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Tangible augmented reality intervention for a product dissection task

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Tangible augmented reality intervention for a product dissection task

by

Chloe Lindsay McPherson

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Co-Majors: Human-Computer Interaction and Mechanical Engineering

Program of Study Committee:
Rafael Radkowski, Major Professor
Stephen Gilbert
Judy Vance

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University
Ames, Iowa
2018

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DEDICATION

For my cousin, Briant C. White.
For my grandfather, Otis C. Hayes.

“If you are kind, useful, and fearless, you will do great things.”
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ABSTRACT

Functional decomposition is a process used by engineers and designers for identifying functions in various design tasks. The concepts of function and functional decomposition are important in engineering to understand for converting complex problems into abstractions. However, research results indicate that engineers and designers struggle to apply functional decomposition methods during design tasks, such as product dissection, due to the abstract nature of product functions. Augmented reality, coupled with tangible objects, provides a platform on which information about different design aspect models can be blended and presented to the user during a product dissection or other design task. Past research discusses the interrelations between function, behavior and structure, and explains how providing information on one area contributes to understanding in the other areas.

This research develops an AR application to overlay context-sensitive information about product behavior and structure during a product design task, a product dissection, to contribute to users’ understanding of function. A user study was conducted to evaluate the effectiveness of this AR-supported product dissection. Participants were asked to dissect a hair dryer and toy dart blaster and generate a function diagram for each to describe how they work: one dissection using the AR application and the other a physical dissection, to serve as a baseline. Function diagrams allow for comparison of user’s functional understanding. The function diagrams were evaluated for accuracy on several metrics including the total number of functions generated and the number of syntactical, semantic and relational errors present in each diagram. While no statistical or qualitative differences were found between the diagrams generated during the AR-supported and non-AR supported tasks, from study of the
users’ function diagram and pre- and post-study test scores, several observations were made and trends were noted about users’ understanding of function and their difficulty in applying different aspects of functional decomposition.
CHAPTER 1 — INTRODUCTION

Motivation

“Engineering design is the process of devising a system, component or process to meet desired needs. It is a decision-making process in which the basic sciences, mathematics and the engineering sciences are applied to convert resources optimally to meet these stated needs [1].”

The main aim of design research is to improve understanding of engineering design processes and methods and, using this understanding, develop methods and tools to improve industry odds of producing an economically successful product [2]. Engineers may use the engineering design process to facilitate new development, adaptation or revitalization of virtually any system, component or process.

Concept generation is at the heart of engineering design [3]. A common set of methods used in generating concepts are functional decomposition methods. Those methods use the concept “function” to represent the purpose of the intended product. A “function” is what a product, sub-assembly, or part must do, free of any implementation. They are used to denote the transition from an input entity to an output entity. Functional decomposition can be broken down into either “functional analysis,” the process of identifying functions for an already existing artifact or concept, or “functional synthesis,” which is used to identify functions in design where no artifact already exists [4]. In any case, the objective of functional decomposition is a functional model, which combines functional elements, followed by structural and topological elements, resulting in feasible alternative concepts to solve a particular design problem [3].

However, engineers often struggle with fully understanding functional decomposition methods, the generated functional model, and applying them successfully. Previous research has
identified a deficiency in working knowledge of these methods [5] [6] and wide-ranging definitions of function in general [6]. This is most likely due to notions that decomposition is too simple, too complex or not useful [7] and multiple meanings attached to the term function which hamper its use for communication of functional descriptions [8].

Augmented reality (AR) is a promising technology that can mitigate uncertainty of product functions as a user performs a functional decomposition task. AR allows for providing additional information via visual features and to connect the information to a physical object at hand. The connection of information, via visual cues, to a user's perception may contribute to their understanding of their surroundings and objects. Tangible AR, a branch of tangible user interfaces, couples physical representations (tangible objects) with digital representations, blending multiple layers of information to improve user understanding of a physical part. This thesis seeks to explore whether applying the use of a tangible augmented reality visualization during a functional decomposition task helps to improve engineers’ understanding of essential functions.

**Research Goals**

The goal of this research is to examine the effectiveness of an augmented reality (AR) application for use during an AR-supported product dissection with a focus on identifying essential product functions and generating function models. This research aims to see if the context-specific information provided via the AR visualization aids engineering students in their understanding and identification of a product’s functionality.

Engineering design addresses three aspects of a product: the shape, the structure/topology, and the functions/behavior of the product. These different aspects can be
embodied by a set of models (i.e. CAD models), part hierarchies, and functions diagrams, which are used to graphically represent the product’s functions.

Considering the engineering design process, one can assume that shape information and structural information are available at any given time. The goal then, is to improve the user's understanding of functionality through representations of the two remaining aspects of a product: its shape and topology. Therefore, AR technology can be used to provide both additional shape and topological information to the user in a context-sensitive manner.

Two versions of the AR application exist, one that provides additional shape information about the product to the user, and the other that provides both shape and topological information to the user. A traditional physical product dissection supplements this information to the user by default. The information is visually linked to the associated physical components and functional groups. Using this additional information, this thesis investigates two research objectives: first, to verify that presenting additional information (shape and topology) to the user in the form of a virtual representation allows the user to better understand the product’s functions; and second, to verify that context-related information fosters understanding of topology and shape.

To achieve these research objectives, this research implements a controlled study. The study compares an AR-supported product dissection to a traditional product dissection in two modes. Each participant was asked to dissect two products of medium complexity — a hair dryer and a Nerf toy dart blaster — one as an AR-supported dissection and the other as a traditional physical dissection.

Function diagrams produced by each participant while using the AR application will be contrasted with function diagrams generated by each participant when completing the traditional product dissection.
Function diagrams are used in both modes to record the user’s ability to understand the product’s functionality. Users are asked to draw function diagrams while or shortly after they perform the product dissection task. The variance of diagrams is used as indication for the user’s understanding, the less the diagrams vary, the better the common understanding of the product’s functionality.

The results of this study indicate the benefits of AR visualization when performing a functional decomposition task.

**Thesis Outline**

The organization of the following chapters is outlined below.

Chapter 2 provides background on and a literature review for the two major areas that constitute the foundation of this thesis: the engineering design process and functional decomposition methods. The conceptual design phase of the engineering design process is discussed and its importance in transferring functions from abstract to concrete is further explored. Common methods utilized in functional decomposition are described and organized according to their usefulness in abstracting functions and aiding in functional understanding.

Chapter 3 continues literature review, but focuses now on augmented reality (AR) with an emphasis on tangible augmented reality. The chapter describes the benefits and drawbacks of each technology, and delves into prior research that falls at the crossroads of engineering design, AR and tangible AR.

Chapter 4 explains the rationale for this thesis’ two hypotheses. This chapter also discusses the experimental design and set-up for the AR “virtual product dissection” application and user study. The ideation and approach to developing the AR application are covered and the
application is described in conjunction with the hypotheses tied to the application and study. The logistics of the user study itself are addressed, including methods used for participant recruitment, trial assignment, and data recording measures and areas for evaluation.

Chapters 5 and 6 present the raw results of the study and then explores the significance of those results to each of the hypotheses proposed in Chapter 4. Additional charts and discussion are included to illustrate particularly relevant data, and statistical analyses are carried out in refutation or support of each hypothesis. Explanations are offered for cases where experimental results do not concur with the rationale behind each hypothesis and instances when statistical significance has not been found.

Chapter 7 covers conclusions drawn from the data discussed in Chapter 6, as well as identifies the overall implications of this work. Finally, areas for future work are suggested for advancing this project.
CHAPTER 2 — LITERATURE REVIEW: DESIGN & DECOMPOSITION

The conceptual design phase of the engineering design process is characterized by information that is often imprecise, inadequate and unreliable [4]. The goal at this stage is to find a design solution that can achieve the required functions and requirements [9]. As such, conceptual design is a function-laden and function-oriented component of the design process.

Function

To solve a technical problem, a method with clear and easily reproduced relationships between inputs and outputs is needed to identify and clearly communicate a solution [4]. Pahl & Beitz [4] define a function as “the intended input/output relationship of a system whose purpose is to perform a task.” Functions are defined as statements consisting of a noun and a verb pairing, such as “increase pressure” or “channel air.” The noun describes the entity and the verb describes the activity that processes the entity. Common functions are classified into three groups related to the three types of matter that flow throughout the system: energy, material and information [4].

![Figure 1: Representation of a function](image)

A function term can either describe the functionality of the entire product, a subsystem, or an individual part. They are abstract and neutral to any solution. During the product development process, functions are associated with technical solutions to realize a certain product.
Function Diagrams

Function diagrams are tools used to graphically represent the group of functions that a product performs. The diagrams, when assembled, summarize how functions and subfunctions fit together to describe the larger system and help engineers explore solutions for a product. Typically, more than one solution exists for each function, so function diagrams are an excellent tool for communicating ideas from a decomposition method and allow for comparison of understanding between people.

Function diagrams can exist in many forms including a function tree, function structure, or function analysis system technique (FAST) diagram.

Energy-Flow diagram

The energy-flow diagram, sometimes called the “black-box” approach, traces the flow of material, energy and information through a device. Functions are mapped at points of change in these flows. The flow method appears the most in engineering design textbooks [5].

Figure 2 shows an example of a energy-flow diagram. The main element of the function diagram are function elements. According to Pahl & Beitz [4], each function element is represented as a box with the function written inside. Thus, it is also known as the black-box model. Note that each function is comprised of a noun and a verb, which describe the element that is transformed by the inputs and outputs of that function. Single function blocks are linked by the flow(s) of energy, information, and material. Directed arrows between multiple function blocks indicate flows from one block to the other. As each arrow represents a single input to or output from a function block, multiple arrows may connect one function to another, depending on the product. This model does not show hierarchy between functions.
There are no limits to the number of functions, the connections between these functions, and the size of the function diagram. The engineer and/or the product development team determine all the elements going into the creation of a flow diagram.

Figure 2: Flow function diagram of a hair dryer according to [10]. It shows the functions as blocks and their connections via energy, material, and information flow.

Function trees

A function tree is a diagram focused on the vertical relationships between functions, and aims at capturing hierarchical information. The functions, in a noun + verb structure, are placed within individual boxes, similarly to the flow method. It shows the dependencies among the functions of a system (see Figure 3). A function tree is an object-oriented representation of possible solutions that does not show sequence or timing of functions. Functions at the base level of the tree are defined on the part level, and are specified in detail. Each subsequent level above that combines functions into its parent functions. The higher up on the tree a function is placed, the more child functions will be related to it.
The functions in a function tree link to one another on a hierarchical level, where the overall function of a product sits atop the tree. Parent functions link to subsequent functions (subfunctions) connected at a lower level. There are no limits to the size of trees produced—the size of each tree (the number of branches) is determined by the number of product parts that can be defined on the base level of the tree and how those connect to functions at higher levels of the tree.

**Figure 3: Function tree for a hydraulic pump [6]**

**FAST Diagram**

A function analysis system technique diagram, better known as a FAST diagram, organizes the functions that need to be performed by the product or system under study into two categories: how and why, and organizes the functions by how, why and when. The function block furthest to the left in the diagram represents the final goal of the system, or the highest order of the system. The function furthest to the right of the diagram represents what is assumed
or causative, and is the lowest order function. Two sets of dotted lines separate the highest order of the system from the lowest order, and functions placed between the two dotted lines comprise the scope of the design problem and describe ‘what’ needs to be done to move from assumption to goal. The lines connecting each function block show the critical path taken between the lowest and highest order functions.

Figure 4: An example of a FAST diagram for a PC projector. [11]

Functional Decomposition

Functional decomposition is the process by which engineers identify the overall function for a system or product and break that function down into components to understand the complexity of that product or system. Decomposition is commonly applied during design tasks, such as product dissection, reverse engineering, or ideation, and is an important tool used in industry to improve legacy products or to understand a competitor’s product. Functional decomposition is comprised of two processes: functional analysis and functional synthesis. Functional analysis is the process of identifying functions for an already existing product or system. Functional synthesis is the process of identifying functions for a design where no product or system already exists.
**Function Identification Methods**

The most common function identification methods found throughout the literature include the energy-flow, top-down, enumeration and bottom-up methods [5] [6], according to the function diagrams that are used to describe the methods.

The top-down method begins by determining the overall product function, and then proceeds to decompose that function into its subfunctions, continuing until each function is described at the "lowest" level. In the ideal case, one splits the product function into as many subfunctions as necessary to find a solution for each subfunction. For instance, for a vehicle the main function can be "transport people and goods" and the only solution for this is "car." This solution is easy since the car already exits. If one intends to develop a car, the main function can be split into subfunctions such as "provide energy," "transform linear motion into rotation," etc. until it is possible to find a solution for each function.

The bottom-up method, which is the exact opposite of the top-down method, starts with identifying functions for individual functions and then groups these functions into meta-functions, continuing until defining the system’s overall function. The bottom up method is the least commonly used method of the four in the literature.

The enumeration method is less structured than the top-down method, and amounts to writing down all functions in a list that come to mind, but with no particular strategy for defining or arranging them.

Flow diagrams trace the path of energy, information, and/or material through the product or system, or by starting with a hierarchical diagram, which single functions are further connected by flow(s) of information, material, and energy. Functions are not arranged hierarchically, but connected via links between related function blocks.
The methods for identifying functions and decomposing products are independent from the diagrams used to record the processes.

**Related Work**

Functional decomposition, as mentioned above, is a problem-solving strategy used by engineers to take a complex process and break it down into smaller, simpler parts. It is used as a precursor to the conceptual design phase of the engineering design process to understand the functions of the design being examined. When applied to existing concepts the process is known as analysis, and when it is applied to a design where no concept exists, it is known as synthesis. But while functional decomposition has been lauded as an important tool for engineering in industry, it is a subject often difficult for engineers, especially novice engineers, to fully understand and apply successfully [5]. Prior work has identified a deficiency in working knowledge of function, especially when engineers are asked to decompose a product into its sub-functions [5] [6].

*Booth et al.* [5] tested engineering students on product dissection tasks to evaluate which function identification method is most suited for that particular design task. The study used a within-subjects design to compare the three methods. Students performed three product dissections, one with each method, on a hair dryer, power drill and toy dart gun and were asked to generate a function tree to describe how the product worked. The function trees were evaluated based on total number of functions generated, number of syntax errors and the number of unique (relevant and nonredundant) functions. While they did not find any statistical or qualitative differences between the trees produced by each method, their results suggested that a high cognitive load on the task for novices was high enough to obscure any differences between
methods. The study did find that the most difficult part of the functional decomposition process included identifying functions, choosing function verbs and generating function diagrams. They also reported that engineering students did not understand the distinctions between a function, part name and a design requirement.

_Eckert et al. [6]_ tested a group of 20 engineers with identical educational background on a general function decomposition task. The study used subjects who all earned their undergraduate degrees in mechanical engineering from the same university. Subjects were provided with either a hydraulic pump or a maintenance drawing that showed a section of the pump, and were asked to analyze how the pump worked and summarize their understanding in a function tree. The trees were evaluated on level of abstraction and level of detail. The paper mentions that while most subjects left with a sense that they understood the product to their satisfaction, each participant’s understanding varied. This could pose difficulties for design teams where groups typically are not as homogenous. The study found that every subject tested struggled with defining functions and each had a different definition of what function was. The study suggested that the “subjects had very little idea how to go about a functional analysis and each had their own way of doing it [6].”
Function, behavior and structure

The function-behavior-structure (FBS) ontology [12] conceptualizes product and system design into three interrelated categories, function, behavior and structure. “Humans construct connections between function, behavior and structure through experience and through the causal models based on interactions with the object [13].” Function relates to behavior by establishing a connection between a user’s goals and the measurable effects of the object, and behavior is related to structure.

Figure 5: Images of the a) maintenance drawing and b) hydraulic pump used in [6]

Figure 6: Image showing how augmented reality can bridge the gap between shape and topology to assist with functional understanding
Problem Description

The literature review shows that many engineers and engineering students do not completely understand the function model and do not always use functional decomposition methods correctly. This is most likely due to confusion over the meaning of function, or the perception that the process of decomposing a product or system is too simple, too difficult or unimportant. First, the term “function” has no standardized meaning in engineering and as such, engineering students and engineers are taught conflicting definitions of function [8]. While the issue of multiple definitions of function has been acknowledged to hamper the use and communication of functional descriptions, disambiguation of the term has not been embraced by the engineering community [8]. Due to this, “functional descriptions of technical devices are ambiguous in engineering [8]” and can be troublesome. Eckert et al.’s [6] research shows that this is especially an obstacle when working in a team setting. It is likely that people have different solutions for a product in mind, even when talking about the same product; or at least they have a different understanding of the product’s functionality which is most likely a misconception of the functional model. However, function has been related to other design aspects, behavior and structure. While the definition of function often changes, many design methods do agree that function is one of the key concepts in design reasoning [8]. However, even early research in this field indicates that there is no clear connection between function and the structure of a product [14]. A traditional product dissection does not allow the user to know any information about either aspect of the product, but with the addition of AR, information on the shape and/or topology of the product could be communicated to the user. This idea allows for additional information about the product’s components and the relation between these two aspects (shape and topology) to be shared.
CHAPTER 3 — LITERATURE REVIEW: AUGMENTED REALITY

To overcome the gap between concrete and abstract models, this thesis takes the approach of blending the information that both of these models provide using augmented reality. As described in Chapter 2, function-behavior-structure (FBS) addresses engineering design in terms of three aspects of a product or system: function, behavior and structure. These aspects can be embodied by a set of models, such as CAD models, part hierarchies, and functions diagrams. These models are created along the product development process, usually at different steps.

Augmented reality is a tool that can link these aspects, providing a method for connecting a product’s function to its behavior and structure using means of computer graphics.

Advantages of Augmented Reality

Augmented reality (AR) is a human-computer interaction (HCI) technology in which a user perceives both the real and virtual worlds simultaneously. AR superimposes a user’s natural visual perception with computer-generated information, such as 3D models, in order to integrate these virtual objects into the “real world” as seamlessly as possible. This creates the illusion the virtual and real objects exist in the same physical space. AR has the ability to present this information in a context-sensitive way that is intended for a specific task and location (see Figure 7).
Several items of hardware and software are required in order to make use of an AR system. AR systems may take on one of several configurations, but the most important hardware include a viewing device to capture information about the real world. The viewing device may be based around a head-mounted display (HMD) – seen in Figure 8, a monitor-based visualization, or a mobile display. Information about the real world is usually acquired using a video camera. Further, an AR system needs a computational platform to generate the virtual images layered over the image of the real-world environment. The resulting image – virtual images overlaid onto a real-world environment – is displayed in the output device, which appears as a mixture of real and virtual world to the user.
As computers increase in power and technological power but decrease in size, AR has presented itself as a powerful user tool for context-aware mobile computing environments. The increase in power of mobile devices such as tablets and phones provides a novel way for use of AR applications without tethering the user to any specific area.
**Process and Technology Overview**

One integral aspect of all AR systems is the tracking system. Vision-based tracking is the most common form of tracking system. A camera is used to feed images to a computer to process where, if anywhere, an augmented element should appear, based on their read of objects known as tracking targets. The virtual information appears within a scene relative to the position of the tracking targets.

Natural feature tracking and marker-based tracking are two types of vision-based tracking to track objects. Natural feature tracking uses intrinsic features of the object of interest to identify and track this object. Intrinsic features may be color patches, textures, symbols, or any distinct pattern which can be found on the surface of a feature.

Marker-based tracking involves the addition of fiducial markers (Figure 11) to allow the tracking system to identify and track items. They serve as a point of reference and measure for the system to display the augmented information. Although different marker types may be used, the most common one is known as the template marker, seen in Figure 12. It contains a unique pattern, words, or image for identification in the center, which is encased by a black border. When the system has recognized the pattern within the scene (in a video image), the size, position, and orientation of the virtual information are computed using the dimension of the black border. Thus, virtual information is augmented at the location of the marker.
Tangible Augmented Reality

Tangible Augmented Reality describes the idea of using tangible objects to interact with AR content [21]. Tangible AR stems from the idea of tangible user interfaces, which “couple physical representations (e.g. spatially manipulable physical objects) with digital representations (e.g. graphics and audio) [22].” Tangible or graspable objects are easy to interact with because the user is able to move and rotate the objects as any physical object, and any physical interaction is linked to a virtual interaction, which manipulates the state (i.e., appearance, position, etc.) of the virtual information.
Figure 13: Explanation and types of tangible interactions [23]

Tangible Augmented Reality in Product Development

Tangible AR is a useful approach for engineering design because it provides a method for bridging the gap between physical and virtual information. Physical objects allow for a detailed analysis of the shape of the object, however they also hide information (such as functionality and material) and do not allow one to abstract from the given shape and discover alternative solutions. Abstract models, such as functional models and computer-aided design (CAD) models, facilitate exploration of the design space. On the virtual side of things, CAD models have a fundamental issue of intangibility. Viewing results on a computer monitor does not provide the same realistic and tactile feelings as mock-up models or other physical prototypes. There is a discrepancy between visual and tangible interfaces: what we see is not what we touch [24]. AR allows a user to blend physical and abstract models to mitigate this problem.

Tangible AR has already been successfully applied to several physical prototypes, to enhance the user's perception of a product. The Augmented Reality based Reconfigurable Mock-
Up (ARMO), developed by Park et al. [25], enables interactive changes of shapes of products as well as colors, textures and user interfaces.

![ARMO Mock-up construction.](image)

*Figure 14: ARMO Mock-up construction. a) shows each piece of the mock-up and b), c), and d) show variations of the constructed mockup [25]*

![ARMO Mock-up construction.](image)

*Figure 15: ARMO Mock-up construction. a) shows a constructed mock-up and b), c), and d) show rendering of object with different features [25]*

Similarly, augmented foam [24] is another form of tangible AR that was created to help designers make high-fidelity prototypes for design ideas very quickly. Augmented foam applies AR technologies to a physical object, in the form of blue polyurethane foam. Using Augmented Foam, a blue foam mockup is overlaid with a 3D virtual objects, the same CAD models used for mock-up production. Augmented foam was tested using a mug design and a cleaning robot design. In the study, the designers found that this method allowed them to inspect and evaluate the design alternatives interactively and efficiently. The augmented foam also elevated the
feeling of immersion for participants through multi-sense stimuli and spatial interaction between the designers and their results.

Figure 16: General-purpose AR (a1-a3) and Augmented Foam (b1-b6): (a1) Plane marker (a2) Virtual overlay on a (b3) Augmented Foam on a table, (b4-b6) Augmented Foam with corrected hand visibility (various color cups) [24]

Gillet et al. [26] developed an AR system to allow virtual 3D representations of molecular properties to be overlaid only a tangible molecular model. “The physical model provided a powerful, intuitive interface for manipulating the computer models, streamlining the interface between human intent, the physical model, and the computational activity [26].”
In summary, all reported studies indicate the applicability of tangible AR to product development, and the developed prototypes show that blending physical prototypes with AR has the potential to alter the user’s understanding of a prototype for the better. However, tangible AR has been mainly utilized as a shape enhancer to improve the visible outcome with virtual finishing. This thesis uses tangible AR toward improving user’s understanding of the abstract level of functionality.
CHAPTER 4 — APPLICATION DESIGN AND SETUP

To address the obstacles presented in Chapter 2, this thesis planned and designed an AR application to present information about components and the relation between concepts. This chapter is dedicated to outlining the experimental hypotheses along with the design and implementation of the AR interface in order to test these hypotheses. This chapter first explains the hypothesis and further describes the AR interface designed to test these hypotheses.

Hypotheses

The overarching goal of this study is to examine how users understand and evaluate product function and to test whether providing them with shape and topological information during a design task provides the user with a better understanding of the product’s underlying functions. To study the effect of the context-relation and added shape and topology information, a tablet-based AR application was developed to present users with the shape and topology information while performing a product dissection. Following the literature and the conceptional background (Chapters 2 and 3), augmenting physical objects with additional information explaining context related information should support the user’s understanding of the underlying context. Based on the literature and previous research, two hypotheses were developed.

Hypothesis 1 (information hypothesis): posits that context-related visual information, when combining product related visual information with tactile information (AR shape-based or topology-based dissection method), contributes more to functional understanding than tactile information alone (traditional product dissection).
This hypothesis is based on two observations: Abstract concepts are reinforced by feedback from both visual and tactile channels [27], thus, context related visualizations should help to understand the context. Also, as reported by Marshall [28], “three-dimensional forms might be perceived and understood more reality through haptic and proprioceptive perception of tangible representations than through visual representation alone [28].” AR shows significant promise in overcoming visualization and interaction challenges [29].

Hypothesis 2 (context hypothesis) posits that providing users with context-related information about the design of a product related to its topology (interrelation of geometric elements) during a product dissection task will assist in users’ understanding of the product’s functionality more so than providing users with additional information about the design of a product related only to its shape (geometry).

The topology of a design is frequently used to refer “to how components of a design are connected to one another [30].” Yoshikawa [31] used topology to study the structure of abstract design concepts of functions, attributes and their relationships. Rosen and Peters [30] believed that topology may serve as a foundation for engineering design theory and a unifying framework for methods and tools related to the presentation of geometry and behavior. Topology information is context-related information and an AR application can present topology related information in the right context, which may improve understanding of the topology and its underlying functionality. The second hypothesis can be understood as an extension of the first one. While the second hypothesis focuses only on a visual augmentation of an object, the first one also intends to verify Marshall’s claims for product design that physical objects support learning.
Interface Design

To test the hypothesis, a user study with an AR application was conducted. The AR application following three design principles: Early focus on users and tasks, empirical measurement, and iterative design. These principles, adopted from [32] and [33], were used to determine the type of application necessary to test the two hypotheses, their design and how to implement the AR application.

The application was designed and developed in five steps. First, the required application functions to test the hypotheses were determined (see Section: Determining Functions of the AR Application). With the functions determined, a design concept was developed (see Section: Application Design Concepts) and the functional embodiment of these concepts was further detailed and evaluated using paper prototypes [35] (see Section: Paper Prototype and Evaluation - Functional Representation). The paper prototypes were assessed by a focus group and the look and feel of the selected paper prototype were further evaluated (see Section: Paper Prototype and Evaluation - Look & Feel). The final design was implemented and used for the user study.

Determining Functions of the AR Application

The first step of creating the application design involved compiling a list of functions that an AR product dissection application needs to perform. Use cases for the application that would allow the user to achieve the overall goal were determined as well. Six iterations of the AR application were explored before the current design, seen in Figures 34 and 35, were decided upon.

It was assumed that the AR application, in general, needed to provide functionalities to address similar tasks as a traditional production dissection, which involves exploration of the
internal components of a product to gain a sense of understanding as to how the product works.

With the three aspects of an engineering product in mind – shape, topology and function – it was decided that the application for this study would need to support two use cases to address the two hypotheses, which are further referred to as the shape-based use case and the topology-based use case. The shape-based use case utilizes visual widgets that allow a user to better understand the shape of a product. The shape of every product is a carrier of its functionality and understanding the shape of an element and how it interacts with adjacent shape elements allows the user to better understand the original product’s functionality. Interacting shapes are technically called the product's topology. Thus, the second use case, the topology-based use case requires graphical widgets to allow the user to better understand the topology of elements within a product to allow users to better understand the functionality of a product even further. The topology-based use case addresses hypothesis 2, whereas the shape-based use case addresses hypothesis 1. To point out the difference, the shape-based use case asks the user to understand the function from better understanding the shape but to infer the interactions between components. The topology-based use case visualizes theses interactions, thus, further “simplifying” understanding.

Following the basic dissection task and recommendations from previous research in this area, the following function list (visual functions and interaction functions) was compiled.

For the shape-based use case:

- F1: Visualizing 3D parts context related.
- F2: Visualizing part labels.
- F3: Enabling and disabling of visual widgets and 3D models.
- F4: Selecting parts by names.
• F5: Visualizing internal parts, cutting functionality.

**For the topology-based use case:**

• F1: Visualizing 3D parts context related.
• F2: Visualizing part labels.
• F3: Enabling and disabling of visual widgets and 3D models.
• F4: Selecting parts by names.
• F5: Visualizing internal parts, cutting functionality.
• F6: Show internal parts’ topology.
• F7: Show function groupings of internal parts.

Besides these functions, which address the dissection functionality, the AR application needed to provide basic AR functions such as video rendering and tracking, which are not further explained. Also, functions such as a home button, a reset function, an undo function, as well as application navigation functions need to be incorporated, which are also not further explained at this point. It was presumed that shape information would allow the user to better perceive the external boundaries of an object, especially if the object is hidden, and provide information on its color, texture, and location. Names of components are also often unclear to users, which results in confusion when multiple engineers work on the same product [34]. In a study by Eckert et al. [34], during a verbal analysis of a hydraulic pump, participants often pointed at components rather than naming them or had to use a description of the part’s geometry (ex: “cone” for a piston), function (ex: “sealing ring” for a control disk) or create an analogy in order to come up with a name for the component. Errors during product dissection tasks are often due to a user’s previously held beliefs about a product, instead of their observations. Thus, the AR application should to provide users with information on proper component labels.
Application Design Concepts

The overall application design follows a “virtual lens” concept to look at the internal components of the product without having to open them up as indicated in Figure 18. The user moves a virtual lens over a physical device, a hair dryer in this example. While doing so, the virtual lens shows additional information explaining the device. The devices are typical household devices such as a hair dryer, whose functional decomposition have eluded people in past studies [5] [36] [37]. A tablet computer was determined as the best means for representing the virtual lens and the AR application.

Three different types of graphical widgets were selected to provided context-related informations: context-related 3D models are visualized with 3D models (F1). This is a typical approach and often employed in literature. To support functionality F2, a first design suggested
2D text labels, which are linked to a particular location on the product by arrows. Selecting and grouping functions are supported by menu items and the virtual lens metaphor directly supports the cutting function (F5), which allows a user to virtually look into a physical object. A storyboard depicting all required functionalities was created to visualize what the “virtual lens” application would need to look like.

**Paper Prototype and Evaluation - Functional Representation**

To better assess the storyboard concepts, paper prototypes were created. Figure 19 shows one page of the paper prototype of the AR dissection application. The paper prototype shows a tablet computer and a hair dryer as the product being dissected. The visual widgets for the two use cases were added to this paper prototype. Figure 19 depicts 2D text labels and the selection menu. Navigation button widgets and a text field with instructions (for the study) are also visible. The paper prototype was created to show multiple steps throughout the dissection, each step explaining to the user how to properly use the application for dissecting a product.

The objective of the paper prototypes was to evaluate the functional embodiment using graphics to depict widgets for each function: the **functional design**. For example, whether a selection function should be represented as list or as combo widget.
Therefore, several meetings were hosted with engineering students to assess the paper prototypes and to obtain initial feedback. The participants were told of the purpose of the application and about the difficulties faced by engineers when it comes to functional decomposition and were allowed to walk through the prototype application.

As a result, several participants noted that there was no need for a step-by-step process for a product dissection task, but that it was more important to focus on the models and digital information to assist with the end goal – creating a function diagram.

As a result of this focus group evaluation, a final set of application functions were specified. This set includes a scroll menu on the right side of the application for individual component model selection, various buttons for model & label control and page navigation. The final functional design is as follows:

- **3D view**: This is the main video view, which is superimposed with 3D models indicating certain parts of the product under investigation.
- **Label view**: 2D text labels can be added to the main video view. The labels show the
name of a certain part and are linked to the part by an arrow.

- **Function group:** Certain parts belong to a functional unit, e.g. power supply, air flow, etc.
  The groups are shown as 3D models.

- **Selection menu:** A selection menu allows the user to select single parts to display. The selected parts are highlighted in the menu and visualized as 3D models. Multiple parts can be shown at the same time.

From an interaction point-of-view, the two modes for the application favor two different modalities, which is the main difference between the shape-based and topology-based cases for this study.

- **Shape-based information:** Here, the application provides functions that allow the user to browse through all parts of a certain product. The user gains understanding of the functionality by turning on and off the 3D models and labels for certain parts.

- **Topology-based information:** In this mode, the user can browse through the function groups of a product in addition to the parts browsing. Identifying function groups help the user to:
  
  o a) better understand how the parts of the product contribute to a function, and
  
  o b) understand how the parts within a function group work together to perform the main function.

*Paper Prototype and Evaluation - Look & Feel*

Based on the feedback of the focus group and the set of application functions that need to be implemented for the study, the look and feel of the application was finalized. Five digital prototype options for the application design were developed (Figures 20-24). The design options
followed a typical border layout GUI concept, with a main area for the AR video and the graphical content and other widgets organized at the left and right edge of the frame. With a tablet as the preferred device in mind, it is assumed that the user can easily access the widgets at the left and right border when holding the tablet computer at the left and right edges. All five prototypes follow this layout concept. Button widgets are used to realize the different functions. The prototypes mainly differ in their appearance (Figures 20-24).

Figure 20: Application Design Option 1

Figure 21: Application Design Option 2
Figure 22: Application Design Option 3

Figure 23: Application Design Option 4
A second focus group evaluation was conducted. Participants were asked to assess whether or not the design complies with Nielsen’s [39] heuristics for consistency, user control and flexibility. As a result, option 5, shown in Figure 24, was selected. The focus group was conducted with engineering graduate students (6 in total).

**Application Feature Implementation**

The section introduces the final implementation of all features. The application was realized with ARMaker, which combines OpenSceneGraph and ARToolkit capabilities. A single application was built for each use case, encompassing both interfaces (shape and topology) linked via a ‘Home’ page screen (Figure 25).
Figure 26 shows the main interface for the shape-based use case. The left side of the application shows button widgets providing access to the different visual functions of the application. The right side shows a selection menu, which allows the user to select different 3D components to display. Each selected component is visualized in the main area. This area, which covers the entire display area, realizes the virtual lens metaphor. It shows a video background, displaying the area behind the tablet, along with context-related 3D objects and 2D text labels. The functionality for the shape-based use case essentially allows the user to browse through all parts of a product and to visualize the parts as a graphical overlay onto the physical part.
The interface matches the design as described. Note that the function groups button widget is shown in the topology-based use case only. The groups would appear in a left selection menu.
CHAPTER 5 — USER STUDY STRUCTURE AND DESIGN

A user study was conducted to evaluate the hypotheses using the two interfaces as described, in order to investigate the merits of AR for aiding a product dissection task. The main difference between these interfaces is the information access: The shape-based use case permits the user to access information about single parts whereas the topology-based use case also provides topology information in the form of function groups. This project was submitted to the Institutional Review Board of Iowa State University and subsequently approved and carried out as the user study in this thesis. The approval memo may be found in Appendix G.

User Study Structure

The user study mimics a typical product dissection task in engineering with the goal to create a function diagram. Since both hypotheses predict that AR improves the result of a dissection task, the study approach was to compare an AR-based dissection with a regularly performed dissection on a per-person basis. This requires a repeated measure test and a within-subject study design to determine the individual improvement of each participant. Therefore, each participant was asked to perform two product dissections, one using the AR application (mode 1) and one as a traditional dissection using a screwdriver to serve as a baseline (mode 2). Mode 1 consisted of either the shape-based or topology-based application options. Following previous studies [4] [5] [6], it was decided that the objective for each participant was to create a function diagram of the product, which is the typical outcome of a product dissection task.

Three different products are used for the study include a toy dart blaster, a hair dryer and a clothes iron (Figure 28). The clothes iron, a Sunbeam® Steam Master®, has an approximate
height of 5.5”, width of 4.9” and depth of 12.4” when face down on its soleplate. The weight of the iron is 1.4 pounds. The model used for the toy dart blaster is a Nerf N-Strike Maverick Rev-6 blaster with a length of 12”, height of 8.9”, and a width of 3” at the barrel. This type of blaster, with six foam darts loaded, weighs 1.1 pounds. The hair dryer used is a Conair® Hospitality Series 1875-watt compact styler/hair dryer. The dryer has a height of 9.5”, width of 7.25” and depth of 3.5”. It also has two heat/speed settings and weighs 1.2 pounds.

![Figure 28: a) Sunbeam clothes iron, b) Nerf toy dart blaster, and c) Conair hair dryer](image)

Note that the iron was only used in application practice, to allow participants to familiarize themself with the application. The toy dart blaster and the hair dryer were used for the study tasks. Both the hair dryer and toy dart blaster have been used for product dissection tasks in several previous studies [5] [6], thus using the same components facilitates comparison of the results. Both are considered products of medium level complexity [4] [5].

Given these two modes, the topology-based and the shape-based use case, as well as the two products for the study, participants needed to be split among eight different trials. Splitting participants among the eight trials was initially done via true random assignment using an 8-sided die. Each of the eight trials, seen in Table 1, was associated with a single side of the die,
which was rolled prior to the arrival of each participant. However, over the course of the study, the random assignment of participants was not evenly distributed among the 8 trials. For the last 13 participants, the die was rolled to assign participants only to the less commonly assigned trials (5, 6 and 8), so that there would be even representation among the 8 trials for data analysis. A six-sided die was used to split participants among these three trials. Each of the three trials was associated with two opposing sides of the die.

Table 1: Dissection methods and orders for each of the eight trials

<table>
<thead>
<tr>
<th>Trial #</th>
<th>First Dissection</th>
<th>Second Dissection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dissection Method</td>
<td>Product</td>
</tr>
<tr>
<td>1</td>
<td>Traditional Dissection</td>
<td>Hair Dryer</td>
</tr>
<tr>
<td>2</td>
<td>Traditional Dissection</td>
<td>Hair Dryer</td>
</tr>
<tr>
<td>3</td>
<td>Traditional Dissection</td>
<td>Nerf</td>
</tr>
<tr>
<td>4</td>
<td>Traditional Dissection</td>
<td>Nerf</td>
</tr>
<tr>
<td>5</td>
<td>Augmented Reality</td>
<td>Hair Dryer</td>
</tr>
<tr>
<td>6</td>
<td>Augmented Reality</td>
<td>Hair Dryer</td>
</tr>
<tr>
<td>7</td>
<td>Augmented Reality</td>
<td>Nerf</td>
</tr>
<tr>
<td>8</td>
<td>Augmented Reality</td>
<td>Nerf</td>
</tr>
</tbody>
</table>

Study procedure

Upon arrival, each participant was brought individually into the study work area, shown in Figure 29. This workstation was located in a secluded corner of the Design and Build Lab (DABL) within VRAC, free from distractions. After reading and signing the informed consent document (Appendix D), each participant was assigned a participant ID number to include on each document for the remainder of the study. The participant was then asked to complete a pre-questionnaire (Appendix E) to document their prior experience with different aspects of the engineering design process.
Following the pre-questionnaire, participants reviewed a slideshow conveying information on functions, functional modeling and how to create a functional model (Appendix F). The intent of this slideshow-lesson was to familiarize or re-familiarize participants with the process of functional decomposition and generating a function model for this study using the energy-flow approach.

Next, participants viewed a slide describing the AR application (Figure 30) in order to be introduced the application and its functionality.

*Figure 29: Study work area*

*Figure 30: Slide on the application interface, from the decomposition lesson*
Participants were allowed two minutes to familiarize themselves with the AR application using the example product (clothes iron). Participants were instructed that they should avoid occluding the fiducial markers from the tablet camera’s view and to make sure that the entirety of the marker was always visible on the tablet’s screen. Either action would prevent the application from properly reading the information on the marker.

The intervention started after the participants completed the training session. In this step, each participant was asked to perform two product dissections: one as a traditional product dissection and the other using one of the two AR application interfaces (shape- or topology-based) to virtually view the product’s internal components. One dissection was performed on the hair dryer and the other on the toy dart blaster. The experimenter announced to the participant in which order the participant had to dissect which product, according the Table 1. Tools were provided for the physical dissection.

After each dissection was completed, each participant was asked to produce a function structure model of the product they just dissected.

After completing both dissections, each participant was provided with a multiple choice questions and a post-questionnaire (Appendix E).

Participants were not given a time limit for performing each dissection and thus were allowed to use as much time as they required to complete each dissection and associated function diagram.

Data recording

Data for this study was recorded in multiple ways:

1. Function structure diagrams. The experimenter took photos of each diagram.
2. Function diagram identification questions (multiple choice questions).
3. Pre- and post-questionnaire.

4. Time and event logs.

**Function structure diagrams:** Each participant was asked to complete a function structure diagram for each dissection task to represent their understanding of how the product worked. A white rectangular magnetic dry erase board was provided to participants to produce each function diagram during or after the dissection task performance. The board measured 48” wide and 31” tall. Sixty-five laminated, magnetic 1.5” x 2.5” cards, each containing a function verb and a space for writing a corresponding substantive were lined along the bottom of the dry erase board (see Figure 31). A second set of these function verb cards were laid out on a nearby table within the work area. The function verbs listed on the cards were taken from the Functional Basis, a standardized set of function-related terminology [40]. Both sets were organized in alphabetical order. Four dry erase markers – one black, one blue, one green and one red – were also provided in the work area.

![Function verb cards](image1.jpg)

![Function diagram](image2.jpg)

*Figure 31: a) Examples of function verb cards provided to participant b) Example of a function diagram, generated by a participant.*
The function structure diagram is the main method to measure the user’s understanding of the product. The experimenter took a photo of each function structure diagram when the participant concluded the study. Before photographing, the experimenter wrote a key code beside each diagram on the dry erase board to include in the photo.

**Function diagram identification questions:** Each participant was shown two function diagrams before and after the dissection tasks were performed and asked to identify the product based on the diagram (multiple choice question). Three products were presented for each diagram from which the participant had to choose. The function structure models in both the pre-test and post-test were the same. Thus, each participant was given the opportunity to update his/her answers to the initial two questions after the dissection was completed.

**Pre- and post-questionnaire:** The pre-questionnaire (Appendix E) asked each participant about prior experience with different aspects of the engineering design process such as function diagram knowledge and about their design understanding in general. Also, demographic information about the participant (gender, age range, highest degree, program association) were collected.

The post-questionnaire (Appendix E) asked the participant to reflect on their experience during the study and answer questions associated with their perceived performance, levels of frustration, confusion among others throughout the study’s activities.

**Time and event logs:** During the two dissections, the experimenter used a timeline to manually record data points based on observed participant actions. At 15-second intervals, the experimenter marked each time that the participant performed any of the following tasks:

- Reviewed the function lesson, and which slide was being reviewed.
- Reviewed the multiple-choice function diagram questions asked earlier.
• Started and stopped product disassembly.
• Picked up and set down the tablet application.
• Examined the physical product.
• Started and stopped building their function diagram at the dry erase board.

**User Study Participants**

A total of 44 users participated in this study. All but one participant completed all aspects of the study. This study was aimed towards participants with a background in an engineering field, particularly in mechanical engineering. The process of functional decomposition is largely used by engineering students and professionals, so participants who have a background in an engineering field are more likely to have the appropriate prior knowledge to understand the tasks being asked of them in this study.

Participants were recruited from within Iowa State University, within both the College of Engineering and the Human-Computer Interaction graduate program. Participants were recruited initially via several Iowa State University email lists, posters promoting the study hanging up in engineering buildings on the Iowa State campus, and via word of mouth. The email lists used included the mechanical engineering undergraduate student list, the mechanical engineering graduate student list, and the mass mail list for the Virtual Reality Application Center (VRAC) which contained students and faculty of the HCI graduate student program and all undergraduate research assistants. Sixty-eight percent of participants fell within the 18-25 age range with the other 32% falling within the 26-35 age range. The gender breakdown of participants was 63% male and 37% female.
Demographic Information

Fifty-four percent of participants were graduate students, pursuing either their Masters or doctoral degree. Thirty-nine percent of participants were undergraduate students and the other 7% of participants included nonstudents. Figure 32 shows the full breakdown of participants by college class. Students who had completed their sophomore year or beyond were specifically targeted for participation in the study, as most engineering curricula cover the principles of engineering design during the first two years of study.

The participant group consisted of 28 men and 16 women. In the population, 16 as Asian or Pacific Islander, 15 participants identified as White, 9 as Black or African-American, and 4 as Latino.

Out of the sample, 84.1% of the participants either were engineering students or had obtained at least their Bachelor’s degree in an engineering field. Of that 84.1%, 51.4% of these participants either were students in mechanical engineering or had earned their degree in mechanical engineering. Out of the entire sample, 41% of the participants fell into the category of mechanical engineering.
student or who had obtained their degree in mechanical engineering. A breakdown of participants by field can be found in Figure 33. Participants were randomly divided among the eight counterbalanced trials. With 44 total participants, trials 1, 3, 5, and 7 each had six participants, and trials 2, 4, 6, and 8 each had five participants assigned. Table 2 shows the breakdown of participants by the eight counterbalanced trials.

### Table 2: Breakdown of Participant by Trial

<table>
<thead>
<tr>
<th>Trial #</th>
<th>First Dissection</th>
<th>Second Dissection</th>
<th>Number of Assigned Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TD / dryer</td>
<td>ARS / dart blaster</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>TD / dryer</td>
<td>ART / dart blaster</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>TD / dart blaster</td>
<td>ARS / hair dryer</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>TD / dart blaster</td>
<td>ART / hair dryer</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>ARS / hair dryer</td>
<td>TD / dart blaster</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>ART / hair dryer</td>
<td>TD / dart blaster</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>ARS / dart blaster</td>
<td>TD / dryer</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>ART / dart blaster</td>
<td>TD / dryer</td>
<td>5</td>
</tr>
</tbody>
</table>

**Prior Knowledge and Experience**

In the pre-questionnaire, participants were asked about their past experience with three different aspects of functional decomposition. These questions included experience modeling in CAD (Figure 34), performing product dissections (Figure 35) and decomposing a product into its functions (Figure 36). For each of the three questions, participants were asked to respond yes or no to if they had ever worked within that area. If they responded yes, they were prompted to select a frequency category, 0-5, 6-10, 11-50 and more than 50. Additionally, participants were asked if they had prior exposure to augmented reality or virtual reality, shown in Figure 37.

More than half of the group reported that they had either never modeled in CAD or had modeled less than 5 products. A majority of participants stated that they had never performed a
product dissection. Just under half (20 of 44 participants) reported having created a function model. Surprisingly, when asked about exposure to either augmented or virtual reality, over 60% of participants said they had.

![Figure 34: Prior experience modeling using CAD software](image1)

![Figure 35: Prior experience performing a product dissection](image2)
Figure 36: Prior experience creating function models

![Bar chart showing the number of function models generated by participants with different levels of experience.]

Figure 37: Previous experience with augmented and virtual reality

![Bar chart showing the number of participants who have experienced augmented reality or virtual reality.]

Yes: 28, No: 10, Unsure: 5
CHAPTER 6 — USER STUDY RESULTS, ANALYSIS, AND DISCUSSION

This section presents the results of the user study. The obtained data was analyzed in three ways. First, a quantitative analysis of the function structures was performed. Second, a qualitative analysis was performed. Second, individual function structures were qualitatively assessed and dependencies to groups of participants were evaluated. Third, the questionnaires were evaluated. The section ends with a discussion and starts next with a repetition of the hypotheses.

Hypotheses

The hypotheses for this study are as follows:

**Hypothesis 1** (information hypothesis) posits that additional visual information, when combined with tactile information (AR shape-based or topology-based dissection method), contributes more to a user’s functional understanding than tactile information alone (traditional product dissection).

**Hypothesis 2** (context hypothesis) posits that providing users with context-related information about the design of a product related to its topology (interrelation of geometric elements) during a product dissection task will assist in users’ understanding of the product’s functionality more so than providing users with additional information about the design of a product related only to its shape (geometry).

The two hypotheses allow the researcher to postulate that a user gains better understanding of the functionality of a physical product when it is augmented with additional information unveiling its composition. Mechanical parts implement the functionality of a
product, and knowing their location allows for a better understanding of the product’s functionality. Beyond that, understanding will further improve when the additional information explains the topology of a product. The topology unveils the interaction of parts. Extending the previous statement, the interaction between mechanical parts implements the functionality of a product, thus, knowing their location and interaction with each other allows for a better understanding of the product’s functionality.

**Quantitative Analysis – Function Structure Diagrams**

In the context of this study, functional understanding was measured using function structure diagrams, created by the participants after conducting a dissection task. This analysis evaluated the quality of the diagrams in terms of error. It was adopted from the study carried out in [5]. The number of classification errors made by each participant were counted. The number of errors is related to the quality of the diagram. Classification errors were classified into three areas: syntactical, semantics and relational. Syntactical errors measured the number of parts or components that participants mislabeled or did not label at all. An error was classified as the use of an incorrect component name, as defined by the component names provided in the AR application, regardless if the provided function fit the definition of a function [4] as being a noun and subject pairing.

<table>
<thead>
<tr>
<th>Error Classifications</th>
<th>Classification of Error in SPSS</th>
<th>Description of each classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Syntactical</td>
<td>$k_0$</td>
<td>Error in component name used, as compared to list of product components for each product and shared via both AR interfaces</td>
</tr>
<tr>
<td>Semantics</td>
<td>$k_1$</td>
<td>Error in name of function</td>
</tr>
<tr>
<td>Relational</td>
<td>$k_2$</td>
<td>Error in the flow of material, energy and information through the system</td>
</tr>
</tbody>
</table>

*Table 3: Description of three error categories and their associated mapping in SPSS*
Table 4: Description of the three dissection method categories and their associated mapping in SPSS

<table>
<thead>
<tr>
<th>Dissection Method</th>
<th>Classification of Method in SPSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional product dissection</td>
<td>NAR</td>
</tr>
<tr>
<td>AR shape-based interface</td>
<td>ARS or shape</td>
</tr>
<tr>
<td>AR topology-based interface</td>
<td>ART or topology</td>
</tr>
</tbody>
</table>

Semantics errors looked at each individual function provided on each individual function block. The phrasing of the function itself was evaluated for accuracy. A function was considered an error if the participant added a noun plus verb pairing but it did not make logical sense to the system. It would also be counted as an error if a portion (either the noun or verb slot) on a function was left blank; or if the input/output relations did not match the function transformed within the function block that they entered into and out of.

Relational errors checked the accuracy and correctness of the flow of energy, material and information through the system, through checking the directional arrows connecting the individual function blocks. A given relation was considered an error if the material, energy, or information moving throughout the system is conserved or did not make logical sense to the system as a whole. Also, an incorrectly classified relation (classified by material, energy or information) between two function blocks counted as an error.

Figures 38 and 39 show a distribution of the data for number of syntactical, semantic, and relational errors committed during the study by participants. Both of these graphs show each data point as an individual point, not as a within-subject design comparing each participant’s number of errors from their AR/non-AR dissections against each other. Figure 38 compares the number of errors clustered by the type of error committed, displaying the information by dissection method. Figure 39 compares the number of errors committed clustered by dissection method,
displaying the information by type of error. Individual data points marked on the graphic with a *
are considered outliers to the data set. Individual data points marked on the graphic with a ○
are considered to be possible outliers.

Figure 38: Clustered box plot distribution of errors, by dissection mode
Figure 39: Clustered box plot distribution of errors, by error classification

Evaluating Hypotheses

For Hypothesis 1, statistical significance was sought to establish a difference between the AR dissection and non-AR dissection for all three types of possible errors (syntactical, semantic, and relational). Representing the amount of errors for the traditional (non-AR) dissection and the AR dissection as $k_{X,NAR}$ and $k_{X,AR}$, respectively, the null and alternative hypotheses for each classification of error is as follows. Below, $k_0$ represents syntactical errors, $k_1$ represents semantic errors, and $k_2$ represents relational errors.
Syntactical Errors

\[ H_0: \ k_{0,NAR} = k_{0,AR} \]
\[ H_a: \ k_{0,NAR} \neq k_{0,AR} \]

Semantic Errors

\[ H_0: \ k_{1,NAR} = k_{1,AR} \]
\[ H_a: \ k_{1,NAR} \neq k_{1,AR} \]

Relational Errors

\[ H_0: \ k_{2,NAR} = k_{2,AR} \]
\[ H_a: \ k_{2,NAR} \neq k_{2,AR} \]

A p-test was conducted between the two data sets for each pairing to determine the likelihood of equal variance between the sets (homoscedasticity). Consequently, a paired t-test was performed to compare the number of errors committed during a participant’s traditional and AR dissection, regardless of whether the AR dissection was the shape-based or topology-based interface. The results of this test were \( t(42) = 0.476 \), \( t(42) = 0.765 \) and \( t(42) = 0.094 \) for \( k_0 \), \( k_1 \), and \( k_2 \), respectively, and thus insufficient to reject the null hypothesis.

**Paired Samples Test**

<table>
<thead>
<tr>
<th>Paired Differences</th>
<th>Paired Samples Test</th>
<th>Paired Differences</th>
<th>Paired Samples Test</th>
<th>Paired Differences</th>
<th>Paired Samples Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>Std. Deviation</td>
<td>Std. Error Mean</td>
<td>Mean</td>
<td>Std. Error Mean</td>
<td>Mean</td>
</tr>
<tr>
<td>Pair 1</td>
<td>error count of part names in AR diagram - error count of part names in non-AR diagram</td>
<td>- .32558</td>
<td>2.96564</td>
<td>.45229</td>
<td>-1.23833</td>
</tr>
<tr>
<td>Pair 2</td>
<td>error count of functions in AR diagram - error count of functions in non-AR diagram</td>
<td>.13853</td>
<td>3.04367</td>
<td>.46426</td>
<td>- .79726</td>
</tr>
<tr>
<td>Pair 3</td>
<td>error count of arrow relationships in AR diagram - error count of arrow relationships in non-AR diagram</td>
<td>.93023</td>
<td>3.66167</td>
<td>.64316</td>
<td>- .16589</td>
</tr>
</tbody>
</table>

*Figure 40: Results from a paired sample t-test examining the relationships between the AR and non-AR number of errors for each classification*
For Hypothesis 2, a statistical test was conducted to compare the number of errors committed during each mode of the AR dissection (shape-based and topology-based). Through this as well as the information from the boxplot distributions in Figures 38 and 39, the difference in errors committed by participants using the shape-based and topology-based AR dissection were not deemed statistically significant. Thus, rendering no difference in effectiveness of either application mode.

**Discussion**

Figure 38 and Figure 39 indicate that the number of errors is evenly distributed regardless of the dissection mode and the condition. This would indicate that the AR technology does not provide the assistance to users as postulated. The statistical analysis confirms this observation. No statistical significant results can be found.

However, several trends can be noticed.

A slight trend towards an improvement can be noticed in Figure 39 for the topology-based use case and the shape-based use case. Starting with the latter, the mean error value is lower for the name-of-component-error, $k_0$. Thus, showing a user the component names reduces the errors that they make. This indicates that the user recognizes the components correctly and could correctly relate them to their location in the function diagram model. Although this result is not statistically noticeable, the trend can be observed.

The users were mostly unable to find the correct technical function verb for a part. Note that the AR application does not show the function verb, and the participants had to defer it from their knowledge of parts. Although the majority of all participants were engineers, the results show that their knowledge about these common products, hair dryers and toy dart blasters, was too limited to find relevant terms to describe their functions.
An additional finding in the data unveils and which the experimenter observed pertains to the nationality of the study participants. The study did not exclude participants from countries where English is not the main language spoken. Several participants encountered problems with finding the right terms to use in their verb-noun pairs. It was even noticed that one participant used a dictionary to look up which words to use. It is assumed that this could be one reason for the high standard error.

Analyzing the topology-based use case, it can be noticed that the AR application reduces the standard error of the name-of-component-error $k_0$ and the verb-of-component-error $k_1$. In this application mode, the users are able to see the links between single parts of a function group. It is assumed that this helps the user to find the right terms for a group of parts, for all parts that are connected to a group. Thus, the error does not scatter and is mostly due to additional single parts the participants add to the function structure.

No trend can be noticed when analyzing the relational error: the number of incorrect linked functions. Since it is more difficult to identify correct relations than identifying correct entities, this was expected for every non-AR test and even the shape-based use case. For the topology-based use case, a reduced error was expected since the participants can see the part grouped to function groups, thus, the topology and the functional links are revealed. It might be possible that the participants did not understand that function groups were visualized in the application. It is also possible that the visualization was still not sufficient to allow the participants to transfer the knowledge into the generation of a function structure.

In summary, trends are noticeable that indicate advantages that AR supports the user dissecting a product thus, improving the user’s understanding of the abstract concept of functionality. However, further studies would be required to enhance this observation.
Qualitative Analysis – Function Structure Diagrams

The qualitative analysis evaluates the function structure diagrams on a per-participant basis. Each function structure was evaluated for proper use of verb-noun pairings, use of provided function verbs and part names provided within the application, and the correctness of connections drawn between function blocks, and rates each diagram on a scale of good, moderate and poor. Each function structure was judged by how fully it described the function of the product. As a result, each diagram was then given an overall score of “good,” “moderate,” or “poor.” A function structure is considered as “good” when function subjects and verbs as well as the links between function blocks are mostly correct so that the overall function of the product is recognizable. “Moderate” functions structures show mostly correct words and incorrect links. The overall function of the product is still noticeable. “Poor” function structures show wrong terms, no or wrong relations between functions and an overall function is not noticeable. The number of diagrams that fall into each category are shown in Table 5.

<table>
<thead>
<tr>
<th>Category</th>
<th>Total number of diagrams, including both AR dissection + Non-AR dissection</th>
<th>Number of hair dryer diagrams</th>
<th>Number of toy dart blaster diagrams</th>
<th>Number of AR dissection diagrams</th>
<th>Number of non-AR dissection diagrams</th>
<th>Only the second diagram created by each participant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>13</td>
<td>8</td>
<td>5</td>
<td>5</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Moderate</td>
<td>42</td>
<td>16</td>
<td>26</td>
<td>25</td>
<td>17</td>
<td>23</td>
</tr>
<tr>
<td>Poor</td>
<td>31</td>
<td>19</td>
<td>12</td>
<td>13</td>
<td>18</td>
<td>17</td>
</tr>
</tbody>
</table>
In Table 5, the first column and row indicate the categories that diagrams were sorted into and different types of diagrams, respectively. The second column shows how many the 86 diagrams created in this study (43 AR diagrams, 43 non-AR diagrams) were classified as good, moderate and poor. The third and fourth columns further distinguish how diagrams created for specifically the hair dryer or the toy dart blaster were rated. The fourth and fifth columns show how diagrams created during the AR dissection mode versus the non-AR dissection mode compare. The last column shows how each participant’s second diagram created ranks.

When comparing participants’ first diagrams to their second diagrams, it was found that 6 participants’ second diagrams were rated better than their first, 22 were rated the same as their first, and 15 were rated worse than their first diagram created. For example, if a participant’s first diagram was rated as moderate, and their second diagram was rated as good, then they would be one of 6 participants whose second diagram was more accurate than their first. Breaking it down further, one participant improved the rating between their first and second diagram from bad to good; and five participants improved the rating between their first and second diagrams, improving from bad on their first diagram to scoring moderate on their second diagram.

These ratings were then compared alongside demographic data on participants to see if any trends appeared that would support or oppose assumptions made by the researchers. The next sections show function structure examples for each category and further discusses the observations.

**Function Diagram Examples (Good, Moderate, Poor)**

In this section, six participants’ function structures were cherry-picked and shown to explain the difference between examples of good, moderate, and poor function structures
(Figures 41 through 46). This should help the reader to understand the differences between each classification. All function structures have been evaluated and all function structures assigned to one category are of similar style.

**Good Function Structure Examples**

Figure 41 shows the function structure generated from participant 016 during their physical (non-AR) dissection of the hair dryer.

![Figure 41: Function structure created by participant 016 while performing the physical dissection of the hair dryer. This example is a good representation of the functions of a hair dryer.](image)

This function structure is considered as good by the researcher because it logically describes the system on which it is designed. The participant successfully depicts the interactions between energy (electricity), material (air), and information (interaction with the buttons on the device) and how this process meets the product’s intended goal: to “blow” hot or cold air out of the system. This is identified through the correct use of colors for each type of energy, material and information, clear verb-noun phrases used to show function, using proper titles for parts of the system such as coils and blade, and linking each function and item of information together to form the hair dryer system.
This participant is a Ph.D. student in human-computer interaction who had prior experience modeling products with CAD and with augmented and/or virtual reality, but no prior experience with dissecting products or functional modeling. This participant used the AR application only lightly (0-50 clicks) during their AR dissection task. This participant correctly identified the electric toothbrush and pencil sharpener in both the pre- and post-questionnaire – they stated in their post-questionnaire that they were unsure of their performance on the study tasks. This participant identified the Nerf dart blaster as more challenging than the hair dryer to dissect and decompose into its functions.

Figure 42 shows the function structure generated by participant 053 during their AR dissection of the Nerf dart blaster. This function diagram is also rated as good because the participant correctly incorporated terminology found within the application on each of his/her function blocks.

![Figure 42: Function structure created by participant 053 while performing the AR dissection of the Nerf dart blaster. This example is a good representation of the functions for a Nerf dart blaster.](image)

This is a Masters student in computer science who did not have prior experience modeling products with CAD. This participant has had experience dissecting products and
creating functional models, and with augmented and/or virtual reality. This participant used the AR application only lightly during their AR dissection task. This participant correctly identified the electric toothbrush and pencil sharpener in both the pre- and post-questionnaire and stated in their post-questionnaire that they believed they performed somewhat successfully on the study tasks. This participant also identified the Nerf dart blaster as more challenging than the hair dryer to dissect and decompose into its functions.

**Moderate Function Structure Examples**

Figures 43 and 44 depict moderate function structures generated by participants. Figure 43 shows the structure created by participant 009 while performing the AR dissection of the hair dryer. This function structure is considered as moderate because the participants demonstrated a general understanding of the product. The correct function names are an indication of this. However, there are errors visible in the functions’ labeling as well as how they are connected. The function structure also includes flowing material, energy and information, but omits how the imported air moves through the system – the “Cool button” and the “High” and “Low” heat settings determine if cold or warm air will be exported from the system, and at what velocity.

*Figure 43: Function structure created by participant 009 while performing the AR dissection of the hair dryer. This example is a moderate representation of the functions for a hair dryer.*
This function structure was prepared by a Ph.D. student in mechanical engineering. On the pre-questionnaire, they stated that they had experience with modeling products in CAD but had not performed a product dissection or done any functional modeling and had never experienced augmented and/or virtual reality prior to the study. This participant used the AR application only lightly during their AR dissection task. This participant correctly identified the electric toothbrush and pencil sharpener in both the pre- and post-questionnaire and stated in their post-questionnaire that they believed they performed somewhat successfully on the study tasks. This participant also identified the Nerf dart blaster as more challenging than the hair dryer to dissect and decompose into its functions. Figure 44 shows the structure of the Nerf dart blaster. It is considered as moderate because the participants demonstrated a general understanding of the product. The correct function names are an indication for this. However, there are errors visible in the function labeling as well as how they are connected. It also includes material, energy and information, but does not describe how the actions listed on each function block is achieved. Both errors lead to less accurate function structures.

Figure 44: Function structure created by participant 035 while performing the physical dissection of the Nerf dart blaster. This example is a moderate representation of the functions for a Nerf dart blaster.
This participant is a Ph.D. student in computer science with prior experience in modeling products with CAD and with augmented and/or virtual reality, but no prior experience with dissecting products or functional modeling. This participant used the AR application only lightly during their AR dissection task. The participant only successfully identified the electric toothbrush on the pre- and post-questionnaires, and they analyzed their performance on the study as successful. This participant identified the hair dryer as more challenging than the Nerf dart blaster to dissect and decompose into its functions.

**Poor Function Structure Examples**

The function structures shown in Figures 45 and 46 are considered poor. The function structures vary in which way they are inaccurate, so it is difficult to know whether to attribute the quality of these structures to lesser understanding of how each product functions or to confusion on how to perform the task identified in the study. In general, neither the function labels are correct nor are the function interactions. This indicates that the participants did not gain an adequate understanding of the product.

![Function structure generated by participant 036 during the AR dissection of the Nerf dart blaster. This example is a poor representation of the functions for a Nerf dart blaster.](image-url)
The function structure in Figure 45 was created by a Ph.D. student in mechanical engineering. On the pre-questionnaire, they stated that they had experience with modeling products in CAD and product dissection, and had experienced augmented and/or virtual reality, but had not done any prior functional modeling. This participant made use of the AR application a medium amount during their AR dissection task. This participant also only successfully identified the electric toothbrush on the pre- and post-questionnaires – they stated in the post-questionnaire, they analyzed their performance on the study as successful. This participant identified the hair dryer as more challenging than the Nerf dart blaster to dissect and decompose into its functions.

Figure 46: Function structure generated by participant 014 while performing the physical dissection of the hair dryer. This example is a poor representation of the functions for a hair dryer.

The function structure in Figure 46 was created by Ph.D. student in mechanical engineering. This participant has had experience modeling products with CAD, but has not had experience dissecting products, creating functional models, or with augmented and/or virtual
reality. This participant made use of the AR application a medium amount during their AR dissection task. This participant did not correctly identify either the electric toothbrush or the pencil sharpener in either the pre- or post-questionnaire, thought they still rated their performance on the study tasks as somewhat successful. This participant also identified the Nerf dart blaster as more challenging than the hair dryer to dissect and decompose into its functions.

Discussion

The qualitative analysis unveiled several trends.

A general assumption by the experimenter was that participants with a background in mechanical engineering, particularly those who had already completed their bachelor’s degree, would create more accurate function structures. In the United States, accredited mechanical and similarly named engineering undergraduate programs are required to teach students to model, analyze, design and realize physical systems, components and processes, so it was assumed that participants with this educational background would have learned this skillset at some point during their education. In fact, both of the participants representing the poor examples of function structures are Ph.D. students in mechanical engineering, countering the assumption that Ph.D. students studying mechanical engineering are likely to perform better on the study based on their educational backgrounds.

Tables 6-8 show breakdowns of the function diagrams split between good, moderate and poor based on participant educational background and current standing. One assumption made by the researcher was that participants further along in their education would perform better on the study tasks since they had progressed further in their coursework (i.e. a Masters student should perform greater than a Freshman). These results are shown in Tables 6 and 7. Table 6
shows that a much higher percentage of graduate students generated “good” function structure diagrams when compared to their undergraduate counterparts. The three non-student participants each completed their Bachelors degree in an engineering field, and all scored either “good” or “moderate” on both of their diagrams. Table 7 breaks these demographics down further, showing how participants’ diagrams were rated based upon what year of study they were currently in (i.e. Undergraduate Junior). From this table it is seen that all participants that created “good” diagrams were upperclassmen (juniors and seniors), graduate students, or non-students who had already completed their Bachelor’s. This does correspond to the researcher’s assumption that participants further along in their degree program would have a greater knowledge of engineering design and product function coming into the study. Table 8 depicts how participants’ diagrams were rated based upon whether the participant studied mechanical engineering, another form of engineering or a field other than engineering. Accredited mechanical engineering undergraduate programs are required to teach students to model, analyze, design and realize physical systems, components and processes [1], and so it was assumed that participants with this educational background would perform better on the dissection tasks and generate better function structure diagrams. Most engineering undergraduate programs include courses on analysis and design in some form, so the researcher also assumed that participants with a background in any form of engineering would perform better than participants without any engineering background.
Table 6: Distribution of good, moderate, and poor diagrams based on undergraduate student, graduate student, or non-student participant classification, by degree

<table>
<thead>
<tr>
<th>Participant Classification, by Degree</th>
<th>Undergraduate Student</th>
<th>Graduate Student</th>
<th>Non-Student</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>1</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Moderate</td>
<td>18</td>
<td>21</td>
<td>3</td>
</tr>
<tr>
<td>Poor</td>
<td>15</td>
<td>16</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 7: Distribution of good, moderate, and poor diagrams based on student classification and year of study

<table>
<thead>
<tr>
<th>Classification, by Year</th>
<th>Undergrad Freshman</th>
<th>Undergrad Sophomore</th>
<th>Undergrad Junior</th>
<th>Undergrad Senior</th>
<th>Master's Student</th>
<th>PhD Student</th>
<th>Non-student</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Moderate</td>
<td>3</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>5</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>Poor</td>
<td>1</td>
<td>4</td>
<td>8</td>
<td>2</td>
<td>1</td>
<td>15</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 8: Distribution of good, moderate, and poor diagrams based on participants’ area of study (or past area for non-students)

<table>
<thead>
<tr>
<th>Background</th>
<th>Mechanical Engineering</th>
<th>Other Engineering</th>
<th>Non-Engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>8</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Moderate</td>
<td>19</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>Poor</td>
<td>11</td>
<td>14</td>
<td>6</td>
</tr>
</tbody>
</table>

The rating also showed that participants who created good and moderate function structures all only made light use of the AR application (defined as pressing buttons within the application between 1-50 times) while performing their AR dissections. Both participant examples who generated poor function structures used the application a medium amount (making 51-75 clicks within the application). This might have two reasons. Participants with a good function understanding did need the AR application, but only to find the correct terms. However, they already had a mental model of the underlying functionality and were able to transfer this into a function structure. This would indicate that the good participants are good in any case and do not need support from the application. This observation also indicates that the AR application
does not support participants with little functional understanding. Participants who clicked often apparently searched for guidance, which the application did not provide. The AR application uses mechanical engineering terminology and concepts, which might be not relatable for a wide range of people. Game-based concepts might be better for those participants, which is subject to further studies.

Table 9: Distribution of good, moderate and poor diagrams during the AR dissection tasks, based on application use as measured by number of clicks within application.

<table>
<thead>
<tr>
<th>Click Rate in AR application</th>
<th>Light (0-50 clicks)</th>
<th>Medium (51-100 clicks)</th>
<th>Heavy (≥101 clicks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Moderate</td>
<td>12</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Poor</td>
<td>7</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

Application use

It was thought that participant background may factor into the frequency of application use during the study. While each participant was granted the use of the AR application during one of the product dissection tasks, not all participants made use of this tool equally. Figures 47 and 48 show boxplot distributions of application use, measured by the number of buttons pressed during that session, by educational field of study and level of education, in order to see a difference in frequency of application usage based on one of these factors.

Graduate students tended to use the application slightly less often than undergraduate students. Application use for participants with an engineering background fell within a slightly narrower range. Usage by participants in graduate programs (Figure 48) fell within a narrower range than that of undergraduate participants. Both trends are likely due to a higher familiarity with the subject matter of the study for these subsets of participants, thus a higher comfort level with the application, less reliance upon the application and a lower probability of pressing
random buttons within the application — though of course several outliers exist. Figures 47 and 48 relate to what is seen in Tables 6 and 8 on graduate students and students in mechanical engineering: A higher percentage of graduate students and students in mechanical engineering performed created good and moderate function structures; these two groups made use of the application slightly less than participants in other groups likely due to their familiarity with the material, fitting the idea that participants who created good or moderate function structures used the application slightly less than those who created poor function structures.

Figure 49 shows a box plot distribution based on change in answers on the function structure pre-test and post-test. The five categories represented on the chart are: answered both questions correctly on the pre- and post-test, answered one question correctly on the pre- and post-test, number of correct responses decreased between pre- and post-test, answered both questions incorrectly on the pre- and post-test, number of correct responses increased between pre- and post-test. Excluding outliers, the click rate range for participants who answered both questions on pre- and post-test correctly was on average slightly lower than ranges for participants that performed less well on the pre- and post-test.

From Table 9 and Figure 49, participants who generated moderate or good function structures, and also participants who performed better on the pre- and post-test both used the AR application less than groups of participants who created poor function structures and/or performed poorly on the pre- and post-test, fitting the claim that participants with a good function understanding did need to use the AR application in order to perform well. Further discussion on the results of the pre- and post-test begin on page 86.
Figure 47: Box plot distribution of application use during AR task, by educational field
Figure 48: Box plot distribution of application use, by level of education
Figure 49: Box plot distribution of application use, by change in function structure pre- and post-test scores. The pre-test included two multiple choice questions to identify function structures. The post-test included the same two questions, revisited.
Questionnaire and Test Analysis

Participants were asked a range of questions within the pre- and post-study questionnaires. The questionnaires in their entirety may be found within Appendix E.

Participant Self-Reported Prior Knowledge and Experience

In the pre-questionnaire, participants were asked about their past experience with three different aspects of functional decomposition. These questions included experience modeling using CAD software (Figure 50), performing product dissections (Figure 51) and decomposing a product into its functions (Figure 52). For each of the three questions, participants were asked to respond yes or no on whether they had ever worked within that area. If they responded yes, they were prompted to select a frequency category, 0-5, 6-10, 11-50 and more than 50, measured in number of products that they have modeled, dissected or decomposed. Additionally, participants were asked if they had prior exposure to augmented reality or virtual reality, shown in Figure 53.

More than half of the group reported that they had either never modeled in CAD or had modeled fewer than 5 products. A majority of participants stated that they had never performed a product dissection. Just under half (20 of 44 participants) reported having created a function model. When asked about exposure to either augmented or virtual reality, over 60% of participants said they had. Overall, the majority of participants in this study had at least some prior experience working with CAD models and with augmented reality. Most participants did not, however, report prior experience with performing product dissections or generating function models – this is counter to the assumption that most students studying engineering, particularly mechanical engineering, have been exposed to both activities at some point in their undergraduate coursework.
Figure 50: Prior experience modeling using CAD software

Figure 51: Prior experience performing a product dissection
Figure 52: Prior experience creating function models

Figure 53: Previous experience with augmented and virtual reality
Engineering and Design Values

As part of the pre-study questionnaire, participants were given a list of 22 common design activities and asked to identify the 6 most important and 6 least important design activities, based on their experience. During design-focused courses, engineering students are taught ways to approach and solve an engineering design problem. Understanding which design activities participants hold in highest and lowest regard may serve as an indication of which types of tasks they are most and least willing to spend effort, time and focus on.

Figures 54 and 55 show the pre-questionnaire selections that participants made for most- and least important design activities, respectively. The six most important design activities that participants chose, in order, were: understanding the problem, brainstorming ideas, creating prototypes, identifying constraints, making decisions, and testing products. In order, participants selected as the six least important design activities: sketching ideas, making trade-offs, applying methods of creativity, generating alternatives, abstracting functions, and visualizing data.

To test whether the study tasks influenced participant opinion on what they consider the most and least important design activities, participants were given the same list of common design activities during the post-questionnaire and asked to again rank their opined most important and least important design activities.

Figures 56 and 57 show the overall selections that participants made after their participation in the study. On the post-questionnaire, the top six most important design activities that participants chose, in order were: understanding the problem, identifying constraints, brainstorming ideas, creating prototypes, building models, decomposing products and visualizing data. Decomposing products and visualizing data tied for the sixth slot. On the post-questionnaire, the six least important design activities, in order, were: generating alternatives,
making trade-offs, applying methods of creativity, sketching ideas, understanding others’ point of view, and running user tests.

Participants consistently ranked understanding the problem, brainstorming ideas, creating prototypes, and identifying constraints as the most important design activities on the pre- and post-study questionnaire and sketching ideas, making trade-offs, applying methods of creativity, and generating alternatives as the least important design activities on both the pre- and post-study questionnaires.

After participating in the study, participants were much more likely to include decomposing products and/or visualizing data and products in their list of most important activities — visualizing data and decomposing products, respectively, went from ranked sixth and seventh on the least important list during the pre-questionnaire to being tied for sixth on the most important list in the post questionnaire. Though with the study’s emphasis on both areas during study tasks, participants may have felt pressured to select these as important either to please the researchers or due to thinking that they were the “correct” answers.

**Function Structure Tests**

Participants were given a ‘pre-test’ consisting of two multiple choice questions regarding function structures. Both questions asked participants to identify the product represented by a provided function structure and were given three options to select from. After participating in the dissection tasks associated with the study, the participants were given a ‘post-test,’ wherein they were presented with the same two function structures and were given the opportunity to change their responses previously given to the two structures.
Figure 54: List of design activities in descending order for what participants listed as the most important prior to participation in the study.
Figure 55: List of design activities in descending order for what participants listed as the least important prior to participation in the study.
Figure 56: List of design activities in descending order for what participants listed as the most important after participation in the study.
Figure 57: List of design activities in descending order for what participants listed as the least important after participation in the study.
Figure 58: Participants were given a pre-study test consisting of two questions asking them to identify products when provided with their function structures. Participants were given the opportunity to revise their answers in a post-study test. This chart shows how accurately participants scored between the pre- and post-test.

Analyzing the Function Structure Test Results

Of the 43 participant scores included, only three participants answered more questions correctly on the post-test than the pre-test, effectively improving their score. Two participants answered fewer questions correctly on the post-test than the pre-test, effectively worsening their score. As an example, one participant who improved their score on the post-test only correctly identified one product in the pre-test, but correctly identified both products in the post-test. The remaining 38 participants’ performance remained the same on both the pre- and post-tests: either identifying both products correctly, only one product correctly, or neither product correctly on both the pre- and post-tests, as shown in Figure 58.

The participants in this ‘consistent’ group spent, on average, more time completing their AR task than the Non-AR task, while participants in both the ‘improved’ and ‘worsened’ groups spent, on average, more time completing their Non-AR task than their AR task. The consistent
group utilized the AR application during their AR task more than the other two groups, averaging 68.7 application button clicks per use, compared to 57 clicks for the ‘improved’ group and just 22.5 clicks for the ‘worsened’ group.

The vast majority of students in the consistent group came from engineering backgrounds (83.3%), with roughly half of those students coming from mechanical engineering. Exactly half of the consistent participants were graduate students. Over 70% of this group had previously used CAD, just under 50% had performed a product dissection before, and two-thirds had not experienced functional modeling or function structures.

All three participants in the ‘improved’ group were undergraduate students in engineering fields other than mechanical engineering. Two of the participants had prior exposure to CAD, only one had experienced product dissection, and none had experienced functional modeling.

The ‘worsened’ group included one graduate student in mechanical engineering and one undergraduate student in a non-engineering field. Of these two participants, the non-engineering undergraduate student had exposure to CAD and neither participant had experienced a product dissection or functional modeling.

Table 10 shows how participants performed on both the pre-test and post-test, divided by whether the participant was an undergraduate or graduate student, or a non-student. Table 11 depicts this same information, but breaks down by whether participants studied mechanical engineering, another area of engineering or a non-engineering subject (all three non-student participants completed their bachelor’s degrees in mechanical engineering and are thus included in that category). Though not statistically supported, graduate students in any engineering field may be more likely to perform better on the pre- and post-tests, though this is likely from prior engineering knowledge, including experience visualizing products in CAD software, than from
use of the AR application during the AR task. The AR application may only assist participants with an engineering mindset who understand product structure from prior experience visualizing products in CAD, but no formal training in product dissections or functional modeling, forcing them to rely more heavily on the AR application to further their understanding of the product’s internal functions. This engineering mindset may not necessarily need to be mechanical engineering.

Table 10: Participant responses on pre- and post-test broken down by educational level.

<table>
<thead>
<tr>
<th></th>
<th>Answered both questions correct in pre- and post-test</th>
<th>Answered one question correct in pre- and post-test</th>
<th>Answered neither question correct in pre- and post-test</th>
<th>Participant increased their number of correct responses between pre- and post-test</th>
<th>Participant decreased their number of correct responses between pre- and post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undergraduate Student</td>
<td>6</td>
<td>6</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Graduate Student</td>
<td>9</td>
<td>9</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Non-Student</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 11: Participant responses on pre- and post-test broken down by educational field.

<table>
<thead>
<tr>
<th></th>
<th>Answered both questions correct in pre- and post-test</th>
<th>Answered one question correct in pre- and post-test</th>
<th>Answered neither question correct in pre- and post-test</th>
<th>Participant increased their number of correct responses between pre- and post-test</th>
<th>Participant decreased their number of correct responses between pre- and post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Engineering</td>
<td>9</td>
<td>7</td>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Other Engineering</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Non-Engineering</td>
<td>5</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
Comparison Among Participants

Of the six participants whose function structures are shown in Figures 41 through 46, five are Ph.D. students, three of which are studying mechanical engineering: participants 009, 014, and 036. Participant 016 is pursuing a Ph.D. in Human-Computer Interaction and participant 053 is a master’s student in computer science. In fact, both of the participants representing the poor examples of function structures are Ph.D. students in mechanical engineering, countering the assumption that Ph.D. students studying mechanical engineering are likely to perform better on the study based on their educational backgrounds.

All six participants, apart from 053 (Figure 42), have had prior experience with modeling products using CAD software. Though participants 053 (Figure 42) and 036 (Figure 45) were the only two of the six who identified that they had experience with either product dissections or functional modeling. With nearly all the participants having experience in CAD, it is difficult to identify whether that has any impact on their performance during the study.

For the participants who created good and moderate function structures, all only made light use of the AR application (defined as pressing buttons within the application between 1-50 times) while performing their AR dissections. Two of the three participants generating poor function structures use the application a medium amount (making 51-75 clicks within the application).

Results from the post-questionnaire indicate that this group of participants considered the AR application often difficult to use, and several had difficulty understanding the tasks that they were asked to perform. It is possible that the application interface only assisted participants who already understood the product’s structure.

The questionnaire also shows this group agreed that visual information on a product,
presented through a product model simulation, would contribute to their understanding of product function more than seeing textual information. The AR application provided visual information to the user in the shape-based mode, and both visual and textual information to the user in the topology-based mode. One hypothesis predicted that textual information, when combined with visual information, would provide more context for participants to create more accurate function structures. It is likely that the textual information provided by the AR application only assisted participants who already understood the product’s structure.

Participants who performed well in this study likely gained their understanding of product function and structure prior to their participation in the study, likely from past courses, although this idea is not statistically supported. The AR application would only have aided this group of participants during the study. Other participants likely spent the bulk of the study working to understand the material and the addition of the AR application overcomplicated the study for them. This group seems to include the participants who merely copied the three function blocks shown in Figure 64 from the example provided and did not put genuine effort into creating their function structures and performed poorly. The application should be tested with a group of students solely from one background (e.g. mechanical engineering students all at the same level in their studies), to test whether the application will make a difference in a particular population.

**Identifying function structures**

This study measured participants’ ability to identify function structures by testing them on two function structures prior to completing the study’s tasks, and the same two function structures after completing the tasks.
Generally, in this study participants whose function structures accurately depicted their given products’ functions were more likely to answer the questions on identifying function structures in the pre- and post-questionnaires correctly. But the ability to identify a product from viewing its function structure does not correlate to being able to properly create them or not. Four of the participants (016, 053, 009 and 036) all correctly identified the two products in both the pre- and post-questionnaire questions on function structures, though the function structures that these participants created themselves during the task ranged widely in their accuracy.

Testing participants on only two function structures before and after the intervention does not provide enough information to fully measure participant understanding of function structures. Future studies should assess participants more thoroughly – it is recommended to include ten questions on function structure identification in the pre- and post-questionnaire.

Feedback

When participants reached the end of the user study, they were given a post-test and a post-questionnaire to complete. The post-questionnaire can be found in Appendix E.

Participant Feedback

In the post-questionnaire, participants were asked what was the more challenging product to decompose, the hair dryer or the Nerf toy dart blaster. Participants overwhelmingly responded that the Nerf toy dart blaster was more challenging to decompose into its functions. While both products were considered to be of medium complexity [4][5], clearly one product was more difficult for participants in this study to maneuver than the other.
Participants were asked to rate various aspects of their participation in the study using a 5-point Likert scale. The categories included rating their perceived performance, amount of effort exerted, and levels of frustration, confusion, ease of use, and fun using the application. Figures 60-66 show the distribution of responses to the seven self-evaluating questions. They were also asked how the addition of visual and textual information contributed to their understanding of product function, Figures 67 through 70.

Most of the feedback was generally positive, though frustration, confusion and ease of use scores varied more, with more participants experiencing issues in these areas. Participant feedback in these areas, particularly where participants struggled, should be considered in future iterations of this application and study.
Figure 60: Participants rate their performance in the study

Figure 61: Participants rate the amount of effort they had to expend completing the study
Figure 62: Participants rated their level of frustration during the study

Figure 63: Participants rated their levels of confusion during the study
Figure 64: Participants rate the clarity of instruction for application use

Figure 65: Participants rate the enjoyability experienced in using the application
Application Evaluation

When asked to evaluate the effectiveness of the application on their understanding of function, thirty-three participants agreed that visual information contributed to their understanding of product function. Thirty-seven responded in kind as related to textual information. On whether visual or textual information was more integral to their understanding than the other, the general consensus was that textual information did not lend as much knowledge as visual information. While more than half of participants responded to these questions in the affirmative, the results of both the quantitative and qualitative analyses do not seem to support that participants’ function structure diagrams were significantly improved in the presence of either additional visual or textual information.
Figure 67: Participants rate if visual information contributed to their understanding of function

Figure 68: Participants rate if textual information contributed to their understanding of function
Figure 69: Participants rate if visual information is more helpful than textual information

Figure 70: Participants rate if textual information is more helpful than visual information
CHAPTER 7 — CONCLUSIONS AND FUTURE WORK

This thesis has taken an approach to evaluate how the addition of contextual shape and topology information provided a product dissection task contributes to functional understanding. This approach involved development of an AR-supported product dissection application with two interfaces. Both interfaces of the application were tested against a traditional product dissection to see how the presence of shape and topological information during a dissection altered a user’s application of functional decomposition, as compared to during a traditional product dissection.

A user study was conducted in which participants were instructed to perform two product dissections, one an AR-supported dissection using one interface of the application and the other a traditional product dissection to serve as a baseline. Participants were asked to generate a function diagram based on their understanding of the product for both dissections. Dissections were counterbalanced to avoid seeing a learning effect. The function diagrams generated by participants were compared by analyzing the number of errors made in the following areas: syntax errors, semantics errors and relational errors between functions. Each function diagram generated was further evaluated qualitatively for proper use of verb-noun pairings, use of provided function verbs and part names provided within the application, and the correctness of connections drawn between function blocks to determine trends within the data. Function diagrams were then rated as “good,” “moderate,” or “poor.” Examples from several participants within each category were presented to depict the differences between each category.

Future iterations of this study should eliminate the topology-mode of the AR application and merely test one AR application mode versus a baseline to determine if any statistical
significance occurs. Additional questions should be added to the pre- and post-study tests to gain a better sense of how participants alter their responses after the study. Participants should be tested on their identification of function diagrams between performing the two dissections to gauge any changes after performing one dissection or two. Many participants struggled to grasp generating an energy-flow diagram. A future study should consider testing participants on generating function trees, a slightly simpler form of function diagram.

Future work in the area of applying augmented reality to support design tasks should focus on providing dynamic visualizations of the flow of energy, material and information throughout the system. While providing visualizations in the form of product component models and labeling to convey deeper product knowledge is a step in the right direction to assist engineers and designers, providing a visual demonstration of how matter and signals move throughout the system will further strengthen the tie between AR and visualizing function. Providing information that further highlights the interrelationships between product components, behavior and structure using AR to visualize those connections will improving understanding of product function.
REFERENCES


[16] Microsoft hololens. Available at: https://www.microsoft.com/microsoft-hololens/en-us


[20] ARToolKit, Available at: https://www.hitl.washington.edu/artoolkit/


## APPENDIX A

### THE FUNCTIONAL BASIS

*Table 6 The functions and flows that comprise the functional basis reconciled flow set [40]*

<table>
<thead>
<tr>
<th>Class (Primary)</th>
<th>Secondary</th>
<th>Tertiary</th>
<th>Correspondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branch</td>
<td>Separate</td>
<td></td>
<td>Isolate, sever, disjoin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Divide</td>
<td>Detach, isolate, release, sort, split, disconnect, subtract</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extract</td>
<td>Refine, filter, purify, percolate, strain, clear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Remove</td>
<td>Cut, drill, lathe, polish, sand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distribute</td>
<td>Diffuse, dispel, disperse, dissipate, diverge, scatter</td>
</tr>
<tr>
<td>Channel</td>
<td>Import</td>
<td></td>
<td>Form entrance, allow, input, capture</td>
</tr>
<tr>
<td></td>
<td>Export</td>
<td></td>
<td>Dispose, eject, emit, empty, remove, destroy, eliminate</td>
</tr>
<tr>
<td></td>
<td>Transfer</td>
<td></td>
<td>Carry, deliver</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transport</td>
<td>Advance, lift, move</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transmit</td>
<td>Conduct, convey</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Guide</td>
<td>Direct, shift, steer, straighten, switch</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Translate</td>
<td>Move, relocate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rotate</td>
<td>Spin, turn</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Allow DOF</td>
<td>Constrain, unfasten, unlock</td>
</tr>
<tr>
<td>Connect</td>
<td>Couple</td>
<td></td>
<td>Associate, connect</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Join</td>
<td>Assemble, fasten</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Link</td>
<td>Attach</td>
</tr>
<tr>
<td></td>
<td>Mix</td>
<td></td>
<td>Add, blend, coalesce, combine, pack</td>
</tr>
<tr>
<td>Control Magnitude</td>
<td>Actuate</td>
<td></td>
<td>Enable, initiate, start, turn-on</td>
</tr>
<tr>
<td></td>
<td>Regulate</td>
<td></td>
<td>Control, equalize, limit, maintain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increase</td>
<td>Allow, open</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decrease</td>
<td>Close, delay, interrupt</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Change</td>
<td>Adjust, modulate, clear, demodulate, invert, normalize, rectify, reset, scale, vary, modify</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increment</td>
<td>Amplify, enhance, magnify, multiply</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decrement</td>
<td>Attenuate, dampen, reduce</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shape</td>
<td>Compact, compress, crush, pierce, deform, form</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Condition</td>
<td>Prepare, adapt, treat</td>
</tr>
<tr>
<td></td>
<td>Stop</td>
<td></td>
<td>End, halt, pause, interrupt, restrain</td>
</tr>
<tr>
<td></td>
<td>Prevent</td>
<td></td>
<td>Disable, turn-off</td>
</tr>
<tr>
<td></td>
<td>Inhibit</td>
<td></td>
<td>Shield, insulate, protect, resist</td>
</tr>
<tr>
<td>Convert</td>
<td>Convert</td>
<td></td>
<td>Condense, create, decode, differentiate, digitize, encode, evaporate, generate, integrate, liquefy, process, solidify, transform</td>
</tr>
<tr>
<td>Provision</td>
<td>Store</td>
<td></td>
<td>Accumulate</td>
</tr>
<tr>
<td></td>
<td>Contain</td>
<td></td>
<td>Capture, enclose</td>
</tr>
<tr>
<td></td>
<td>Collect</td>
<td></td>
<td>Absorb, consume, fill, reserve</td>
</tr>
<tr>
<td></td>
<td>Supply</td>
<td></td>
<td>Provide, replenish, retrieve</td>
</tr>
<tr>
<td>Signal</td>
<td>Sense</td>
<td></td>
<td>Feel, determine</td>
</tr>
<tr>
<td></td>
<td>Detect</td>
<td></td>
<td>Discern, perceive, recognize</td>
</tr>
<tr>
<td></td>
<td>Measure</td>
<td></td>
<td>Identify, locate</td>
</tr>
<tr>
<td></td>
<td>Indicate</td>
<td></td>
<td>Announce, show, denote, record, register</td>
</tr>
<tr>
<td></td>
<td>Track</td>
<td></td>
<td>Mark, time</td>
</tr>
<tr>
<td></td>
<td>Display</td>
<td></td>
<td>Emit, expose, select</td>
</tr>
<tr>
<td>Support</td>
<td>Process</td>
<td></td>
<td>Compare, calculate, check</td>
</tr>
<tr>
<td></td>
<td>Stabilize</td>
<td></td>
<td>Steady</td>
</tr>
<tr>
<td></td>
<td>Secure</td>
<td></td>
<td>Constrain, hold, place, fix</td>
</tr>
<tr>
<td></td>
<td>Position</td>
<td></td>
<td>Align, locate, orient</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Overall increasing degree of specification</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX B

XML SCRIPTS

Test_hairdryer.xml

<?xml version="1.0" encoding="UTF-8"?>
<ns1:ARPrototypingToolkit xmlns:ns1="ARProToXML"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="https:/vrac.iastate.edu/~rafael/xml/ARProTo.xsd">
  <Statemachine file="../Chloe_research/test/files/test_hairdryer.py" />

  <Viewer window="false" x="0" y="912" width="1368" height="912" display="0"
win_scale="2.0" />

  <Models>

    <!--VISIBLE 3D MODELS-->

    <Model3D userID="nerf1" label="nerf1">
      <Position X="0.0" Y="0.0" Z="0.0"/>
      <Scale SX="0.2" SY="0.2" SZ="0.2"/>
      <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
      <File name="../Chloe_research/test/models/nerf1.osgb"/>
    </Model3D>

    <Model3D userID="part_teapot" label="teapot">
      <Position X="0.0" Y="0.0" Z="0.0"/>
      <Scale SX="1.0" SY="1.0" SZ="1.0"/>
      <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
      <File name="../Chloe_research/test/labels/all_hd_tags.osg"/>
    </Model3D>

    <Model3D userID="full_model" label="Full_Model">
      <Position X="0.0" Y="0.0" Z="0.0"/>
      <Scale SX="1.0" SY="1.0" SZ="1.0"/>
      <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
      <!-- <File name="../Chloe_research/test/models/full_model_top.osg"/> -->
      <File name="../Chloe_research/test/models/Hairdryer.osg"/>
    </Model3D>

    <Model3D userID="part_ais" label="Air_Inlet_Screen">
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      <Scale SX="1.0" SY="1.0" SZ="1.0"/>
      <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
      <File name="../Chloe_research/test/models/Air_Inlet_Screen.osg"/>
    </Model3D>

    <Model3D userID="part_bh" label="Back_housing">
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      <Scale SX="1.0" SY="1.0" SZ="1.0"/>
      <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
      <File name="../Chloe_research/test/models/Back_housing.osg"/>
    </Model3D>

  </Models>
</ns1:ARPrototypingToolkit>
<Model3D userID="part_cb" label="Cool_button">
    <Position X="0.0" Y="0" Z="0.0"/>
    <Scale SX="1.0" SY="1.0" SZ="1.0"/>
    <Orientation RX="0.0" RY="0" RZ="0.0"/>
    <File name="../Chloe_research/test/models/Cool_button.osg"/>
</Model3D>

<Model3D userID="part_cbc" label="Cool_button_cover">
    <Position X="0.0" Y="0" Z="0.0"/>
    <Scale SX="1.0" SY="1.0" SZ="1.0"/>
    <Orientation RX="0.0" RY="0" RZ="0.0"/>
    <File name="../Chloe_research/test/models/Cool_button_cover.osg"/>
</Model3D>

<Model3D userID="part_cw" label="Copper_wiring">
    <Position X="0.0" Y="0" Z="0.0"/>
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    <Orientation RX="0.0" RY="0" RZ="0.0"/>
    <File name="../Chloe_research/test/models/Copper_wiring.osg"/>
</Model3D>

<Model3D userID="part_ec" label="Electrical_cable">
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    <Orientation RX="0.0" RY="0" RZ="0.0"/>
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<Model3D userID="part_f" label="Fan">
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    <Orientation RX="0.0" RY="0" RZ="0.0"/>
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    <Scale SX="1.0" SY="1.0" SZ="1.0"/>
    <Orientation RX="0.0" RY="0" RZ="0.0"/>
    <File name="../Chloe_research/test/models/Front_grate.osg"/>
</Model3D>

<Model3D userID="part_fh" label="Front_housing">
    <Position X="0.0" Y="0" Z="0.0"/>
    <Scale SX="1.0" SY="1.0" SZ="1.0"/>
</Model3D>
<Orientation RX="0.0" RY="0" RZ="0.0"/>
<File name="../Chloe_research/test/labels/bh_label.osg"/>
</Model3D>

<Model3D userID="label_cb" label="cool_button_label">
<Position X="0.0" Y="0" Z="0.0"/>
<Scale SX="1.0" SY="1.0" SZ="1.0"/>
<Orientation RX="0.0" RY="0" RZ="0.0"/>
<File name="../Chloe_research/test/labels/cb_label.osg"/>
</Model3D>

<Model3D userID="label_cbc" label="cool_button_cover_label">
<Position X="0.0" Y="0" Z="0.0"/>
<Scale SX="1.0" SY="1.0" SZ="1.0"/>
<Orientation RX="0.0" RY="0" RZ="0.0"/>
<File name="../Chloe_research/test/labels/cbc_label.osg"/>
</Model3D>

<Model3D userID="label_cw" label="copper_wiring_label">
<Position X="0.0" Y="0" Z="0.0"/>
<Scale SX="1.0" SY="1.0" SZ="1.0"/>
<Orientation RX="0.0" RY="0" RZ="0.0"/>
<File name="../Chloe_research/test/labels/cw_label.osg"/>
</Model3D>

<Model3D userID="label_ec" label="electrical_cable_label">
<Position X="0.0" Y="0" Z="0.0"/>
<Scale SX="1.0" SY="1.0" SZ="1.0"/>
<Orientation RX="0.0" RY="0" RZ="0.0"/>
<File name="../Chloe_research/test/labels/ec_label.osg"/>
</Model3D>

<Model3D userID="label_f" label="fan_label">
<Position X="0.0" Y="0" Z="0.0"/>
<Scale SX="1.0" SY="1.0" SZ="1.0"/>
<Orientation RX="0.0" RY="0" RZ="0.0"/>
<File name="../Chloe_research/test/labels/f_label.osg"/>
</Model3D>

<Model3D userID="label_fg" label="front_gate_label">
<Position X="0.0" Y="0" Z="0.0"/>
<Scale SX="1.0" SY="1.0" SZ="1.0"/>
<Orientation RX="0.0" RY="0" RZ="0.0"/>
<File name="../Chloe_research/test/labels/fg_label.osg"/>
</Model3D>

<Model3D userID="label_fh" label="front_housing_label">
<Position X="0.0" Y="0" Z="0.0"/>
<Scale SX="1.0" SY="1.0" SZ="1.0"/>
<Orientation RX="0.0" RY="0" RZ="0.0"/>
<File name="../Chloe_research/test/labels/fh_label.osg"/>
<ARToolKit camera_config="camera_config" threshold="130" scale="15">

  <Pattern id="0">
    <File value="../../Chloe_research/test/markers/hair.pat"/>
    <Dimension value="80"/>
    <Model3D userID="part_ais"/>
    <Model3D userID="full_model"/>
    <Model3D userID="part_bh"/>
    <Model3D userID="part_cb"/>
    <Model3D userID="part_cbc"/>
    <Model3D userID="part_cw"/>
    <Model3D userID="part_ec"/>
    <Model3D userID="part_f"/>
    <Model3D userID="part_fh"/>
    <Model3D userID="part_fg"/>
    <Model3D userID="part_he"/>
    <Model3D userID="part_m"/>
    <Model3D userID="part_ms"/>
    <Model3D userID="part_oos"/>
    <Model3D userID="part_oosc"/>
    <Model3D userID="part_teapot"/>

    <Model3D userID="label_ais"/>
    <Model3D userID="label_bh"/>
    <Model3D userID="label_cb"/>
    <Model3D userID="label_cbc"/>
    <Model3D userID="label_cw"/>
    <Model3D userID="label_ec"/>
    <Model3D userID="label_f"/>
    <Model3D userID="label_fh"/>
    <Model3D userID="label_fg"/>
    <Model3D userID="label_he"/>
    <Model3D userID="label_m"/>
    <Model3D userID="label_ms"/>
    <Model3D userID="label_oos"/>
    <Model3D userID="label_oosc"/>

    <Model3D userID="nerf1"/>
  </Pattern>

</ARToolKit>

<MenuBar position_x="1620" position_y="200" height="600" width="300">

  <MenuItemAttributes>
    <ItemSize width="300" height="80"/>
    <HighlightColor color_red="0.5" color_green="0.0" color_blue="1.0"/>
  </MenuItemAttributes>

</MenuBar>
<MenuBar>

<Menu> <!-- i.e. Buttons -->

<!-- Buttons for Home Screen that appears when starting the application "Home_page" -->

<MenuButton id="Shape_based" parent="Shape_based" size_x="300" size_y="200" pos_x="550" pos_y="350" url="../Chloe_research/test/buttons/Shape_based.png" toggle="false" submenu="menu00" />

<MenuButton id="Topology_based" parent="Topology_based" size_x="300" size_y="200" pos_x="1100" pos_y="350" url="../Chloe_research/test/buttons/Topology_based.png" toggle="false" submenu="menu00" />

<MenuButton id="Quit" parent="Quit" size_x="100" size_y="100" pos_x="25" pos_y="50" url="../Chloe_research/test/buttons/Quit3.png" toggle="false" submenu="menu00" />

<!-- Buttons for Shape_screen -->

<MenuButton id="Home1" parent="Home" size_x="120" size_y="120" pos_x="8" pos_y="900" url="../Chloe_research/test/buttons/Home_button.png" toggle="false" submenu="menu01" />

<MenuButton id="3D_view1" parent="3D_view" size_x="125" size_y="125" pos_x="8" pos_y="750" url="../Chloe_research/test/buttons/3D_view.png" toggle="false" />
submenu="menu01" />

<MenuButton id="Label_view1" parent="Label_view" size_x="115" size_y="115" pos_x="12" pos_y="600" url="./Chloe_research/test/buttons/Label_view.png" toggle="false" submenu="menu01" />

<MenuButton id="Quit1" parent="Quit" size_x="100" size_y="100" pos_x="25" pos_y="50" url="./Chloe_research/test/buttons/Quit3.png" toggle="false" submenu="menu01" />

<MenuButton id="All_models1" parent="All_models" size_x="300" size_y="120" pos_x="1615" pos_y="930" url="./Chloe_research/test/buttons/All_models.png" toggle="false" submenu="menu01" />

<MenuButton id="No_models1" parent="No_models" size_x="300" size_y="120" pos_x="1615" pos_y="810" url="./Chloe_research/test/buttons/No_models.png" toggle="false" submenu="menu01" />

<!--Buttons for Topology_screen -->

<MenuButton id="Home2" parent="Home" size_x="120" size_y="120" pos_x="8" pos_y="900" url="./Chloe_research/test/buttons/Home_button.png" toggle="false" submenu="menu02" />

<MenuButton id="3D_view2" parent="3D_view" size_x="125" size_y="125" pos_x="8" pos_y="750" url="./Chloe_research/test/buttons/3D_view.png" toggle="false" submenu="menu02" />

<MenuButton id="Label_view2" parent="Label_view" size_x="115" size_y="115" pos_x="12" pos_y="600" url="./Chloe_research/test/buttons/Label_view.png" toggle="false" submenu="menu02" />

<MenuButton id="Group_view2" parent="Group_view" size_x="115" size_y="115" pos_x="12" pos_y="450" url="./Chloe_research/test/buttons/Group_view.png" toggle="false" submenu="menu02" />

<!-- <MenuButton id="Quit2" parent="Quit" size_x="100" size_y="100" pos_x="25" pos_y="50" url="./Chloe_research/test/buttons/Quit3.png" toggle="false" submenu="menu02" />

<MenuButton id="All_models2" parent="All_models" size_x="300" size_y="120" pos_x="1615" pos_y="930" url="./Chloe_research/test/buttons/All_models.png" toggle="false" submenu="menu02" />

<MenuButton id="No_models2" parent="No_models" size_x="300" size_y="120" pos_x="1615" pos_y="810" url="./Chloe_research/test/buttons/No_models.png" toggle="false" submenu="menu02" />

<MenuButton id="Airflow" parent="Airflow2" size_x="124" size_y="90" pos_x="10" pos_y="460" url="./Chloe_research/test/buttons/AG.png" toggle="false" submenu="menu02" />

<MenuButton id="Electrical" parent="Electrical2" size_x="124" size_y="90" pos_x="10" pos_y="340" url="./Chloe_research/test/buttons/EG.png" toggle="false" submenu="menu02" />

<MenuButton id="Heating" parent="Heating2" size_x="124" size_y="90" pos_x="10" pos_y="220" url="./Chloe_research/test/buttons/HG.png" toggle="false" submenu="menu02" />

</Menu>

<Configurations startConfig="Home_screen" >

<Configuration configID="Home_screen" >

</Configuration>

</Configurations>
<Configuration configID="Shape_screen" >
  <Content userID="part_teapot" />
  <Content userID="full_model" />
  <Content userID="part_ais" />
  <Content userID="part_bh" />
  <Content userID="part_ec" />
  <Content userID="part_f" />
  <Content userID="part_fh" />
  <Content userID="part_he" />
  <Content userID="part_m" />
  <Content userID="part_ch" />
  <Content userID="part_cbc" />
  <Content userID="part_cw" />
  <Content userID="part_fg" />
  <Content userID="part_ms" />
  <Content userID="part_oos" />
  <Content userID="part_oosc" />
  <Content userID="nerf1" />
  <Content userID="nerf2" />
  <Content userID="gray_bar" />
</Configuration>

<Model3D userID="label_ais" />
<Model3D userID="label_bh" />
<Model3D userID="label_ch" />
<Model3D userID="label_cbc" />
<Model3D userID="label_cw" />
<Model3D userID="label_ec" />
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<Model3D userID="label_he" />
<Model3D userID="label_m" />
<Model3D userID="label_ms" />
<Model3D userID="label_oos" />
<Model3D userID="label_oosc" />

<MenuButton userID="Quit" />
<MenuButton userID="Home1" />
<MenuButton userID="3D_view1" />
<MenuButton userID="Label_view1" />
<MenuButton userID="All_models1" />
<MenuButton userID="No_models1" />

<MenuItem userid="Air_Inlet_Screen" />
<MenuItem userid="Back_housing" />
<MenuButton userID="Home2" />
<MenuButton userID="3D_view2" />
<MenuButton userID="Label_view2" />
</!--<MenuButton userID="Group_view2" -->
<MenuButton userID="All_models2" />
<MenuButton userID="No_models2" />

<MenuItem userid="Air_Inlet_Screen" />
<MenuItem userid="Back_housing" />
<MenuItem userid="Cool_button" />
<MenuItem userid="Cool_button_cover" />
<MenuItem userid="Copper_wiring" />
<MenuItem userid="Electrical_cable" />
<MenuItem userid="Fan" />
<MenuItem userid="Front_grate" />
<MenuItem userid="Front_housing" />
<MenuItem userid="Heating_element" />
<MenuItem userid="Mica_sheet" />
<MenuItem userid="Motor" />
<MenuItem userid="On_off_switch" />
<MenuItem userid="On_off_switch_cover" />

<MenuItem userID="Airflow" />
<MenuItem userID="Heating" />
<MenuItem userID="Electrical" />
</Configuration>
</Configurations>
</ns1:ARPrototypingToolkit>

Test_nerf.xml

<?xml version="1.0" encoding="UTF-8"?>
<ns1:ARPrototypingToolkit xmlns:ns1="ARProToXML"
xmns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="https://vrac.iastate.edu/~rafael/xml/ARProTo.xsd">
  <Statemachine file="../Chloe_research/test/files/test_nerf.py" />
  <Viewer window="false" x="0" y="912" width="1368" height="912" display="0"
  win_scale="2.0" />
</ns1:ARPrototypingToolkit>

<!-- userID="slide" />
  userID="trigger" />
  userID="screws" />
  userID="right_housing" />
  userID="piston_spring" />
</!--
<Models>
  <Model3D userID="nerf1" label="nerf1">
    <Position X="0.0" Y="0.0" Z="0.0"/>
    <Scale SX="0.5" SY="0.5" SZ="0.5"/>
    <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
    <File name="../Chloe_research/test/models/nerf1.osgb"/>
  </Model3D>
  
  <Model3D userID="slide" label="slide">
    <Position X="-8.0" Y="-3.25" Z="0.0"/>
    <Scale SX="0.55" SY="0.55" SZ="0.55"/>
    <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
    <File name="../Chloe_research/test/models/slide.osgb"/>
  </Model3D>
  
  <Model3D userID="trigger" label="trigger">
    <Position X="-8.0" Y="-3.25" Z="0.0"/>
    <Scale SX="0.55" SY="0.55" SZ="0.55"/>
    <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
    <File name="../Chloe_research/test/models/trigger.osgb"/>
  </Model3D>
  
  <Model3D userID="screws" label="screws">
    <Position X="-8.0" Y="-3.25" Z="0.0"/>
    <Scale SX="0.55" SY="0.55" SZ="0.55"/>
    <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
    <File name="../Chloe_research/test/models/screws.osgb"/>
  </Model3D>
</Models>
</Model3D>

<Model3D userID="right_housing" label="right_housing">
  <Position X="-8.0" Y="-3.25" Z="0.0"/>
  <Scale SX="0.55" SY="0.55" SZ="0.55"/>
  <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
  <File name="..\Chloe_research\test\models\right_housing.osgb"/>
</Model3D>

<Model3D userID="piston_spring" label="piston_spring">
  <Position X="-8.0" Y="-3.25" Z="0.0"/>
  <Scale SX="0.55" SY="0.55" SZ="0.55"/>
  <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
  <File name="..\Chloe_research\test\models\piston_spring.osgb"/>
</Model3D>

<Model3D userID="piston" label="piston">
  <Position X="-8.0" Y="-3.25" Z="0.0"/>
  <Scale SX="0.55" SY="0.55" SZ="0.55"/>
  <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
  <File name="..\Chloe_research\test\models\piston.osgb"/>
</Model3D>

<Model3D userID="rotator" label="rotator">
  <Position X="-8.0" Y="-3.25" Z="0.0"/>
  <Scale SX="0.55" SY="0.55" SZ="0.55"/>
  <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
  <File name="..\Chloe_research\test\models\part1.osgb"/>
</Model3D>

<Model3D userID="muzzle" label="muzzle">
  <Position X="-8.0" Y="-3.25" Z="0.0"/>
  <Scale SX="0.55" SY="0.55" SZ="0.55"/>
  <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
  <File name="..\Chloe_research\test\models\muzzle.osgb"/>
</Model3D>

<Model3D userID="left_housing" label="left_housing">
  <Position X="-8.0" Y="-3.25" Z="0.0"/>
  <Scale SX="0.55" SY="0.55" SZ="0.55"/>
  <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
  <File name="..\Chloe_research\test\models\left_housing.osgb"/>
</Model3D>

<Model3D userID="barrel" label="barrel">
  <Position X="-8.0" Y="-3.25" Z="0.0"/>
  <Scale SX="0.55" SY="0.55" SZ="0.55"/>
  <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
  <File name="..\Chloe_research\test\models\barrel.osgb"/>
</Model3D>
<Model3D userID="air_plunger" label="air_plunger">
  <Position X="-8.0" Y="-3.25" Z="0.0"/>
  <Scale SX="0.55" SY="0.55" SZ="0.55"/>
  <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
  <File name="../Chloe_research/test/models/air_plunger.osgb"/>
</Model3D>

<Model3D userID="plunger_release" label="plunger_release">
  <Position X="-8.0" Y="-3.25" Z="0.0"/>
  <Scale SX="0.55" SY="0.55" SZ="0.55"/>
  <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
  <File name="../Chloe_research/test/models/actual_trigger.osgb"/>
</Model3D>

<Model3D userID="half-slide" label="halfslide">
  <Position X="-8.0" Y="-3.25" Z="0.0"/>
  <Scale SX="0.55" SY="0.55" SZ="0.55"/>
  <Orientation RX="0.0" RY="0.0" RZ="0.0"/>
  <File name="../Chloe_research/test/models/half-slide.osgb"/>
</Model3D>

<!-- 3d labels for 3d models -->

<Model3D userID="slide_label" label="slide">
  <Position X="0.0" Y="0" Z="0.0"/>
  <Scale SX="1.0" SY="1.0" SZ="1.0"/>
  <Orientation RX="0.0" RY="0" RZ="0.0"/>
  <File name="../Chloe_research/test/labels/s2-label.osg"/>
</Model3D>

<Model3D userID="trigger_label" label="trigger">
  <Position X="0.0" Y="0" Z="0.0"/>
  <Scale SX="1.0" SY="1.0" SZ="1.0"/>
  <Orientation RX="0.0" RY="0" RZ="0.0"/>
  <File name="../Chloe_research/test/labels/t2-label.osg"/>
</Model3D>

<Model3D userID="screws_label" label="screws">
  <Position X="0.0" Y="0" Z="0.0"/>
  <Scale SX="1.0" SY="1.0" SZ="1.0"/>
  <Orientation RX="0.0" RY="0" RZ="0.0"/>
  <File name="../Chloe_research/test/labels/sc-to-yellow-label.osg"/>
  <File name="../Chloe_research/test/labels/sc-to-standard-label.osg"/>
</Model3D>

<Model3D userID="righthousing_label" label="righthousing">
  <Position X="0.0" Y="0" Z="0.0"/>
  <Scale SX="1.0" SY="1.0" SZ="1.0"/>
  <Orientation RX="0.0" RY="0" RZ="0.0"/>
  <File name="../Chloe_research/test/labels/rh2-label.osg"/>
</Model3D>
<Model3D userID="label_ps" label="pistonspring_label">
  <Position X="0.0" Y="0" Z="0.0"/>
  <Scale SX="1.0" SY="1.0" SZ="1.0"/>
  <Orientation RX="0.0" RY="0" RZ="0.0"/>
  <File name="../Chloe_research/test/labels/ps2-label.osg"/>
</Model3D>

<Model3D userID="label_p" label="pistonassembly_label">
  <Position X="0.0" Y="0" Z="0.0"/>
  <Scale SX="1.0" SY="1.0" SZ="1.0"/>
  <Orientation RX="0.0" RY="0" RZ="0.0"/>
  <File name="../Chloe_research/test/labels/pa2-label.osg"/>
</Model3D>

<Model3D userID="label_mz" label="muzzle_label">
  <Position X="0.0" Y="0" Z="0.0"/>
  <Scale SX="1.0" SY="1.0" SZ="1.0"/>
  <Orientation RX="0.0" RY="0" RZ="0.0"/>
  <File name="../Chloe_research/test/labels/m2-label.osg"/>
</Model3D>

<Model3D userID="label_lh" label="lefthousing_label">
  <Position X="0.0" Y="0" Z="0.0"/>
  <Scale SX="1.0" SY="1.0" SZ="1.0"/>
  <Orientation RX="0.0" RY="0" RZ="0.0"/>
  <File name="../Chloe_research/test/labels/lh2-label.osg"/>
</Model3D>

<Model3D userID="label_b" label="barrel_label">
  <Position X="0.0" Y="0" Z="0.0"/>
  <Scale SX="1.0" SY="1.0" SZ="1.0"/>
  <Orientation RX="0.0" RY="0" RZ="0.0"/>
  <File name="../Chloe_research/test/labels/b2-label.osg"/>
</Model3D>

<Model3D userID="label_ap" label="airplunger_label">
  <Position X="0.0" Y="0" Z="0.0"/>
  <Scale SX="1.0" SY="1.0" SZ="1.0"/>
  <Orientation RX="0.0" RY="0" RZ="0.0"/>
  <File name="../Chloe_research/test/labels/ap2-label.osg"/>
</Model3D>

<Model3D userID="label_pr" label="plungerrelease_label">
  <Position X="0.0" Y="0" Z="0.0"/>
  <Scale SX="1.0" SY="1.0" SZ="1.0"/>
  <Orientation RX="0.0" RY="0" RZ="0.0"/>
  <File name="../Chloe_research/test/labels/pr2-label.osg"/>
</Model3D>

<Model3D userID="label_r" label="rotator_label"/>
<Model3D userID="label_pr" />
<Model3D userID="label_r" />

</Pattern>

</ARToolKit>

<MenuBar position_x="1620" position_y="200" height="600" width="300">

<MenuItem Attributes>
<ItemSize width="300" height="80"/>
<HightlightColor color_red="0.5" color_green="0.0" color_blue="1.0"/>
</MenuItemAttributes>

(MenuItem userid="Air_plunger" imagefile="../Chloe_research/test/buttons/AP.png"/>
(MenuItem userid="Barrel" imagefile="../Chloe_research/test/buttons/B.png" />
(MenuItem userid="Left_housing" imagefile="../Chloe_research/test/buttons/LH.png"/>
(MenuItem userid="Muzzle" imagefile="../Chloe_research/test/buttons/M.png" />
(MenuItem userid="Piston_spring" imagefile="../Chloe_research/test/buttons/PS.png" />
(MenuItem userid="Plunger_release" imagefile="../Chloe_research/test/buttons/PlungerRelease.png" />

<!-- <MenuItem userid="Piston" imagefile="../Chloe_research/test/buttons/PA.png" /> -->

(MenuItem userid="Right_housing" imagefile="../Chloe_research/test/buttons/RH.png" />
(MenuItem userid="Rotator" imagefile="../Chloe_research/test/buttons/Rotator.png" />

(MenuItem userid="Screws" imagefile="../Chloe_research/test/buttons/Screw.png" />
(MenuItem userid="Slide" imagefile="../Chloe_research/test/buttons/S.png" />
(MenuItem userid="Trigger" imagefile="../Chloe_research/test/buttons/T.png" />

</MenuBar>

<Menu> <!--i.e. Buttons-->

<!--Buttons for Home Screen that appears when starting the application
"Home_page"-->

<MenuButton id="Shape_based" parent="Shape_based" size_x="300" size_y="200"
pos_x="550" pos_y="350" url="../Chloe_research/test/buttons/Shape_based.png" toggle="false"
submenu="menu00" />

<MenuButton id="Topology_based" parent="Topology_based" size_x="300"
size_y="200" pos_x="1100" pos_y="350" url="../Chloe_research/test/buttons/Topology_based.png"
toggle="false" submenu="menu00" />

<MenuButton id="Quit" parent="Quit" size_x="100" size_y="100" pos_x="25"
pos_y="50" url="../Chloe_research/test/buttons/Quit3.png" toggle="false" submenu="menu00" />

<!--Buttons for Shape_screen -->

</Menu>
<MenuButton id="Home1" parent="Home" size_x="120" size_y="120" pos_x="8" pos_y="900" url="../Chloe_research/test/buttons/Home_button.png" toggle="false" submenu="menu01" />
<MenuButton id="3D_view1" parent="3D_view" size_x="125" size_y="125" pos_x="8" pos_y="750" url="../Chloe_research/test/buttons/3D_view.png" toggle="false" submenu="menu01" />
<MenuButton id="Label_view1" parent="Label_view" size_x="115" size_y="115" pos_x="12" pos_y="600" url="../Chloe_research/test/buttons/Label_view.png" toggle="false" submenu="menu01" />
<MenuButton id="Quit1" parent="Quit" size_x="100" size_y="100" pos_x="25" pos_y="50" url="../Chloe_research/test/buttons/Quit3.png" toggle="false" submenu="menu01" />
<MenuButton id="All_models1" parent="All_models" size_x="300" size_y="120" pos_x="1615" pos_y="930" url="../Chloe_research/test/buttons/All_models.png" toggle="false" submenu="menu01" />
<MenuButton id="No_models1" parent="No_models" size_x="300" size_y="120" pos_x="1615" pos_y="810" url="../Chloe_research/test/buttons/No_models.png" toggle="false" submenu="menu01" />

<!--Buttons for Topology_screen -->

<MenuButton id="Home2" parent="Home" size_x="120" size_y="120" pos_x="8" pos_y="900" url="../Chloe_research/test/buttons/Home_button.png" toggle="false" submenu="menu02" />
<MenuButton id="3D_view2" parent="3D_view" size_x="125" size_y="125" pos_x="8" pos_y="750" url="../Chloe_research/test/buttons/3D_view.png" toggle="false" submenu="menu02" />
<MenuButton id="Label_view2" parent="Label_view" size_x="115" size_y="115" pos_x="12" pos_y="600" url="../Chloe_research/test/buttons/Label_view.png" toggle="false" submenu="menu02" />
<MenuButton id="Quit2" parent="Quit" size_x="100" size_y="100" pos_x="25" pos_y="50" url="../Chloe_research/test/buttons/Quit3.png" toggle="false" submenu="menu02" />
<MenuButton id="All_models2" parent="All_models" size_x="300" size_y="120" pos_x="1615" pos_y="930" url="../Chloe_research/test/buttons/All_models.png" toggle="false" submenu="menu02" />
<MenuButton id="No_models2" parent="No_models" size_x="300" size_y="120" pos_x="1615" pos_y="810" url="../Chloe_research/test/buttons/No_models.png" toggle="false" submenu="menu02" />

<MenuButton id="Cocking" parent="CG" size_x="124" size_y="90" pos_x="10" pos_y="460" url="../Chloe_research/test/buttons/CockingGroup.png" toggle="false" submenu="menu02" />
<MenuButton id="TG" parent="TG" size_x="124" size_y="90" pos_x="10" pos_y="340" url="../Chloe_research/test/buttons/TriggerGroup.png" toggle="false" submenu="menu02" />
<MenuButton id="Airflow" parent="AG" size_x="124" size_y="90" pos_x="10" pos_y="220" url="../Chloe_research/test/buttons/ReleaseGroup.png" toggle="false" submenu="menu02" />

<Configuration configID="Home_screen">
  <Content userID="Title" />
  <MenuButton userID="Shape_based" />
  <MenuButton userID="Topology_based" />
  <MenuButton userID="Quit" />
</Configuration>

<Configuration configID="Shape_screen">
  <Model3D userID="nerf1" />
  <Model3D userID="slide" />
  <Model3D userID="trigger" />
  <Model3D userID="screws" />
  <Model3D userID="right_housing" />
  <Model3D userID="piston_spring" />
  <Model3D userID="piston" />
  <Model3D userID="rotator" />
  <Model3D userID="muzzle" />
  <Model3D userID="left_housing" />
  <Model3D userID="barrel" />
  <Model3D userID="air_plunger" />
  <Model3D userID="plunger_release" />
  <Model3D userID="label_s" />
  <Model3D userID="label_t" />
  <Model3D userID="label_sc" />
  <Model3D userID="label_rh" />
  <Model3D userID="label_ps" />
  <Model3D userID="label_mz" />
  <Model3D userID="label_lh" />
  <Model3D userID="label_b" />
  <Model3D userID="label_ap" />
  <Model3D userID="label_pr" />
  <Content userID="gray_bar" />
  <MenuItem userid="Slide" />
  <MenuItem userid="Trigger" />
  <MenuItem userid="Screws" />
  <MenuItem userid="Right_housing" />
  <MenuItem userid="Piston_spring" />
  <MenuItem userid="Piston" />
  <MenuItem userid="Rotator" />
  <MenuItem userid="Muzzle" />
  <MenuItem userid="Left_housing" />
</Configuration>
<MenuItem userid="Barrel" />
<MenuItem userid="Air_plunger" />
<MenuItem userid="Plunger_release" />

<MenuButton userID="Quit" />
<MenuButton userID="Home2" />
<MenuButton userID="3D_view2" />
<MenuButton userID="Label_view2" />
<!-- <MenuButton userID="Group_view2" -->
<!-- -->
<MenuButton userID="All_models2" />
<MenuButton userID="No_models2" />

<MenuItem userID="Cocking" />
<MenuItem userID="Airflow" />
<MenuItem userID="TG" />

</Configuration>

</Configurations>

</ns1:ARPrototypingToolkit>
APPENDIX C

PYTHON SCRIPTS

Test_hairdryer.py

from ctypes import *
ar = cdll.LoadLibrary("ARPyInt.dll")

import time
currentStep = 0
oldStep = 0
timerActive = False

submenus = ["menu00","menu01","menu02"] # buttons
steps = ["Home_screen","Shape_screen","Topology_screen"] # models
button_states = [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0];
model_names =
["part_ais","part_bh","part_cb","part_cbc","part_cw","part_ec","part_f","part_fg","part_fh","part_he"
,"part_m","part_ms","part_oos","part_oosc"];

group_states = [0,0,0] # group_airflow, group_heating, group_elec
group_airflow = ["part_ais","part_f","part_fg","part_ec","part_m"]
group_heating = ["part_cb","part_cw","part_he","part_oos"]
group_elec = ["part_ec","part_cw","part_m","part_oos"]

# "part_ais"
# "part_bh"
# "part_cb"
# "part_cbc"
# "part_cw"
# "part_ec"
# "part_f"
# "part_fg"
# "part_fh"
# "part_he"
# "part_m"
# "part_ms"
# "part_oos"
# "part_oosc"

def model2Idx(model_name):
    global model_names
    print "lookup inde for ", model_name
    index = -1
    try:
        index = model_names.index(model_name)
except ValueError:
    print "model does not exist"
    print "have index ", index
    return index;

def toggleModel(model_name):
    print "toggle model ", model_name
    global button_states
    global model_names

    index = model2Idx(model_name);
    if index > -1:
        if button_states[index] == 0:
            ar.enableModel(model_name)
            button_states[index] = 1;
        elif button_states[index] == 1:
            ar.disableModel(model_name)
            button_states[index] = 0;

def locEnableModel(model_name):
    global button_states
    global model_names

    index = model2Idx(model_name);
    if index > -1:
        ar.enableModel(model_name)
        button_states[index] = 1;

def locDisableModel(model_name):
    global button_states
    global model_names

    index = model2Idx(model_name);
    if index > -1:
        ar.disableModel(model_name)
        button_states[index] = 0;

def toggleGroup(group_index, group):
    global group_states;

    if(group_states[group_index] == 0):
        group_states[group_index] = 1
        for x in group:
locEnableModel(x)
elif(group_states[group_index] == 1):
group_states[group_index] = 0
for x in group:
locDisableModel(x)

def onPatternIn(pattern_id):
    #fires when 'identify a pattern' placed in background
    print "Pattern in event", pattern_id
    global predict_visible
    # store the message to a file
    message = "on pattern in\n";
    message += str(pattern_id);
    ar.writeLog(message)
    if (currentStep ==1 or currentStep ==2):
        if pattern_id == 0:
            predict_visible = True
            print "Marker 0 now visible"

def onPatternOut(pattern_id):
    #fires when 'identify a pattern' removed from the background
    #print "Pattern out event", pattern_id
    #markerPresent[pattern_id] = False
    global predict_visible
    # store the message to a file
    message = "on pattern out\n";
    message += str(pattern_id);
    ar.writeLog(message)
    if pattern_id == 0:
        predict_visible = False
        print "Marker 0 now lost"

def onInit(frameid):
    #fires when you start the application
    global currentStep
    print "Open file."
    # Open the log file
    ar.openLogFile("C:/AR Tools/ARMaker/bin/records/functional_hairdryer_study.txt", "Chloe McPherson\nSurface Pro 4\nStudy 01\nStudy to test an AR app for virtual product dissection")
print "INIT Application."
ar.setWorldReferenceMarker(0)
ar.enableVideoBackground()
ar.switchToSubMenu(submenus[0])
ar.enableMenuBar("false")

ar.disableModel("part_teapot")
ar.disableModel("part_ais")
ar.disableModel("part_bh")
ar.disableModel("part_cb")
ar.disableModel("part_cbc")
ar.disableModel("part_cw")
ar.disableModel("part_ec")
ar.disableModel("part_f")
ar.disableModel("part_fg")
ar.disableModel("part_fh")
ar.disableModel("part_he")
ar.disableModel("part_m")
ar.disableModel("part_ms")
ar.disableModel("part_oos")
ar.disableModel("part_oosc")
ar.disableModel("nerf1")

ar.remove3DModelFromMarker("label_ais")
ar.remove3DModelFromMarker("label_bh")
ar.remove3DModelFromMarker("label_cb")
ar.remove3DModelFromMarker("label_cbc")
ar.remove3DModelFromMarker("label_cw")
ar.remove3DModelFromMarker("label_ec")
ar.remove3DModelFromMarker("label_f")
ar.remove3DModelFromMarker("label_fg")
ar.remove3DModelFromMarker("label_fh")
ar.remove3DModelFromMarker("label_he")
ar.remove3DModelFromMarker("label_m")
ar.remove3DModelFromMarker("label_ms")
ar.remove3DModelFromMarker("label_oosc")
ar.remove3DModelFromMarker("label_oos")

def switchTo(step):
    global currentStep
    global steps
    global oldStep;
    #print "switchTo is successfully called. step received: ", steps[currentStep]

    currentStep = step
    ar.setScene(steps[currentStep])
ar.switchToSubMenu(submenus[currentStep])
    print "switchTo is successfully called. menu received: ", submenus[currentStep]
if currentStep != oldStep:
    print "Switched to step: ", steps[currentStep]
    oldStep = currentStep

def onFrame(frameid):
    global currentStep
    global timerActive
    global start
    global true_position
    global true_position_stored
    global true_rotation
    global true_scale_stored
    ar.setWorldReferenceMarker(0)

def onMenuAction(item, action):  # Controls buttons on the scroll menu/menu bar
    print "[Py] Item pressed :", item
    global currentStep
    global num_pred
    global predict_visible
    global button_states
    # Store the message to a file
    message = "item pressed\n";
    message += item;
    message += "\n";
    message += str(currentStep)
    message += "\n";
    message += str(button_states)
    ar.writeLog(message)

    if (currentStep == 1 or currentStep == 2):
        if item == "Air_Inlet_Screen":
            if button_states[0] == 0:
                print "Show air inlet screen"
                ar.enableModel("part_ais")
                ar.enableModel("label_ais")
                button_states[0] = 1;
            elif button_states[0] == 1:
                print "Hide air inlet screen"
                ar.disableModel("part_ais")
                ar.disableModel("label_ais")
                button_states[0] = 0;

        if item == "Back_housing":
            if button_states[1] == 0:
print "Show back housing"
ar.enableModel("part_bh")
ar.enableModel("label_bh")
button_states[1] = 1;
elif button_states[1] == 1:
    print "Hide back housing"
ar.disableModel("part_bh")
ar.disableModel("label_bh")
button_states[1] = 0;

if item == "Cool_button":
    if button_states[2] == 0:
        print "Show cool button"
ar.enableModel("part_cb")
ar.enableModel("label_cb")
button_states[2] = 1;
elif button_states[2] == 1:
    print "Hide cool button"
ar.disableModel("part_cb")
ar.disableModel("label_cb")
button_states[2] = 0;

if item == "Cool_button_cover":
    if button_states[3] == 0:
        print "Show cool button cover"
ar.enableModel("part_cbc")
ar.enableModel("label_cbc")
button_states[3] = 1;
elif button_states[3] == 1:
    print "Hide cool button cover"
ar.disableModel("part_cbc")
ar.disableModel("label_cbc")
button_states[3] = 0;

if item == "Copper_wiring":
    if button_states[4] == 0:
        print "Show copper wiring"
ar.enableModel("part_cw")
ar.enableModel("label_cw")
button_states[4] = 1;
elif button_states[4] == 1:
    print "Hide copper wiring"
ar.disableModel("part_cw")
ar.disableModel("label_cw")
button_states[4] = 0;

if item == "Electrical_cable":
    if button_states[5] == 0:
        print "Show electrical cable"
ar.enableModel("part_ec")
ar.enableModel("label_ec")
button_states[5] = 1;
elif button_states[5] == 1:
    print "Hide electrical cable"
ar.disableModel("part_ec")
ar.disableModel("label_ec")
button_states[5] = 0;

if item == "Fan":
    if button_states[6] == 0:
        print "Show fan"
ar.enableModel("part_f")
ar.enableModel("label_f")
        button_states[6] = 1;
    elif button_states[6] == 1:
        print "Hide fan"
ar.disableModel("part_f")
ar.disableModel("label_f")
        button_states[6] = 0;

if item == "Front_grate":
    if button_states[7] == 0:
        print "Show front grate"
ar.enableModel("part_fg")
ar.enableModel("label_fg")
        button_states[7] = 1;
    elif button_states[7] == 1:
        print "Hide front grate"
ar.disableModel("part_fg")
ar.disableModel("label_fg")
        button_states[7] = 0;

if item == "Front_housing":
    if button_states[8] == 0:
        print "Show front housing"
ar.enableModel("part_fh")
ar.enableModel("label_fh")
        button_states[8] = 1;
    elif button_states[8] == 1:
        print "Hide front housing"
ar.disableModel("part_fh")
ar.disableModel("label_fh")
        button_states[8] = 0;

if item == "Heating_element":
    if button_states[9] == 0:
        print "Show heating element"
ar.enableModel("part_he")
ar.enableModel("label_he")
        button_states[9] = 1;
    elif button_states[9] == 1:
        print "Hide heating element"
ar.disableModel("part_he")
ar.disableModel("label_he")
button_states[9] = 0;

if item == "Mica_sheet":
    if button_states[10] == 0:
        print "Show mica sheet"
ar.enableModel("part_ms")
ar.enableModel("label_ms")
button_states[10] = 1;
    elif button_states[10] == 1:
        print "Hide mica sheet"
ar.disableModel("part_ms")
ar.disableModel("label_ms")
button_states[10] = 0;

if item == "Motor":
    if button_states[11] == 0:
        print "Show motor"
ar.enableModel("part_m")
ar.enableModel("label_m")
    elif button_states[11] == 1:
        print "Hide motor"
ar.disableModel("part_m")
ar.disableModel("label_m")
button_states[11] = 0;

if item == "On_off_switch":
    if button_states[12] == 0:
        print "Show on/off switch"
ar.enableModel("part_oos")
ar.enableModel("label_oos")
button_states[12] = 1;
    elif button_states[12] == 1:
        print "Hide on/off switch"
ar.disableModel("part_oos")
ar.disableModel("label_oos")
button_states[12] = 0;

if item == "On_off_switch_cover":
    if button_states[13] == 0:
        print "Show on/off switch cover"
ar.enableModel("part_oosc")
ar.enableModel("label_oosc")
button_states[13] = 1;
    elif button_states[13] == 1:
        print "Hide on/off switch cover"
ar.disableModel("part_oosc")
ar.disableModel("label_oosc")
button_states[13] = 0;
def onMenuButton(button):
    # Controls regular buttons
    print "[Py] Button pressed :", button
    global currentStep
    global num_pred
    global predict_visible
    # global button_states
    global group_states;
    global group_airflow
    global group_heating
    global group_elec

    # store the message to a file
    message = "button pressed\t"
    message += button;
    message += "\t"
    message += str(currentStep)
    ar.writeLog(message)

    if button == "Airflow"
        if (currentStep == 2):
            print "Show airflow group------"
            toggleGroup(0, group_airflow)

    if button == "Heating"
        if (currentStep == 2):
            print "Show heating group"
            toggleGroup(1, group_heating)

    if button == "Electrical"
        if (currentStep == 2):
            print "Show electrical group"
            toggleGroup(2, group_elec)

    if button == "3D_view1"
        print "Changed to 3D view"
        ar.remove3DModelFromMarker("label_ais")
        ar.remove3DModelFromMarker("label_bh")
        ar.remove3DModelFromMarker("label_cb")
        ar.remove3DModelFromMarker("label_cbc")
        ar.remove3DModelFromMarker("label_cw")
        ar.remove3DModelFromMarker("label_ec")
        ar.remove3DModelFromMarker("label_f")
        ar.remove3DModelFromMarker("label_fg")
        ar.remove3DModelFromMarker("label_fh")
        ar.remove3DModelFromMarker("label_he")
        ar.remove3DModelFromMarker("label_m")
        ar.remove3DModelFromMarker("label_ms")
        ar.remove3DModelFromMarker("label_oosc")
if button == "Label_view1":
    print "Changed to label view"
    ar.set3DModelToMarker("label_ais", 0);
    ar.set3DModelToMarker("label_bh", 0)
    ar.set3DModelToMarker("label_cb", 0)
    ar.set3DModelToMarker("label_cbc", 0)
    ar.set3DModelToMarker("label_cw", 0)
    ar.set3DModelToMarker("label_ec", 0)
    ar.set3DModelToMarker("label_f", 0)
    ar.set3DModelToMarker("label_fg", 0)
    ar.set3DModelToMarker("label_fh", 0)
    ar.set3DModelToMarker("label_he", 0)
    ar.set3DModelToMarker("label_m", 0)
    ar.set3DModelToMarker("label_ms", 0)
    ar.set3DModelToMarker("label_oosc", 0)
    ar.set3DModelToMarker("label_oos", 0)

if button == "3D_view2":
    print "Changed to 3D view"
    ar.remove3DModelFromMarker("label_ais")
    ar.remove3DModelFromMarker("label_bh")
    ar.remove3DModelFromMarker("label_cb")
    ar.remove3DModelFromMarker("label_cbc")
    ar.remove3DModelFromMarker("label_cw")
    ar.remove3DModelFromMarker("label_ec")
    ar.remove3DModelFromMarker("label_f")
    ar.remove3DModelFromMarker("label_fg")
    ar.remove3DModelFromMarker("label_fh")
    ar.remove3DModelFromMarker("label_he")
    ar.remove3DModelFromMarker("label_m")
    ar.remove3DModelFromMarker("label_ms")
    ar.remove3DModelFromMarker("label_oosc")
    ar.remove3DModelFromMarker("label_oos")

if button == "Label_view2":
    print "Changed to label view"
    ar.set3DModelToMarker("label_ais", 0);
    ar.set3DModelToMarker("label_bh", 0)
    ar.set3DModelToMarker("label_cb", 0)
    ar.set3DModelToMarker("label_cbc", 0)
    ar.set3DModelToMarker("label_cw", 0)
    ar.set3DModelToMarker("label_ec", 0)
    ar.set3DModelToMarker("label_f", 0)
    ar.set3DModelToMarker("label_fg", 0)
    ar.set3DModelToMarker("label_fh", 0)
    ar.set3DModelToMarker("label_he", 0)
    ar.set3DModelToMarker("label_m", 0)
    ar.set3DModelToMarker("label_ms", 0)
    ar.set3DModelToMarker("label_oosc", 0)
ar.set3DModelToMarker("label_oos", 0)

# ("label_ais")
# ("label_bh")
# ("label_cb")
# ("label_cbc")
# ("label_cw")
# ("label_ec")
# ("label_f")
# ("label_fg")
# ("label_fh")
# ("label_he")
# ("label_m")
# ("label_ms")
# ("label_oos")
# ("label_oosc")
# ("label_oos")

if button == "Shape_based":
    if (currentStep == 0):
        print "Moved to Shape-based screen from Home screen"
        switchTo(currentStep+1)
        ar.showMenuBar("true")
        ar.enableMenuBar("true")

        ar.disableModel("part_teapot")
        ar.disableModel("part_ais")
        ar.disableModel("part_bh")
        ar.disableModel("part_cb")
        ar.disableModel("part_cbc")
        ar.disableModel("part_cw")
        ar.disableModel("part_ec")
        ar.disableModel("part_f")
        ar.disableModel("part_fg")
        ar.disableModel("part_fh")
        ar.disableModel("part_he")
        ar.disableModel("part_m")
        ar.disableModel("part_ms")
        ar.disableModel("part_oos")
        ar.disableModel("part_oosc")
        ar.disableModel("full_model")
        ar.disableModel("nerf1")

        ar.disableModel("label_ais")
        ar.disableModel("label_bh")
        ar.disableModel("label_cb")
        ar.disableModel("label_cbc")
        ar.disableModel("label_cw")
        ar.disableModel("label_ec")
        ar.disableModel("label_f")
        ar.disableModel("label_fg")
        ar.disableModel("label_fh")
ar.disableModel("label_he")
ar.disableModel("label_m")
ar.disableModel("label_ms")
ar.disableModel("label_oosc")
ar.disableModel("label_oos")

if button == "Topology_based":
    if (currentStep == 0):
        print "Moved to Topology-based screen from Home screen"
        switchTo(currentStep+2)
        ar.showMenuBar("true")
        ar.enableMenuBar("true")

        ar.disableModel("part_teapot")
ar.disableModel("part_ais")
ar.disableModel("part_bh")
ar.disableModel("part_cb")
ar.disableModel("part_cbc")
ar.disableModel("part_cw")
ar.disableModel("part_ec")
ar.disableModel("part_f")
ar.disableModel("part_fg")
ar.disableModel("part_fh")
ar.disableModel("part_he")
ar.disableModel("part_m")
ar.disableModel("part_ms")
ar.disableModel("part_oos")
ar.disableModel("part_oos")
ar.disableModel("full_model")
ar.disableModel("nerf1")

if button == "Home1":
    if (currentStep == 1):
        print "Moved to Home screen from Shape-based screen"
        switchTo(currentStep == 0)
        ar.enableMenuBar("false")

        ar.disableModel("part_teapot")
ar.disableModel("part_ais")
ar.disableModel("part_bh")
ar.disableModel("part_cb")
ar.disableModel("part_cbc")
ar.disableModel("part_cw")
ar.disableModel("part_ec")
ar.disableModel("part_f")
ar.disableModel("part_fg")
ar.disableModel("part_fh")
ar.disableModel("part_he")
ar.disableModel("part_m")
ar.disableModel("part_ms")
ar.disableModel("part_oos")
ar.disableModel("part_oosc")
ar.disableModel("full_model")
ar.disableModel("nerf1")

if button == "Home2":
    if(currentStep == 2):
        print "Moved to Home screen from Topology-based screen"
        switchTo(currentStep == 0)
ar.enableMenuBar("false")

    ar.disableModel("part_teapot")
ar.disableModel("part_ais")
ar.disableModel("part_bh")
ar.disableModel("part_cb")
ar.disableModel("part_cbc")
ar.disableModel("part_cw")
ar.disableModel("part_ec")
ar.disableModel("part_f")
ar.disableModel("part_fg")
ar.disableModel("part_fh")
ar.disableModel("part_he")
ar.disableModel("part_m")
ar.disableModel("part_ms")
ar.disableModel("part_oos")
ar.disableModel("part_oos")
ar.disableModel("full_model")
ar.disableModel("nerf1")

if button == "Quit":
    print "Application voluntarily closed from Home screen"
ar.exit_ar()

if button == "Quit1":
    print "Application voluntarily closed from Shape-based screen"
ar.exit_ar()

if button == "Quit2":
    print "Application voluntarily closed from Topology-based screen"
ar.exit_ar()

if button == "All_models1":
    print "Show all models"
ar.enableModel("full_model")

if button == "All_models2":
    print "Show all models"
ar.enableModel("full_model")

if button == "No_models1":
    print "Hide all models"
ar.disableModel("part_teapot")
ar.disableModel("part_ais")
ar.disableModel("part_bh")
ar.disableModel("part_cb")
ar.disableModel("part_cbc")
ar.disableModel("part_cw")
ar.disableModel("part_ec")
ar.disableModel("part_f")
ar.disableModel("part_fg")
ar.disableModel("part_fh")
ar.disableModel("part_he")
ar.disableModel("part_m")
ar.disableModel("part_ms")
ar.disableModel("part_oos")
ar.disableModel("part_oosc")
ar.disableModel("full_model")
ar.disableModel("nerf1")

ar.disableModel("label_ais")
ar.disableModel("label_bh")
ar.disableModel("label_cb")
ar.disableModel("label_cbc")
ar.disableModel("label_cw")
ar.disableModel("label_ec")
ar.disableModel("label_f")
ar.disableModel("label_fg")
ar.disableModel("label_fh")
ar.disableModel("label_he")
ar.disableModel("label_m")
ar.disableModel("label_ms")
ar.disableModel("label_oos")
ar.disableModel("label_oosc")

if button == "No_models2":
    print "Show no models"
ar.disableModel("part_teapot")
ar.disableModel("part_ais")
ar.disableModel("part_bh")
ar.disableModel("part_cb")
ar.disableModel("part_cbc")
ar.disableModel("part_cw")
ar.disableModel("part_EC")
ar.disableModel("part_f")
ar.disableModel("part_fg")
ar.disableModel("part_fh")
ar.disableModel("part_he")
ar.disableModel("part_m")
ar.disableModel("part_ms")
ar.disableModel("part_oos")
ar.disableModel("part_oosc")
ar.disableModel("full_model")
Test_nerf.py

from ctypes import *
ar = cdll.LoadLibrary("ARPyInt.dll")

import time
currentStep = 0
oldStep = 0
timerActive = False

submenus = ["menu00","menu01","menu02"] #buttons
steps = ["Home_screen","Shape_screen","Topology_screen"] #models
button_states = [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0];
model_names = ["air_plunger","barrel","plunger_release","left_housing","muzzle","rotator","piston_spring","right_housing","screws","half-slide","trigger"]
group_states = [0,0,0] #group_cocking, group_trig, group_airflow
group_cocking = ["half-slide","release_plunger","air_plunger","piston_spring"]
group_trig = ["trigger","plunger_release","rotator","barrel"]
group_airflow = ["air_plunger","piston_spring","barrel","muzzle"]

def model2Idx(model_name):
    global model_names
    print "lookup inde for ", model_name
    index = -1
    try:
index = model_names.index(model_name)
except ValueError:
    print "model does not exist"
    print "have index ", index
    return index;

def toggleModel(model_name):
    print "toggle model ", model_name
global button_states
global model_names
    index = model2Idx(model_name);
    if index > -1:
        if button_states[index] == 0:
            ar.enableModel(model_name)
            button_states[index] = 1;
        elif button_states[index] == 1:
            ar.disableModel(model_name)
            button_states[index] = 0;

def locEnableModel(model_name):
    global button_states
global model_names
    index = model2Idx(model_name);
    if index > -1:
        ar.enableModel(model_name)
        button_states[index] = 1;

def locDisableModel(model_name):
    global button_states
global model_names
    index = model2Idx(model_name);
    if index > -1:
        ar.disableModel(model_name)
        button_states[index] = 0;

def toggleGroup(group_index, group):
    global group_states;
    if(group_states[group_index] == 0):
        group_states[group_index] = 1
for x in group:
    locEnableModel(x)
elif(group_states[group_index] == 1):
    group_states[group_index] = 0
    for x in group:
        locDisableModel(x)

# "air_plunger"
# "barrel"
# "plunger_release"
# "left_housing"
# "muzzle"
# "rotator"
# "piston_spring"
# "right_housing"
# "screws"
# "slide"
# "trigger"

def onPatternIn(pattern_id):
    # fires when 'identify a pattern' placed in background

    print "Pattern in event", pattern_id
    global predict_visible

    # store the message to a file
    message = "on pattern in\t";
    message += str(pattern_id);
    ar.writeLog(message)

    if (currentStep == 1 or currentStep == 2):
        if pattern_id == 0:
            predict_visible = True
            print "Marker 0 now visible"

def onPatternOut(pattern_id):
    # fires when 'identify a pattern' removed from the background
    #print "Pattern out event", pattern_id
    # markerPresent[pattern_id] = False
    global predict_visible

    # store the message to a file
    message = "on pattern out\t";
    message += str(pattern_id);
    ar.writeLog(message)

    if pattern_id == 0:
        predict_visible = False
def onInit(frameid):
    #fires when you start the application
    global currentStep
    print "Marker 0 now lost"
    print "Open file."
    # Open the log file
    ar.openLogFile("C:/AR Tools/ARMaker/bin/records/functional_nerf_study.txt", "Chloe McPherson\nSurface Pro 4\nStudy 01\nStudy to test an AR app for virtual product dissection")
    print "INIT Application."
    ar.setWorldReferenceMarker(0)
    ar.enableVideoBackground()
    ar.switchToSubMenu(submenus[0])
    ar.enableMenuBar("false")
    ar.disableModel("nerf1")
    ar.disableModel("air_plunger")
    ar.disableModel("barrel")
    ar.disableModel("plunger_release")
    ar.disableModel("left_housing")
    ar.disableModel("muzzle")
    ar.disableModel("rotator")
    ar.disableModel("piston_spring")
    ar.disableModel("slide")
    ar.disableModel("right_housing")
    ar.disableModel("screws")
    ar.disableModel("trigger")
    ar.remove3DModelFromMarker("label_s")
    ar.remove3DModelFromMarker("label_t")
    ar.remove3DModelFromMarker("label_sc")
    ar.remove3DModelFromMarker("label_rh")
    ar.remove3DModelFromMarker("label_ps")
    ar.remove3DModelFromMarker("label_mz")
    ar.remove3DModelFromMarker("label_lh")
    ar.remove3DModelFromMarker("label_b")
    ar.remove3DModelFromMarker("label_ap")
    ar.remove3DModelFromMarker("label_pr")
    ar.remove3DModelFromMarker("label_p")

    # "label_s")
    # "label_t")
    # "label_sc")
    # "label_rh")
    # "label_ps")
    # "label_p")
def switchTo(step):
    global currentStep
    global steps
    global oldStep;
    #print "switchTo is successfully called. step received: ", steps[currentStep]
    currentStep = step
    ar.setScene(steps[currentStep])
    ar.switchToSubMenu(submenus[currentStep])
    print "switchTo is successfully called. menu received: ", submenus[currentStep]
    if currentStep != oldStep:
        print "Switched to step: ", steps[currentStep]
        oldStep = currentStep

def onFrame(frameid):
    global currentStep
    global timerActive
    global start
    global true_position
    global true_position_stored
    global true_rotation
    global true_scale_stored
    ar.setWorldReferenceMarker(0)

def onMenuAction(item, action): #Controls buttons on the scroll menu/menu bar
    print "[Py] Item pressed : ", item, ": ", action
    global currentStep
    global num_pred
    global predict_visible
    global button_states

    # store the message to a file
    message = "item pressed\\n";
    message += item;
    message += "\\n";
    message += str(currentStep)
message += "\t"
message += str(button_states)
ar.writeLog(message)

if (currentStep == 1 or currentStep == 2):
    if item == "Air_plunger":
        if button_states[0] == 0:
            print "Show air plunger"
ar.enableModel("air_plunger")
ar.enableModel("label_ap")
        button_states[0] = 1;
        elif button_states[0] == 1:
            print "Hide air plunger"
ar.disableModel("air_plunger")
ar.disableModel("label_ap")
        button_states[0] = 0;

    if item == "Barrel":
        if button_states[1] == 0:
            print "Show barrel"
ar.enableModel("barrel")
ar.enableModel("label_b")
        button_states[1] = 1;
        elif button_states[1] == 1:
            print "Hide barrel"
ar.disableModel("barrel")
ar.disableModel("label_b")
        button_states[1] = 0;

    if item == "Plunger_release":
        if button_states[2] == 0:
            print "Show plunger release"
ar.enableModel("plunger_release")
ar.enableModel("label_pr")
        button_states[2] = 1;
        elif button_states[2] == 1:
            print "Hide plunger release"
ar.disableModel("plunger_release")
ar.disableModel("label_pr")
        button_states[2] = 0;

    if item == "Left_housing":
        if button_states[3] == 0:
            print "Show left housing"
ar.enableModel("left_housing")
ar.enableModel("label_lh")
        button_states[3] = 1;
        elif button_states[3] == 1:
            print "Hide left housing"
ar.disableModel("left_housing")
ar.disableModel("label_lh")
button_states[3] = 0;

if item == "Muzzle":
    if button_states[4] == 0:
        print "Show muzzle"
ar.enableModel("muzzle")
ar.enableModel("label_mz")
button_states[4] = 1;
    elif button_states[4] == 1:
        print "Hide muzzle"
ar.disableModel("muzzle")
ar.disableModel("label_mz")
button_states[4] = 0;

if item == "Rotator":
    if button_states[5] == 0:
        print "Show ____"
ar.enableModel("rotator")
ar.enableModel("label_r")
button_states[5] = 1;
    elif button_states[5] == 1:
        print "Hide ____"
ar.disableModel("rotator")
ar.disableModel("label_r")
button_states[5] = 0;

if item == "Piston_spring":
    if button_states[6] == 0:
        print "Show piston spring"
ar.enableModel("piston_spring")
ar.enableModel("label_ps")
button_states[6] = 1;
    elif button_states[6] == 1:
        print "Hide piston spring"
ar.disableModel("piston_spring")
ar.disableModel("label_ps")
button_states[6] = 0;

if item == "Right_housing":
    if button_states[7] == 0:
        print "Show right housing"
ar.enableModel("right_housing")
ar.enableModel("label_rh")
button_states[7] = 1;
    elif button_states[7] == 1:
        print "Hide right housing"
ar.disableModel("right_housing")
ar.disableModel("label_rh")
button_states[7] = 0;
if item == "Screws":
    if button_states[8] == 0:
        print "Show screws"
        ar.enableModel("screws")
        ar.enableModel("label_sc")
        button_states[8] = 1;
    elif button_states[8] == 1:
        print "Hide screws"
        ar.disableModel("screws")
        ar.disableModel("label_sc")
        button_states[8] = 0;

if item == "Slide":
    if button_states[9] == 0:
        print "Show slide"
        ar.enableModel("half-slide")
        ar.enableModel("label_s")
        button_states[9] = 1;
    elif button_states[9] == 1:
        print "Hide slide"
        ar.disableModel("half-slide")
        ar.disableModel("label_s")
        button_states[9] = 0;

if item == "Trigger":
    if button_states[10] == 0:
        print "Show trigger"
        ar.enableModel("trigger")
        ar.enableModel("label_t")
        button_states[10] = 1;
    elif button_states[10] == 1:
        print "Hide trigger"
        ar.disableModel("trigger")
        ar.disableModel("label_t")
        button_states[10] = 0;

def onMenuButton(button):
    # Controls regular buttons
    print "[Py] Button pressed : ", button
    global currentStep
    global num_pred
    global predict_visible
    global button_states
    global group_states;
    global group_cocking
    global group_trig
    global group_airflow

    # store the message to a file
    message = "button pressed\n"
    message += button;
message += "\t"
message += str(currentStep)
ar.writeLog(message)

if button == "Cocking":
    if (currentStep == 2):
        print "Show cocking mechanism group"
toggleGroup(0, group_cocking)

if button == "TG":
    if (currentStep == 2):
        print "Show trigger mechanism group"
toggleGroup(1, group_trig)

if button == "Airflow":
    if (currentStep == 2):
        print "Show airflow/release group"
toggleGroup(2, group_airflow)

if button == "3D_view1":
    print "Changed to 3D view"
ar.remove3DModelFromMarker("label_s")
ar.remove3DModelFromMarker("label_t")
ar.remove3DModelFromMarker("label_sc")
ar.remove3DModelFromMarker("label_rh")
ar.remove3DModelFromMarker("label_ps")
ar.remove3DModelFromMarker("label_mz")
ar.remove3DModelFromMarker("label_lh")
ar.remove3DModelFromMarker("label_b")
ar.remove3DModelFromMarker("label_ap")
ar.remove3DModelFromMarker("label_pr")
ar.remove3DModelFromMarker("label_r")

if button == "3D_view2":
    print "Changed to 3D view"
ar.remove3DModelFromMarker("label_s")
ar.remove3DModelFromMarker("label_t")
ar.remove3DModelFromMarker("label_sc")
ar.remove3DModelFromMarker("label_rh")
ar.remove3DModelFromMarker("label_ps")
ar.remove3DModelFromMarker("label_mz")
ar.remove3DModelFromMarker("label_lh")
ar.remove3DModelFromMarker("label_b")
ar.remove3DModelFromMarker("label_ap")
ar.remove3DModelFromMarker("label_pr")
ar.remove3DModelFromMarker("label_r")

# "label_s")
# "label_t")
# "label_sc")
# "label_rh")
if button == "Label_view1":
    print "Changed to label view"
    ar.set3DModelToMarker("label_s", 0);
    ar.set3DModelToMarker("label_t", 0)
    ar.set3DModelToMarker("label_sc", 0)
    ar.set3DModelToMarker("label_rh", 0)
    ar.set3DModelToMarker("label_ps", 0)
    ar.set3DModelToMarker("label_mz", 0)
    ar.set3DModelToMarker("label_lh", 0)
    ar.set3DModelToMarker("label_b", 0)
    ar.set3DModelToMarker("label_ap", 0)
    ar.set3DModelToMarker("label_pr", 0)
    ar.set3DModelToMarker("label_r", 0)

if button == "Label_view2":
    print "Changed to label view"
    ar.set3DModelToMarker("label_s", 0);
    ar.set3DModelToMarker("label_t", 0)
    ar.set3DModelToMarker("label_sc", 0)
    ar.set3DModelToMarker("label_rh", 0)
    ar.set3DModelToMarker("label_ps", 0)
    ar.set3DModelToMarker("label_mz", 0)
    ar.set3DModelToMarker("label_lh", 0)
    ar.set3DModelToMarker("label_b", 0)
    ar.set3DModelToMarker("label_ap", 0)
    ar.set3DModelToMarker("label_pr", 0)
    ar.set3DModelToMarker("label_r", 0)

if button == "Shape_based":
    if (currentStep == 0):
        print "Moved to Shape-based screen from Home screen"
        switchTo(currentStep+1)
        ar.showMenuBar("true")
        ar.enableMenuBar("true")
        ar.disableModel("nerf1")
        ar.disableModel("air_plunger")
        ar.disableModel("barrel")
        ar.disableModel("plunger_release")
        ar.disableModel("left_housing")
        ar.disableModel("muzzle")
        ar.disableModel("rotator")
        ar.disableModel("piston弹簧")
if button == "Topology_based":
    if (currentStep == 0):
        print "Moved to Topology-based screen from Home screen"
        switchTo(currentStep+2)
        ar.showMenuBar("true")
        ar.enableMenuBar("true")
        ar.disableModel("nerf1")
        ar.disableModel("air_plunger")
        ar.disableModel("barrel")
        ar.disableModel("plunger_release")
        ar.disableModel("left_housing")
        ar.disableModel("muzzle")
        ar.disableModel("rotator")
        ar.disableModel("piston_spring")
        ar.disableModel("slide")
        ar.disableModel("right_housing")
        ar.disableModel("screws")
        ar.disableModel("trigger")
        ar.disableModel("half-slide")
        ar.disableModel("label_s")
        ar.disableModel("label_t")
        ar.disableModel("label_sc")
        ar.disableModel("label_rh")
        ar.disableModel("label_ps")
        ar.disableModel("label_mz")
        ar.disableModel("label_lh")
        ar.disableModel("label_pr")
        ar.disableModel("label_r")
        ar.disableModel("label_ap")
if button == "Home1":
    if (currentStep == 1):
        print "Moved to Home screen from Shape-based screen"
        switchTo(currentStep == 0)
        ar.enableMenuBar("false")

        ar.disableModel("nerf1")
        ar.disableModel("air_plunger")
        ar.disableModel("barrel")
        ar.disableModel("plunger_release")
        ar.disableModel("left_housing")
        ar.disableModel("muzzle")
        ar.disableModel("rotator")
        ar.disableModel("piston_spring")
        ar.disableModel("slide")
        ar.disableModel("right_housing")
        ar.disableModel("screws")
        ar.disableModel("trigger")
        ar.disableModel("half-slide")

        ar.disableModel("label_s")
        ar.disableModel("label_t")
        ar.disableModel("label_sc")
        ar.disableModel("label_rh")
        ar.disableModel("label_ps")
        ar.disableModel("label_mz")
        ar.disableModel("label_lh")
        ar.disableModel("label_b")
        ar.disableModel("label_ap")
        ar.disableModel("label_pr")
        ar.disableModel("label_r")

if button == "Home2":
    if (currentStep == 2):
        print "Moved to Home screen from Topology-based screen"
        switchTo(currentStep == 0)
        ar.enableMenuBar("false")

        ar.disableModel("nerf1")
        ar.disableModel("air_plunger")
        ar.disableModel("barrel")
        ar.disableModel("plunger_release")
        ar.disableModel("left_housing")
        ar.disableModel("muzzle")
        ar.disableModel("rotator")
        ar.disableModel("piston_spring")
        ar.disableModel("slide")
        ar.disableModel("right_housing")
        ar.disableModel("screws")
        ar.disableModel("trigger")
        ar.disableModel("half-slide")
ar.disableModel("label_s")
ar.disableModel("label_t")
ar.disableModel("label_sc")
ar.disableModel("label_rh")
ar.disableModel("label_ps")
ar.disableModel("label_mz")
ar.disableModel("label_lh")
ar.disableModel("label_b")
ar.disableModel("label_ap")
ar.disableModel("label_pr")
ar.disableModel("label_r")

if button == "Quit":
    print "Application voluntarily closed from Home screen"
ar.exit_ar()

if button == "Quit1":
    print "Application voluntarily closed from Shape-based screen"
ar.exit_ar()

if button == "Quit2":
    print "Application voluntarily closed from Topology-based screen"
ar.exit_ar()

if button == "All_models1":
ar.enableModel("air_plunger")
ar.enableModel("barrel")
ar.enableModel("plunger_release")
ar.enableModel("left_housing")
ar.enableModel("muzzle")
ar.enableModel("rotator")
ar.enableModel("piston_spring")
ar.enableModel("slide")
ar.enableModel("right_housing")
ar.enableModel("screws")
ar.enableModel("trigger")
button_states = [1,1,1,1,1,1,1,1,1,1,1,1,1];

if button == "All_models2":
ar.enableModel("air_plunger")
ar.enableModel("barrel")
ar.enableModel("plunger_release")
ar.enableModel("left_housing")
ar.enableModel("muzzle")
ar.enableModel("rotator")
ar.enableModel("piston_spring")
ar.enableModel("slide")
ar.enableModel("right_housing")
ar.enableModel("screws")
ar.enableModel("trigger")
button_states = [1,1,1,1,1,1,1,1,1,1,1,1];

if button == "No_models1":
    ar.disableModel("nerf1")
    ar.disableModel("air_plunger")
    ar.disableModel("barrel")
    ar.disableModel("plunger_release")
    ar.disableModel("left_housing")
    ar.disableModel("muzzle")
    ar.disableModel("rotator")
    ar.disableModel("piston_spring")
    ar.disableModel("slide")
    ar.disableModel("right_housing")
    ar.disableModel("screws")
    ar.disableModel("trigger")
    ar.disableModel("half-slide")
    ar.disableModel("slide")
    ar.disableModel("label_s")
    ar.disableModel("label_t")
    ar.disableModel("label_sc")
    ar.disableModel("label_lh")
    ar.disableModel("label_b")
    ar.disableModel("label_ap")
    ar.disableModel("label_pr")
    ar.disableModel("label_r")
    ar.disableModel("label_ms")
    ar.disableModel("label_mz")
    ar.disableModel("label_lh")
    ar.disableModel("label_br")

button_states = [0,0,0,0,0,0,0,0,0,0,0,0];

if button == "No_models2":
    ar.disableModel("nerf1")
    ar.disableModel("air_plunger")
    ar.disableModel("barrel")
    ar.disableModel("plunger_release")
    ar.disableModel("left_housing")
    ar.disableModel("muzzle")
    ar.disableModel("rotator")
    ar.disableModel("piston_spring")
    ar.disableModel("slide")
    ar.disableModel("right_housing")
    ar.disableModel("screws")
    ar.disableModel("trigger")
    ar.disableModel("half-slide")
    ar.disableModel("slide")
    ar.disableModel("label_s")
    ar.disableModel("label_t")
    ar.disableModel("label_sc")
ar.disableModel("label_rh")
ar.disableModel("label_ps")
ar.disableModel("label_mz")
ar.disableModel("label_lh")
ar.disableModel("label_b")
ar.disableModel("label_ap")
ar.disableModel("label_pr")
ar.disableModel("label_r")

button_states = [0,0,0,0,0,0,0,0,0,0,0,0];
APPENDIX D

INFORMED CONSENT DOCUMENT

Title of Study: Functional decomposition in product dissection tasks utilizing augmented reality visualization

Investigators: Chloe McPherson, Rafael Radkowski

This form describes a research project. It has information to help you decide whether or not you wish to participate. Research studies include only people who choose to take part—your participation is completely voluntary. Please discuss any questions you have about the study or about this form with the project staff before deciding to participate.

Introduction

The objective of this research is to assess the effectiveness of an augmented reality application for functional decomposition during a product dissection task. Functional decomposition is a process that assists engineers to break down products into their functions. However, many engineers still have difficulty identifying and understanding essential functions. Using augmented reality to overlay additional information to participants during product dissection may improve overall understanding of functionality and aid in application of functional decomposition techniques.

You should not participate if you are colorblind or if you are under 18 years of age.

Description of Procedures

If you agree to participate, you will be asked to analyze two common products: a hair dryer and a Nerf toy dart blaster. The session is expected to last roughly 1 hour. You will be asked to perform two product dissections, one a standard physical product dissection and one a virtual product dissection with the aid of an augmented reality (AR) application operating on a tablet computer.

For each dissection, you will be asked to decompose the product into its functions and to create a function structure for each product. For the virtual dissection, text on the tablet computer’s screen will aid you in understanding information about the product’s components and/or function groups in order to analyze all of the functions within the product. At the conclusion of the session, you will be asked to complete a post-study questionnaire.

You can ask questions before the experiment has started, but during the test the investigator will offer no additional assistance. We will record all your interactions with the tablet computer and the AR application (number of times you hit a button and the time you hit the button).

Risks or Discomforts

While participating in this study you may experience the following risks:

- **Simulator sickness**, which can include symptoms such as fatigue, dizziness, and headache. The likelihood and magnitude of this risk is not higher than in normal life (these symptoms may also be present in activities such as driving a car, playing videogames, watching TV, and watching a movie in a movie theater). *In the case of simulator sickness, please close your eyes and inform the experimenter.*

- **Hand/arm discomfort** from holding tablet computer. The tablet’s weight is approx. 1.7 pounds. Due to the long duration of the study, you may experience paroxysm and/or fatigue in your arm. *In this case, place the tablet computer on the table and inform the experimenter.*

- **Informational risks**, Participants may become embarrassed when disclosed that they do not
know how to identify essential functions for functional decomposition. The risk is minimal since research results indicate that functional decomposition is a problem solving strategy often ignored by engineers, and so many engineers do not properly understand how to identify essential functions based on product dissection. Thus it is common not to understand it.

In the case of simulator sickness or discomfort, the experiment will be immediately suspended, so that you can recover.

Benefits
If you decide to participate in this study there will be no direct benefit to you. However, it is hoped that the information gained in this study will benefit society by improving understanding of how digital information that augment physical objects may change a user’s understanding of the environment and how this information foster learning.

Costs and Compensation
You will not have any costs based on your participation in this study. Participants will receive $10 for completing this study. Participants who withdraw prior to completion of the study will receive $5.

Participant Rights
Your participation in this study is completely voluntary and you may refuse to participate or leave the study at any time. If you decide to not participate in the study or leave the study early, it will not result in any penalty or loss of benefits to which you are otherwise entitled. You can skip any questions that you do not wish to answer.

Your choice of whether or not to participate in this study will have no impact on you as a student in any way.

If you have any questions about the rights of research subjects or research-related injury, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or Director, (515) 294-3115, Office for Responsible Research, Iowa State University, Ames, Iowa 50011.

Confidentiality
Records identifying participants will be kept confidential to the extent permitted by applicable laws and regulations and will not be made publicly available. However, auditing departments of Iowa State University, and the Institutional Review Board (a committee that reviews and approves human subject research studies) may inspect and/or copy your records for quality assurance and data analysis. These records may contain private information.

To ensure confidentiality to the extent permitted by law, the particular results of your participation in this study will not be linked to your personal identity in any way. Also, if the results of this study are published, the identities of all participants will remain confidential.

Questions
You are encouraged to ask questions at any time during this study.

- For further information about the study contact Chloe McPherson at cmcphe9@iastate.edu or Dr. Rafael Radkowski at rafael@iastate.edu.
- If you have any questions about the rights of research subjects or research-related injury, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or Director, (515) 294-3115, Office for Responsible Research, Iowa State University, Ames, Iowa 50011.

Consent and Authorization Provisions
Your signature indicates that you voluntarily agree to participate in this study, that the study has been explained to you, that you have been given the time to read the document, and that your questions have been satisfactorily answered. You will receive a copy of the written informed consent prior to your participation in the study.

Participant's Name (printed) ____________________________________________

Participant's Signature ____________________________________________ Date
APPENDIX E
STUDY QUESTIONNAIRES

Pre-Questionnaire

Functional decomposition in product dissection tasks utilizing augmented reality visualization

Participant ID Number: __________

Part I – Experience with Engineering Design and Functional Modeling

1. Have you ever modeled a product using CAD software (e.g. SolidWorks, AutoCAD) before?
   - Yes □
   - No □

2. How many products have you modeled using CAD software?
   - 0-5 □
   - 6-10 □
   - 11-50 □
   - >50 □
   - N/A □

3. Have you ever performed a product dissection? (If No, please skip to question 7)
   - Yes □
   - No □

4. How many products have you dissected?
   - 0-5 □
   - 6-10 □
   - 11-50 □
   - >50 □

5. Have you had any experience with functional modeling or functional decomposition?
   - Yes □
   - No □

6. How many functional models (e.g. function trees) have you created?
   - 0-5 □
   - 6-10 □
   - 11-50 □
   - >50 □

7. Have you ever experienced Augmented Reality (AR) or Virtual Reality (VR) before?
   - Yes □
   - No □
8. Of the design activities below, please select the six MOST important.

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9. Please list any relevant skills for designers that you could not find above.

________________________________________________________________________________________

10. Of the design activities below, please select the six LEAST important.

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Part II – Personal Information

1. **What is your age?**
   - 18-25 □
   - 26-35 □
   - 36-45 □
   - 46-55 □
   - >56 □

2. **What is your sex?**
   - Male □
   - Female □

3. **Please specify your ethnicity.**
   - White or Caucasian □
   - Hispanic or Latino □
   - Black or African American □
   - Native American □
   - Asian/Pacific Islander □
   - Other: __________________

4. **What is the highest level of education you have completed?**
   - High School □
   - B.S./B.A. □
   - M.S./M.A. □
   - Ph.D./M.D. □
   - Other: __________________
   
   a. **If you are a student, what is your major?**
      ____________________________
   
   b. **If you are not a student, what is your profession?**
      ____________________________

5. **If you are a college student, what year in school are you?**
   - Freshman □
   - Sophomore □
   - Junior □
   - Senior □
   - 5th Year Undergrad + □
   - M.S. student □
   - PhD student □

6. **Do you wear corrective lenses (i.e. glasses or contact lenses)?**
   - Yes □
   - No □
Identifying Function Structures Questions (pre-study)

Function Structure 1 (Pre)

Participant ID Number: __________

Circle the product that the following function structure describes.

A. Vacuum Cleaner  
B. Electric Toothbrush  
C. Power Drill
Function Structure 2 (Pre)

Participant ID Number: __________

Circle the product that the following function structure describes.

A. Snow Blower  
B. Food Processor  
C. Pencil Sharpener
Identifying Function Structures Questions (post-study)

Function Structure 1 (Post)

Participant ID Number: __________

Would you like to update your answer to the below question?

☐ Yes  ☐ No

Circle the product that the following function structure describes.

- B. Vacuum Cleaner
- B. Electric Toothbrush
- C. Power Drill
Function Structure 2 (Post)

Participant ID Number: __________

Would you like to update your answer to the below question?

Yes ☐ ☐ No ☐ ☐

Circle the product that the following function structure describes.

B. Snow Blower  B. Food Processor  C. Pencil Sharpener
Post-Questionnaire

Functional decomposition in product dissection tasks utilizing augmented reality visualization

Participant ID Number: __________

For each set of statements below, please select the statement that most accurately reflects your experience engaging in the experiment.

1. Performance
   - ☐ I was very successful in accomplishing the tasks I was asked to do.
   - ☐ I was somewhat successful in accomplishing the tasks I was asked to do.
   - ☐ I am unsure of my performance on the tasks I was asked to do.
   - ☐ I was not very successful at accomplishing the tasks I was asked to do.
   - ☐ I was not successful at all in accomplishing the tasks I was asked to do.

2. Effort
   - ☐ I did not have to work at all to accomplish my level of performance.
   - ☐ I only had to put in a small amount of effort to accomplish my level of performance.
   - ☐ I am not sure how hard I had to work to accomplish my level of performance.
   - ☐ I had to put in some effort to accomplish my level of performance.
   - ☐ I had to put in significant effort to accomplish my level of performance.

3. Frustration
   - ☐ I was not discouraged, irritated, stressed or annoyed at all during these tasks.
   - ☐ Rarely did these tasks make me discouraged, irritated, stressed and annoyed.
   - ☐ I am unsure if I was irritated, stressed and annoyed during these tasks.
   - ☐ At times these tasks made me discouraged, irritated, stressed and annoyed.
   - ☐ These tasks made me very discouraged, irritated, stressed and annoyed.

4. Confusion
   - ☐ I had no difficulty understanding the tasks that I was asked to perform.
   - ☐ I had little difficulty understanding the tasks that I was asked to perform.
   - ☐ I had some difficulty understanding the tasks that I was asked to perform.
   - ☐ I had difficulty understanding all of the tasks that I was asked to perform.
   - ☐ I did not understand the tasks that I was asked to perform.

5. Instruction
   - ☐ The instructions provided in this application were very clear and straightforward.
   - ☐ The instructions provided in this application were usually clear and straightforward.
   - ☐ The instructions provided in this application were sometimes clear and straightforward.
   - ☐ The instructions provided in this application were rarely clear and straightforward.
   - ☐ The instructions provided in this application were never clear and straightforward.

6. Fun
   - ☐ I enjoyed using this application and I would like to use it again.
   - ☐ I would not mind using this application again.
   - ☐ I am unsure if I would use this application again.
   - ☐ I would probably not use this application again.
☐ I did not enjoy using this application and would not use it again.

7. Ease of Use
☐ This application was never difficult to use.
☐ This application was rarely difficult to use.
☐ This application was sometimes difficult at times to use.
☐ This application was often too difficult to use.
☐ This application was too difficult to use.

Use the scale to identify to what extent you agree or disagree with the following statements.

8. The addition of 3D visual information (e.g. simulation of product models) improved my understanding of function.

Strongly Disagree Disagree Neutral Agree Strongly Agree
☐ ☐ ☐ ☐ ☐

9. The addition of textual information (e.g. component labels) improved my understanding of function.

Strongly Disagree Disagree Neutral Agree Strongly Agree
☐ ☐ ☐ ☐ ☐

10. Seeing 3D visual information (e.g. simulation of product models) contributed to my understanding of product function as much as seeing textual information.

Strongly Disagree Disagree Neutral Agree Strongly Agree
☐ ☐ ☐ ☐ ☐

11. Seeing textual information (e.g. component labels) contributed to my understanding of product function as much as seeing 3D visual information.

Strongly Disagree Disagree Neutral Agree Strongly Agree
☐ ☐ ☐ ☐ ☐

12. Of the design activities below, please select the six MOST important.

Abstracting functions ☐ Decomposing products ☐ Modeling designs ☐ Testing products ☐
Applying methods of creativity ☐ Evaluating products ☐ Running user tests ☐ Understanding the problem ☐
### 13. Of the design activities below, please select the six LEAST important.

| Brainstorming ideas | Generating alternatives | Seeking information | Understanding others’ point of view | Building models | Identifying constraints | Setting goals | Visualizing data and products | Communicating findings | Making decisions | Sketching ideas | Creating prototypes | Making trade-offs | Synthesizing ideas | Abstracting functions | Decomposing products | Modeling designs | Testing products | Applying methods of creativity | Evaluating products | Running user tests | Understanding the problem | Brainstorming ideas | Generating alternatives | Seeking information | Understanding others’ point of view | Building models | Identifying constraints | Setting goals | Visualizing data and products | Communicating findings | Making decisions | Sketching ideas | Creating prototypes | Making trade-offs | Synthesizing ideas |
|---------------------|------------------------|---------------------|-----------------------------------|------------------|------------------------|--------------|--------------------------------|------------------------|-------------------|----------------|----------------------|---------------------|---------------------|----------------------|----------------------|---------------------|-------------------------|----------------------|----------------------|----------------------------|----------------------|----------------------|-----------------------------|----------------------|----------------------|----------------------|----------------------|------------------------|-----------------------------|

### 14. Which product was MORE challenging to decompose into its functions?

- [ ] Hair Dryer
- [x] Nerf Toy Dart Blaster
FUNCTIONAL DECOMPOSITION LESSON & PRE-STUDY INFO

July 5, 2016
PI: Chloe McPherson, Rafael Radkowski

Overview

- Function
- Function Structure
- Example
  - 2 Function Structures questions
- Creating a Function Structure
- Application Introduction
Function

- A function describes the relationship of the intended inputs and outputs of a system to perform a task.
- A function is presented as a verb + subject pairing to represent a single task.
  - Each subject + verb pairing becomes an individual function block.
- Inputs and outputs show the flow of material, energy and/or information that is transferred by this function.
  - Multiple inputs and/or outputs can exist for each function.

Function Block

Function Structure

- A function structure is a systematic way to describe a system’s overall function as a combination of function blocks.
- It combines multiple functions by tracing the flow of material, energy and information throughout the system.
  - Functions are mapped to the changes in these flows

These four function blocks from a coffee maker are connected by the different materials (water, ground coffee), energy (electricity) and information (instructions to the system to heat water and start brewing) that move through its system.
Example: Nailer/Nail Gun

Proceed to answer both “Function Structures” questions on the sheet next to you
After answering both questions, continue on in this presentation.
Creating a Function Structure

- Four steps to creating function structures:
  - **Step 1** – Determine overall function
  - **Step 2** – Split overall function into function blocks
  - **Step 3** – Order and connect the function blocks
  - **Step 4** – Consistency check

- The following slides will walk through how to create a function structure with these four steps, using a coffee maker as an example.

---

Creating a Function Structure

**Step 1 – Determine overall function**

- Find the overall function that needs to be accomplished for the product.
Creating a Function Structure

Step 2 – Split overall function into function blocks

- Consider only what needs to be done and not how it should be done. Only those functions that directly support the overall function should be used.
- Add the inputs and outputs for each individual function block. Classify each input/output as material, energy, or information. For each input, draw an arrow entering the function block; for each output draw an arrow exiting the function block.

Function blocks for a coffee maker with their inputs and outputs labeled and classified.

Creating a Function Structure

- Strive to use only the pre-determined verbs when creating functions
  - You will assemble your individual functions and function structures using the cards and white board behind you
  - These cards contain the pre-determined verbs. To create a function, select a card and write your subject(s) on the line below the verb
  - Blank cards are available only for describing any functions not covered by the verb list

Cards with pre-determined function verbs

Examples of words found on the function verb list
Creating a Function Structure

Step 3 – Order and connect the function blocks

- Model all operational sequences by drawing lines to logically connect functions to each other according to their inputs and outputs

Creating a Function Structure

Step 4 – Consistency Check

- Verify the flow labels, validity and continuity for the structure.

Note: You do not need to write "Input" and "Output" when checking your function structure, this is just an example.
Application

This slide gives a brief overview of how the augmented reality application is laid out.

You have now completed the lesson

Next you will now have several minutes to explore the augmented reality application. The researcher will start the application for you.
APPENDIX G

IRB APPLICATION APPROVAL MEMO

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Date: 6/29/2016

To: Chloe McPherson
1520 Howe Hall

CC: Dr. Rafael Radkowski
1520 Howe Hall

From: Office for Responsible Research

Title: Functional decomposition in product dissection tasks utilizing augmented reality visualization

IRB ID: 16-116

Approval Date: 6/28/2016

Date for Continuing Review: 4/5/2017

Submission Type: Modification

Review Type: Expedited

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- Use only the approved study materials in your research, including the recruitment materials and informed consent documents that have the IRB approval stamp.

- Retain signed informed consent documents for 3 years after the close of the study, when documented consent is required.

- Obtain IRB approval prior to implementing any changes to the study by submitting a Modification Form for Non-Exempt Research or Amendment for Personnel Changes form, as necessary.

- Immediately inform the IRB of (1) all serious and/or unexpected adverse experiences involving risks to subjects or others, and (2) any other unanticipated problems involving risks to subjects or others.

- Stop all research activity if IRB approval lapses, unless continuation is necessary to prevent harm to research participants. Research activity can resume once IRB approval is reestablished.

- Complete a new continuing review form at least three to four weeks prior to the date for continuing review as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please be aware that IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. Approval from other entities may also be needed. For example, access to data from private records (e.g., student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. IRB approval in no way implies or guarantees that permission from these other entities will be granted.

Upon completion of the project, please submit a Project Closure Form to the Office for Responsible Research, 202 Kingland, to officially close the project.

Please don’t hesitate to contact us if you have questions or concerns at 515-294-4556 or IRB@iastate.edu.