graph visualization may be generated 'ad-hoc'. As the user interacts and manipulates components new nodes and edges are added to the graph automatically and the visualizations are updated instantly. A customized force-directed layout algorithm is employed to ensure the visualizations are positioned optimally within the given space. As expected, the current disassembly state and disassembly path are dynamically updated and highlighted.

4 CASE STUDIES

For initial evaluations of the usefulness of the application, a wooden interlocking puzzle was selected as the object of interest. A six-piece Burr Puzzle (Fig. 5) was chosen because it is representative of a common product with multiple parts. This puzzle was selected as a case study because of the multiple interlocking parts and different potential assembly sequences. The Burr Puzzle represents significant complexity; affording numerous disassembly sequences (Fig. 1); several of which are not intuitive. The interlocking nature constrains movement of certain components at various stages of disassembly. Fig. 6 shows a user interacting with the virtual puzzle assembly.

Figure 5. A six-piece Burr Puzzle

Although there were numerous paths for disassembly, for the purpose of this research only a small subset of the potential paths were displayed in the immersive environment. Only those operations that required complete removal of a part from the assembly were represented by the graph. Subassembly removal or partial removal tasks were not considered. The nodes on the path were color coded to match the removal of that color part from the assembly. This visual connection served to show the user what parts were removable at any stage in the disassembly process. This disassembly graph used in the study is shown in Fig. 3.

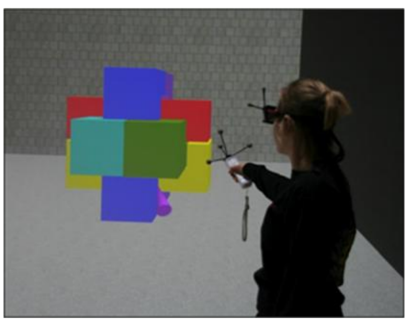

Figure 6. User interacting with virtual geometry

Three cases were examined. In Case 1 the user was asked to disassemble the parts viewing only the puzzle geometry. In Case 2 the user was provided with a basic disassembly graph and instructed to disassemble the puzzle. In Case 3 the user was instructed to follow a given assembly sequence indicated in the disassembly graph. Fig. 7 shows a user interacting with the puzzle and viewing the disassembly graph. Examining the state of the graph in Fig. 7, it shows that the user has removed the red, teal and blue parts. The next step will be to remove either the purple, green or yellow part as indicated in the graph.

A preliminary study was completed. Five individuals from the research lab who had not worked on this application were asked to perform the three cases and provide feedback. Feedback was collected through a survey form.

5 RESULTS AND DISCUSSION

This section will present the results of the users interacting in the three case situations: Geometry only disassembly, disassembly with graph visualization, and disassembly with graph visualization and highlighted sequence. This section concludes with general observations made during the case study.

Case 1

Even without the graph visualization to assist the user, the puzzle's geometry projected in the ICT environment resulted in several benefits not represented in other computer-based evaluation methods. All of the participants indicated that the ability to physically walk around the geometry of the puzzle

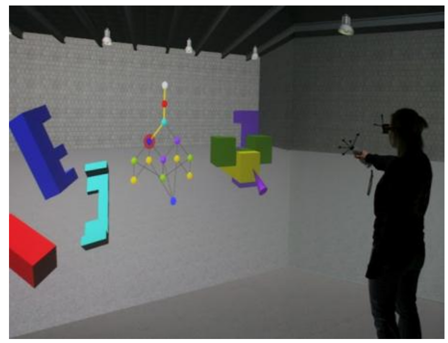

Figure 7. The puzzle geometry and the subset disassembly graph

was crucial for contemplating disassembly opportunities. Walking around the puzzle, a natural interaction method in the ICT environment, provided participants a unique perspective from which to gain valuable understanding of the geometry. Several participants mentioned that this resulted in a stronger understanding of the interconnectedness and physical constraints of the geometry. An improved mental model of the puzzle was another mentioned benefit of this ability. For the majority of participants, executing disassembly operations in the ICT environment required little effort. Removing components was straightforward compared to assembling components, which require components to be positioned and orientated with respect to other components within an assembly. Participants indicated that evaluating and comparing multiple disassembly sequences without the aid of a disassembly graph was difficult. This resulted in participants traversing the same paths multiple times.

Case 2

The presentation of a disassembly graph along with the virtual geometry was the second case tested. For the most part, participants appreciated the disassembly graph visualization as it added a discrete structure to their evaluation process. The visual layout of the graph, i.e. top-down tree structure, proved highly relatable as participants were consistently aware of the starting point and direction of progression. Several participants mentioned that this visual structure mirrored abstractions in other STEM fields. Interaction between the graph and puzzle geometry tended to be a significant factor in learning to use and understand the visualization. Because disassembly sequences were presented graphically, participants did not have to remember what paths they had already explored based on their past actions. Glancing at the graph gave the user a visual cue for remembering previous actions or considerations. In general, participants reported spending more time looking at the graph than looking at the puzzle geometry. Two participants suggested that the graph visualization provided information complementary to the geometric puzzle. They noted that while the puzzle visualization provided insight as to how the components were physically constrained, the graph permitted the extraction of interaction opportunities needed to disassembly the puzzle. Participants also mentioned that the color organization connecting the puzzle with the graph was effective. Other participants mentioned that the graph aided in the confirmation or dismissal of disassembly sequences they were considering. Overall, participants were more successful at traversing and exploring multiple disassembly sequences compared to the geometry-only case.

Case 3

The third and final case presented the participant with a similar graph visualization from the previous method, however, in this trial, one of the disassembly sequences was highlighted (Fig. 8). The participant was asked to disassemble the burr puzzle 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 puzzle geometry. Users were able to quickly traverse the highlighted path and complete the task. While the participants were able to distinguish the highlighted path from other paths, several mentioned that increasing the visual distinctiveness (i.e. increasing edge thickness) would help to make the intended path easier to follow. While the visual layout and structure of the graph was a welcomed organization tool, it also led participants to anchor on the pre-defined path. Before the participants began, it was mentioned that the graph did not represent all disassembly opportunities and if they found additional paths, the graph would update automatically. More than half of the participants only explored paths that were represented in the initial graph. This suggests a possible fixation on pre-defined paths, potentially limiting the user's overall experience and ability to accomplish objectives. One user acted to the contrary and ignored all visualized paths and only sought to find new undiscovered paths. All but one participant found the graph visualization to be too complex as they approached the bottom where the breadth was the largest. Surprisingly, the majority of participants suggested a similar solution to this issue. Users suggested that the visualization of the graph be limited to only show the current state and current part removal opportunities. As this suggestion would appear to ameliorate the complexity of the graph, it may also result in the presentation of less disassembly sequence information hindering the user's ability to evaluate multiple sequences. Participants also mentioned that the graph was smaller than

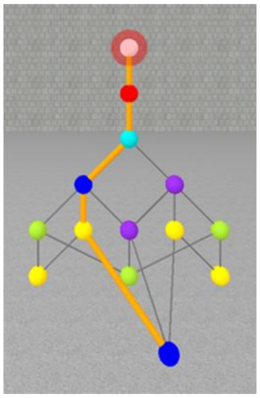

Figure 8. Disassembly graph with optimal path highlighted

anticipated and they thought the graph visualization should make better use of space in the ICT environment.

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 graph updates proved to be successful methods of tying disassembly operations to abstract graph representations.

6 CONCLUSIONS & FUTURE WORK

This paper describes the early stage implementation of an ICT application to aid in the evaluation and training of product disassembly sequences through the use of interactive graph visualizations. This application presents three primary modes of use. First an operator is able to explore the virtual assembly geometry within the ICT environment. Second an operator may use a graph visualization to better understand various disassembly sequences. Third, a highlighted path is offered to present the operator with an opportunity to learn specific sequences and compare it to previous experiences.

This application was initially evaluated through a case study involving five participants and a wooden block puzzle. Throughout the study participants experienced three separate scenarios. The results of the case study indicate several promising areas for future work. Increasing the distinctness of graph components may have a positive effect on the relatability of the visualization and further aid the operator. Additionally, 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 advanced disassembly operations. While the current interaction method is only one-way (geometry to graph), providing two-way interaction may enable new methods for disassembly sequence evaluations. Finally, a more detailed user study with more participants is needed to inform the research direction.

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