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By Trevor W. Wanamaker

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Incorporating Reverse Engineering Methodology into Engineering Curricula

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Is approved by the final examining committee:

Dr. Craig L. Miller
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Dr. Patrick E. Connolly

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INCORPORATING REVERSE ENGINEERING METHODOLOGY INTO ENGINEERING CURRICULUM

A Thesis

Submitted to the Faculty

of

Purdue University

by

Trevor W. Wanamaker

In Partial Fulfillment of the

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of

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To my parents and my sister – for their love and support throughout the years.

To my fiancé, Kate – for her love and support in everything I choose to do.

To my newborn daughter Matilda – for changing our lives for the better.

To my grandparents – for helping make me the person I am today.

To my great aunt Dorothy – for helping make college a possibility.

To my great aunt Catherine – for always helping me.

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ABSTRACT

Wanamaker, Trevor W., M.S., Purdue University, May 2012. Incorporating Reverse Engineering Methodology into Engineering Curricula. Major Professor: Craig L. Miller.

Using a qualitative research approach, this study investigated the thoughts and feelings of students regarding the question, "what factors need to be considered when Reverse Engineering (RE) methodology is incorporated into engineering curricula?" The participants in the study were from the Introduction to Graphics for Manufacturing course at the West Lafayette campus of Purdue University. An RE survey was given to the all students enrolled in the course and 10 select students were given the opportunity to use a 3D handheld scanner in a hands-on learning exercise. Each of the 10 students underwent two interviews with questions pertaining to the study, the course, the technology, and the factors they felt were important to RE. The instructor for the course and an industry professional were interviewed to support the data gathered from the student interviews. The outcome of the study was a list of factors that students, the instructor, and the industry professional felt were important to RE implementation. This study provides information important to implementing RE into engineering curricula and suggestions for future research in the field of RE.

PUBLICATIONS

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CHAPTER 1. INTRODUCTION

The concept of reverse engineering (RE) is not a new idea; however the technology that is used to complete the process is growing and ever changing. The RE process is highly detailed and requires extensive repetitions to complete. A simple explanation of RE was given by a United States District Court in the case of Secure Services Technology, Inc. versus Time and Space Processing, Inc (1989), as, "…the process of starting with a finished product and working backwards to analyze how the product operates or how it was made."

Research showed the majority of RE research focuses on industry and was seldom conducted in education. What makes RE so vital to success in our industrial world? RE is needed to keep products in the market by creating replacement parts for a product that is no longer serviced by the company that manufactured it, replacing parts that were custom made, and many other reasons. The United States Army and other military branches used RE technologies to maintain their planes and other military vehicles that have been in service since before 1955 (Durupt, Remy, & Ducellier, 2010).

Science, technology, engineering, and mathematics (STEM) programs educated students in ways that improved a student's learning and enabled the United States to remain a leader in economics and technology (Lantz, 2009). It is important to educate

students in a way that benefits them as well as industry. Exposing students to a variety of technologies was one way students could be more prepared for industry.

The study, educated students within engineering and technology on RE methodology, specifically 3D scanning. Through this education, students had the ability to give a more educated opinion on what factors from RE they felt were important to their learning. Students who chose to participate were given surveys to determine their knowledge and interest in RE. These surveys were given to students before and after they were given an introduction in RE methodology. The reason for the surveys was to indicate the level of student interest in a widely used industrial practice. Select students were given the opportunity to use 3D scanning technology at a deeper level which allowed them to provide more educated answers through an interview process to determine what parts of RE they felt were important to their education.

The study introduced RE methodology into academia. Through the study, students gained knowledge about industrial practices and were able to apply that knowledge when they entered the work force. Because Purdue University does not offer any classes with RE practices, the study enlightened professors and teachers about student interest in this field. The factors discovered during the study gave insight as to what factors need to be considered before an RE based class could be successfully implemented in technology and engineering curricula.

1.1. Statement of Purpose

A literature of RE in the classroom showed that many universities do not offer courses involving RE methodology. This is also true at Purdue University. When checking Purdue's online course listings it was discovered that there are many courses that offer introductory knowledge in CAD programs. However, there are no courses that use software programs, such as RapidForm, that are needed between 3D scanning and the finished CAD model for cleaning up 3D data.

1.2. Research Question

What factors need to be considered when Reverse Engineering (RE) methodology is incorporated into engineering curricula?

1.3. Scope

Research participants consisted of college-aged students between the ages of 18 to 22 that were enrolled in a STEM program in the fall semester of 2011. Due to convenience and time constraints students outside of this age range were not used. The Institutional Review Board required parental consent for all participants under the age of 18 so anyone below the age of 18 was not invited to participate. The study was limited to students who were enrolled at Purdue University. The students that were involved in this study were enrolled in the *Introduction to Graphics for Manufacturing* (CGT 163) course at Purdue University main campus. The class was comprised of primarily

freshman and sophomore students majoring in various fields of engineering and technology.

Students enrolled in this course were introduced to reverse engineering practices in a lecture style setting as taught by the professor. They were educated on methods of reverse engineering, tools and equipment used, and they were given examples of data collection that were acquired by the researcher using a 3D scanner. All students were given the opportunity to complete surveys regarding the information introduced to them. Select students were chosen through a combination of course grade and test score on the Purdue Visualization Test of Rotations, and given the opportunity to experience reverse engineering on a deeper level. These chosen students were given an opportunity to use 3D scanning equipment and software to reverse engineer a part.

A survey was given to the entire class to determine the relevance of RE to engineering curricula. The students that were chosen were interviewed to obtain more in depth views and opinions on the subject. The study analyzed student knowledge and interests to determine what factors needed to be considered before implementation of reverse engineering into engineering courses could successfully occur.

1.4. Significance

The intension of the study was to determine what factors were important to incorporating RE methodology in technology and engineering curricula. This helped professors and teachers understand how beneficial this incorporation could be. Not only was it important for creating well-rounded students, but it could also give students an

edge in the job market. The ability to share information about a subject that is rarely taught in academia could help set them apart from other job applicants.

Every year universities graduate technologists and engineers that "…enter the workforce ill-equipped for the complex interactions, across many disciplines, of real-world engineered systems" (Wulf & Fisher, 2002, p. 36). Not only did graduates need to be more knowledgeable, but also it was important that students enjoyed what they were learning. If students do not have an interest in what they are learning then it is unlikely that they will make an effort to learn (Pintrich & Schunk, 2002).

1.5. Objectives

The overall goals of this research were to:

1. Determined what factors needed to be considered when introducing RE to college curricula.
2. Analyzed 3D scanning and its limitations.
3. Exposed students to RE technology.

1.6. Assumptions

Assumptions for the study included:

- Those involved in the study performed RE tasks quickly, correctly, and to the best of their ability.

- Students involved in the study answered all questionnaires truthfully and to the best of their knowledge.
- Computer software functioned properly.
- At the delivery time of the study, the participants possessed entry-level 3D modeling abilities which were required for the RE process.

1.7. Limitations

Limitations for the study included:

- The cooperation of students within a manufacturing graphics environment.
- Accessibility of engineering equipment and software due to time constraints.
- Time it took to scan and measure parts.
- Accuracy of the equipment that was being used.
- Interoperability of RE equipment with existing CAD packages.

1.8. Delimitations

Delimitations for the study included:

- The study focused on students enrolled in CGT 163 in the Fall Semester of 2011 at the West Lafayette campus of Purdue University.
- The study focused on implementing RE technology to only selected students in the course.
- The study focused on the use of the following parts of a scooter:

  - Handle tube
  - Bracket
- The study focused on the use of the ZScanner 800 3D laser scanner.
- The study focused on ZScan, RapidForm, and CATIA V5R20 software.

1.9. Definition of Terms

3D Scanning – "the process of gathering data from an undefined 3-dimensional surface" (Sokovic, Cedilnik, & Kopac, 2005, p. 602).

Computer-Aided Design (CAD) – "the use of computer programs and systems to design detailed two- or three-dimensional models of physical objects, such as mechanical parts, buildings, and molecules" (CAD).

Engineering design – "a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints" (Dym, Agogino, Eris, Frey, & Leifer, 2005, p. 104).

Interoperability – "the ability of different types of computers, networks, operating systems, and applications to work together effectively, without prior communication, in order to exchange information in a useful and meaningful manner" (North East Public Observatory, 2007).

Intrinsic Motivation – "motivation to engage in an activity for its own sake" (Pintrich & Schunk, 2002, p. 245).

Metrology – "the science of measurement" (Liming, 2009, p. 10).

Reverse Engineering – "the process of taking something (such as a mechanical device, an electrical component, or a software program) apart and analyzing its workings in detail, usually with the intention to construct a new device or program that does the same function without actually copying anything from the original (Younis, & Tutunji, 2010, p. 1).

Spatial Ability – "the ability to generate, retain, and manipulate abstract visual images" (Lohman, 1979, p.188).

STEM – "science, technology, engineering, and mathematics" (Lantz, Jr., 2009, p. 1).

1.10. Summary

The thesis covered numerous aspects and was intended to help educators and academia as a whole become aware of how RE is important to a future graduate's education. The focus of the study was on RE and how its methodologies can be incorporated to curricula.

Aspects that needed to be addressed in the literature review were the accuracy of RE methods when looking at 3D scanning and metrology, methods in which these practices were performed, as well as how RE has affected industry. The literature review also investigated various RE technologies that could be successfully incorporated into a university when cost, availability, and other factors were considered. The study helped improve a student's knowledge about the RE process by giving them examples.

CHAPTER 2. LITERATURE REVIEW

Reverse engineering, 3D scanning, and metrology are discussed in greater detail because those were the main focuses of the study. Literature regarding the industrial, educational with respect to instructional design, and legal aspects of reverse engineering are discussed as well. Most importantly a review of studies previously conducted on RE in education, RE in industry, and legal cases regarding RE are given to stress how important it was to create a study that was within the legal limits of RE.

2.1. Introduction

In today's world, customers continually want the latest and greatest that technology has to offer. Companies are in a race to manufacture the newest must-have product, which is why it is essential for them to exercise all avenues of design. Reverse engineering is one such avenue that has been gaining attention in industry and education. With the ability to reproduce a product from the original, companies are able to determine how a product was designed, its function, and how it works in order to make a better, more advanced product while avoiding infringing upon another company's work. There are many avenues of research and development but it is necessary for many companies to focus on RE. According to Tang, Zhu, and Xu (2010), "Reverse engineering is not only used to figure out how something works, but also the ways in which it does not work" (p. 724).

2.2. Reverse Engineering

A technological practice that can help companies and consumers is RE. As stated by Durupt, Remy, and Ducellier (2010), "Reverse engineering (RE) is a domain of current interest where physical models are measured in order to obtain a virtual model" (p.1). Reverse engineering is often mistaken for reverse modeling (RM) and vice versa but in fact they are two intertwined but not identical ideas. Reverse modeling is the simple process of measuring a physical part and creating a 3D CAD model from the existing geometry. Although RM is part of the RE process, the RE process continues by taking the model that is created and manufacturing the part.

The RE methodology can be explored from a company standpoint, and a consumer standpoint. Essentially RE is the process of taking a physical product, collecting data from that object, converting that data into a representative 3D model, and includes manufacturing a new product. There is some conflict as far as what phases comprise the RE process. However, depending upon its usage RE may be composed of more steps then data collection, analysis, and creating a 3D model. Table 2.1 shows a comparison of the various RE phases from multiple sources.

Reverse engineering is a process of taking apart a product and analyzing it with the intention of creating a newer product without copying the original (Younis & Tutunji, 2010). The RE process can also be used within a company to create a new part in order to replace a broken or unusable part that the company had created in the past. All models that are created during the RE process should be analyzed to make sure they are functional and meets any requirements that are necessary such as stress analysis.

Table 2.1

Phases of Reverse Engineering (RE)

PHASES	SOURCE
1. Data evaluation 2. Data generation 3. Design verification 4. Design implementation	(Ingle, 1994, p. 9)
1. Data capture 2. Preprocessing 3. Segmentation and surface fitting 4. CAD model creation	(Várady, Martin, & Cox, 1997, p. 256)
1. Digitizing 2. Data segmentation 3. Data fitting	(Sokovic & Kopac, 2005, p. 3)
1. Scanning – Digitizing 2. Processing captured data 3. Surface creation 4. CAM/technical documentation	(Sokovic, Cedilnik, & Kopac 2005, p. 602)
1. Prescreening 2. Observation 3. Dissection 4. Analysis	(Younis & Tutunji, 2010, p. 3)
1. Data capture 2. Merging multiple point clouds 3. Triangulation/decimation 4. Segmentation 5. Surface fitting for simple surfaces 6. Reconstructing linear extrusions and surfaces of revolution 7. Reconstructing smooth multiple regions 8. Building an adjacency graph 9. Constraint identification, constrained fitting 10. B-rep model creation, further beautification 11. Blend reconstruction	(Benkõ, Martin, & Váraday, 2001, p. 840)

2.2.1. Reverse Engineering from an Industry Standpoint

Today's industrial world consists of competition between companies to design and develop new products and technology. As stated before, the United States Army is one group using RE technology to maintain vehicles. Aside from maintenance and replacement part creation, RE can also be used to analyze a current product and redesign it in order to make it better or simply use the knowledge of how it works to create an entirely new product. With RE, companies are able to create new products, redesign existing products, and recreate a product when documentation is no longer available (Sokovic & Kopac, 2005). According to Raja and Fernandes (2008), RE is a key to aerospace manufacturing's future just as much as CAD. "The modern aerospace industry uses reverse engineering for these key reasons:

1. to create legacy parts and hard tooling that do not have CAD models;
2. to overcome obstacles in data exchange and data integrity;
3. to resolve and correct problems arising from discrepancies between the CAD master model and the actual tooling or as-built part; and
4. to ensure quality and performance through computer-aided inspection and engineering analysis" (Raja & Fernandes, 2008, p. 158).

2.2.2. Reverse Engineering from a Consumer Standpoint

When investing in a product a concern for consumers may be the service and part availability over the lifetime of the product. Some products have a lifetime that extends past that of the company that manufactured it, while other companies move forward to new products at a speed that hinders them from manufacturing replacement parts for

older equipment. In many cases products with long life cycles may not have CAD models available because they were designed before the technology existed, or the CAD models may be unusable due to poor design (Thompson, Owen, St. Germain, Stark, & Henderson, 1999).

The United Stated Army is a consumer that relies on RE methods. The Army uses RE technology to maintain military vehicles due to lack of parts availability and documentation about the product such as manuals (Durupt et al., 2010). However, the Army is not the only consumer that may find RE useful. Hobbyists that enjoy restoring products, such as old cars, can find RE methods to be just what they need to finish their project.

Whether it is to restore a product or simply replace a part that is no longer manufactured, many consumers rely on RE based companies. A company such as Rillos Engineering provides RE services to customers for both large and small scale needs. Figure 2.1 shows an example of a 3D CAD model that was created using 2D pictures of a Porsche 911 visor hinge (Rillos Engineering, 2010). This picture shows a CAD model that can result from the RE process.

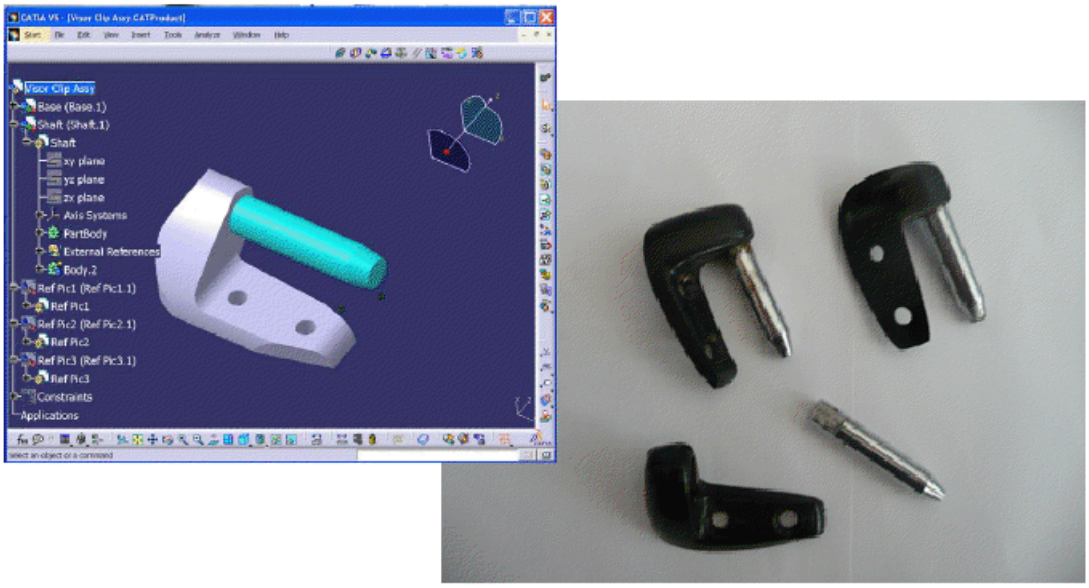

Figure 2.1. 3D model of Porsche 911 visor hinge (Rillos Engineering, 2010).

2.3. Reverse Engineering within Education

Retaining future scientists, engineers, as well as mathematicians within STEM education has become a focus in order to keep the United States "…in the forefront of research" (Lantz, Jr., 2009, p. 1). The idea of STEM programs is to teach scientific or technical content in the fields of science, technology, engineering, and mathematics. A newer approach to STEM education is learning not only from an academic standpoint but also from a real world application at the high school level. One main challenge facing all educators is that design is difficult to teach but also to learn (Dym et al., 2005). They also stated that it is difficult to find faculty that possess the knowledge, capability, and desire to teach engineering design courses, which makes it difficult to find qualified teachers.

The idea of implementing reverse engineering practices into an educational setting has been gaining attention during the last decade. Reverse engineering is seen as "the golden key" by Hess (2000) because it keeps students interested in what they are doing by addressing the question on every engineering student's mind about "what makes it tick?" or rather how does this product function (p.1). Some universities have incorporated RE methodology into the classroom not to find out what factors need to be considered, but rather to see the impact of how RE can affect a student's design thinking. One of the most effective ways to incorporate RE is through project-based learning (PBL) (Dym et al., 2005).

Engineering courses that have implemented some type of RE practice have focused on either the software or mechanical RE process. The RE process for software looks at how the software was created to make it better (Emenike, 2006). The mechanical RE process focuses on how a part or product was made with "…a wide range of manufacturing processes" (Orta, Medoza, Elizalde, & Guerra, 2006, p. 3). There is a course at Robert Morris University that examines RE in the areas of "…history preservation, medical, and forensic applications…" (Sirinterlikci & Mativo, 2010, p. 1). The course at Robert Morris University uses the RE process to show what can be done besides simply creating a 3D model. Reverse engineering is a versatile practice in a variety of areas, which is why implementing this technology in the classroom, could benefit future engineers.

The University of Texas, Massachusetts Institute of Technology, and the United States Air Force Academy have implemented or redesigned a course centered on the

ideals of RE because according to Wood, Jensen, Bezdek, and Otto (2001), "…'designing' distinguishes us as engineers" (p. 363) which is important because recognizing design processes is part of the RE process. These courses consisted of phases to redesign a product through reverse engineering practices that lead to a model to be improved. The main goal for the course was "…to help the students understand the issues involved in embodying a conceptual product design at a hands-on level" (Wood et al., 2001, p. 366).

Philadelphia University in Jordan also implemented RE practices within the mechatronics engineering department. The mechatronics department is a mixture of mechanical and electronics engineering. Reverse engineering is important to Philadelphia University in order to instill what Younis & Tutunji (2010) refers to as the industry "…trust in the design skills of local engineers" (p. 2). The idea of the RE course in the mechatronics department was to expose students to a project-based learning environment for hands-on experience to help improve the student's design abilities (Younis & Tutunji, 2010). One reason RE has been gaining more attention is because it helps in the design process and according to Dym et al. (2005), "…the purpose of engineering education is to graduate engineers who can design, and that design thinking is complex" (p. 103). Design is a challenging concept and these courses in RE can help understand the design process.

Courses involving RE methodology use project-based learning to give hands-on experience as mentioned above, and to help bring out student creativity (Dym et al., 2005; Wood et al., 2001; Younis & Tutunji, 2010). Courses at the universities mentioned

above received positive reviews, confirming that students enjoy learning more when there is a hands-on project based approach. Dym et al. (2005) said it best in saying that, "…reverse engineering has become more popular in engineering curricula today and researchers report that such courses not only improve retention, but also improve student's systems thinking of engineered products when integrated with other design or case study activities" (p. 113).

2.4. The Contribution of Metrology and 3D Scanning to Reverse Engineering

When it comes to RE, there are many ways in which a product or object can be measured in order to obtain the data that is necessary to create a 3D CAD model. According to Sokovic et al. (2005), the most important tool in RE is using different types of scanning systems to obtain an "…exact dimensional description in digital concept…" (p. 398). These scanning systems can be 3D digital scans or metrology scans to find the most accurate and appropriate measurements.

The use of traditional measuring tools, metrology equipment, and 3D scanners are some of the ways that products can be measured. Metrology, which is "the science of measurement" (Liming, 2009, p.10), may consist of using a touch probe device to digitize information from the product. According to Liming (2009), there are three specific types of metrology, scientific, legal, and industrial. This study will be focusing on the latter of the three types that Liming discussed. There are also two different types of digitizing techniques. The first technique is a mechanical hands-on technique, which consists of physically making contact with a surface with sensors and the second is an optical technique, such as a 3D scanner, that uses non-contact methods (Sokovic et al., 2005).

Industrial metrology and 3D scanning are the main focus of the study as they are widely used in RE for a manufacturing/industrial setting (Sokovic et al., 2005). As stated by Liming (2009) metrology "…is critical to the success of many different industries" (p.12).

2.5. Instructional Design and Motivation

When entering a university, students are met with a more demanding course load while attending class meetings less frequently than what was expected over their high school career. According to Hagler and Marcy (1999), college professors lay out what they expect students to learn during class meetings much like in high school but expect the majority of a student's learning to occur outside of the classroom. They also stated that the main purpose of class meetings is to prepare students to learn in an efficient way once they have left the classroom.

Because students are expected to learn vast amounts of information on their own it may be difficult for students to be motivated about what they are learning. Engineering faculty tend to lecture more instead of using in class discussions and cooperative learning techniques inside the classroom. Lecture teaching styles are a large reason why students choose other majors outside of engineering (Courter, Millar, & Lyons, 1998).

When students are not motivated to learn required material it may be hard for students to even make an attempt from the start. Jonassen, Howland, Moore, and Marra (2003) said it best, "in order for students to learn meaningfully, they must be willfully engaged in a meaningful task (p. 20)." For students to be motivated to learn they need to

be exposed to learning techniques that are interesting. Lecture material may at times be uninteresting which is why it could be beneficial to intermingle engineering projects into the curriculum.

At the University of Texas, one of the most popular projects within a mechanical engineering freshman-level course is centered on RE of a children's toy (Otto & Wood, 1998). It was stated by Otto and Wood that this type of project allowed students to use principles learned from their introductory mathematics and physics courses to learn engineering design basics. Allowing students the opportunity to engage in a design project gives them a chance to explore learning through a non-lecture based format.

It is important that students are learning for the sake of learning and not merely to finish something. Intrinsic motivation must be considered when designing a course otherwise some students will just see the information that needs to be learned as a task that needs to be done and not as something that is interesting. According to Pintrich and Schunk (2002), there are four aspects that contribute to intrinsic motivation which are challenge, curiosity, control, and fantasy. Presenting students with an RE project will not only offer students a challenge but also create a sense of curiosity about how a product goes from a 3D scan to a CAD model and finally to its reengineered form.

2.6. Associated Legal Issues

A downfall of reverse engineering is that it approaches the line of legality with concern to patent infringement. According to Beherens and Levary (2008), RE is "…unlawful because it is far too easy to use the process to discover how an existing

program operates and make slight modifications to it and then market the amended versions as a new software product" (p. 198). Although this particular quote refers to computer software, it is equally present for manufacturing. In manufacturing, it would be easy to disassemble a product and analyze its function in order to produce a similar product.

When working on a RE project, the cost associated with the project could exceed all expectations if legal issues, such as patent infringement, pertaining to the projects are not addressed (Ingle, 1994). Ingle also stated that RE is a legal practice unless it infringes upon a patent associated with the component being used. Countries have different rules around patents and what constitutes infringement and these laws color how RE is viewed. As stated by Ingle (1994), do not make the assumption that being familiar with general guidelines will be satisfactory in all cases.

2.7. Importance of Reverse Engineering

Engineering students must be able to approach a design situation with a certain level of competence as well as professionalism to assess an engineering situation properly (May & Strong, 2006). However, some engineering graduates have many weaknesses that industry has pointed out (Todd, Sorenson, & Magleby, 1993). According to Todd et al. (1993), industry gives a list of the top ten weaknesses that they find in engineering graduates that is displayed in Table 2.2.

To better educate engineers it is important for industry to let their needs in education be understood. Industry is very demanding and therefore requires well skilled

engineers that are able to do their job well. According to May and Strong (2006), no matter how drastically engineering practices change, education tends to change slowly. Therefore, it was necessary for industrialists to express their needs in study conducted by Eggert (2002). The top 10 topics and top five activities that were the most important to industry during the Eggert's study are shown in Table 2.3.

Table 2.2

"Industrial Perceptions of Weaknesses in Engineering Graduates" (Todd et al., p.93)

• Technical arrogance
• No understanding of manufacturing processes
• A desire for complicated and "high-tech" solutions
• Lack of design capability or creativity
• Lack of appreciation for considering alternatives
• No knowledge of value engineering
• Lack of appreciation for variation
• All wanting to be analysts
• Poor perception of the overall project engineering process
• Narrow view of engineering and related disciplines
• Not wanting to get their hands dirty
• Considering manufacturing work as boring
• No understanding of the quality process
• Weak communication skills
• Little skill or experience working in teams
• Being taught to work as individuals (p. 93)

Table 2.3

Industry Demands (Eggert, 2002, p. 5)

TOP 10 TOPICS	TOP FIVE ACTIVITIES
1. Teamwork	1. Team design project(s)
2. Engineering design specifications	2. Open-ended problem solving
3. Design for manufacture	3. CAD – solid modeling
4. Overall design process	4. Interdisciplinary design project(s)
5. Design for assembly	5. Design report(s) – Written
6. Creative methods	
7. Project management	
8. Product testing	
9. Tolerancing	
10. Solid modeling	

By incorporating RE methodology into engineering curricula it will be possible to meet many of these industrial requirements. Because RE methodology consists of disassembling a product, measuring the parts, and creating a new product this will allow students learn how the product was manufactured and assembled which fulfills seven of the 10 industrial topic demands. Creating a new product through RE will allow students to experience an open-ended problem, solid CAD modeling as well as a writing design reports. Throughout the RE process parts must be listed in a Bill of Materials and any problems that arise during the process must be documented.

2.8. Summary

This chapter summarized RE and the roles that it plays in industry and education. An overview of industrial, consumer, and educational uses of RE has been discussed. The most important was a summarization of literature pertaining to previous studies involving RE and education. Addressing industrial uses of RE, how to design curriculum for RE, legal issues, and the importance of RE can help to educate students about not just the RE process but concerns surrounding RE.

CHAPTER 3. FRAMEWORK AND METHODOLOGY

The purpose of this research was to determine what factors needed to be considered in the incorporation of RE into education. Due to the nature of the questions that were asked, the best procedure for this study was a qualitative approach.

This chapter outlines methods that were used in this study, including the site for the study, access, sampling, data collection and recording, and procedures for analyzing the data. The chapter concludes with using the instructor and industry perspectives to support the students' perspective that have relation to this study and discuss the trustworthiness of the study and data.

3.1. Theoretical Framework

As outlined in Chapter 2, there were multiple research studies with the idea of incorporating RE into the classroom (Dym et al.; 2005, Orta et al.; 2006, Sirinterlikci & Mativo. 2010; Wood et al., 2001). Among these past studies the framework was consistently centered on a case study of methods to determine the effect that RE had on education and the students but not on factors that are important to students. With those studies in mind, it was important to consider a framework that considered RE in the classroom and the effect on students, and included the outlying factors that may have been overlooked when incorporating RE technology into a classroom setting such as

equipment availability and time to scan. Therefore, the framework of this study was based upon a case study of factors that needed to be considered when incorporating RE methodology into introductory level engineering curricula.

3.2. Methodology

The questions asked in this study were intended to provide insight about what factors students perceived to be important in the incorporation of RE methodology in engineering curricula. What motivated students to be excited about their education? How did students react to using RE technology? What elements of RE did students enjoy or dislike? In order to answer those questions it was important to focus on surveys and a hands-on learning experience through the use of RE technology and equipment.

3.3. Study Environment

Details relevant to the study as well as the course in which the study takes place are outlined in the following sections.

3.3.1. Site of Study

This research took place at Purdue University, which is a land-grant university located in West Lafayette, Indiana with a major focus on research. This demanding research institution offers over 200 undergraduate majors, professional degrees within the fields of pharmacy and veterinary medicine, and more than 70 master's and doctoral programs. As of the 2010 to 2011 academic year, the total enrollment of 39,726 (of

which 3,334 are part-time), consisting of 30,836 undergraduate students, 7,980 graduate students, and 910 professional students (Purdue Data Digest, 2010).

Purdue University is primarily seen as an engineering institution and with a total enrollment of 9,692 students in engineering related fields. Of this, 7,012 are undergraduate students (Purdue Data Digest, 2010). With this many engineering students, Purdue University was an ideal study site.

Due to convenient access to the students, this study was conducted at the West Lafayette campus of Purdue University. As teaching assistant for the course, the researcher was immersed in the student's environment. According to Denzin and Lincoln (2000), a critical aspect regarding qualitative research, was to be in the environment of the students.

3.3.2. Participant Population

The sample for this study was selected from engineering students enrolled in *CGT 163: Introduction to Graphics for Manufacturing* in the Department of Computer Graphics Technology during the fall semester of 2011. The completion of those hours included two lectures per week, each 50 minutes long as well as one lab per week lasting two hours. Due to class size, the students were divided into 18 lab sections taught by five different instructors. Each instructor taught approximately four sections each consisting of approximately 20 to 25 students.

The CGT 163 course was predominately first-year engineering students intending to major in fields of aeronautical and mechanical engineering and some undecided

engineering majors. The focus of the course was CAD and freehand sketching in order to convey engineering design ideas. The CAD portion of the class was platform independent, meaning students were given the option to choose which software they wanted to work with.

CGT 163 was selected because it was an introductory level course, and because CAD software is an important part of the RE process. Through experience with CAD and technical drawings, CGT 163 was the perfect choice to tie in RE technology and the corresponding teaching tools for the equipment that was used. Being a CAD independent course gave the students the opportunity to learn new software such as CATIA, Pro ENGINEER, or Autodesk Inventor. However, if students were well versed in one particular software they were strongly advised not to use it in favor of learning a new CAD package to gain more exposure to the other types of CAD software that are available. Due to the CAD independent form of the course students became well-rounded designers and it gave students a CAD platform base that was necessary with the use of third party software such as RapidForm and ZScan, which was needed with 3D scanning.

3.3.3. Participant Sample

As stated above the CGT 163 course at Purdue University was the population from which the sample was chosen. The main concern for this study was to remove any conflict of interest that may have arisen from the incorporation of RE methods. To remove conflict of interest, no lab sections that were taught by the researcher, who was a teaching assistant, were used. The professor for the course presented information on RE

to all students during the lecture portion of the course after which all students were given a survey. This survey consisted of questions concerning RE practices, CAD incorporation, the students' feelings and opinions towards incorporating RE into the classroom, as well as questions regarding what they liked and disliked about the information. The purpose of the survey was to obtain a broad view of factors that students felt would be important to them.

After completing surveys, 10 students were given the opportunity to complete hands-on exercises using a ZScan 3D scanner. The 10 students were selected using a combination of course grade and individual scores on the Purdue Spatial Visualization Test: Rotations (PSVT-R). All students were given the PSVT-R as a course assignment to assess spatial ability during the laboratory portion of the class. Once the test was completed, the students' scores were averaged with their current course grades and ranked from highest score to lowest score. The highest and lowest five scoring students were presented with the opportunity to use 3D scanning technology. Choosing the highest and lowest scoring students allowed the researcher to test if spatial ability was a factor that needed to be considered in RE incorporation. The ten students were monitored closely by the researcher outside of the scheduled class time and were interviewed in a one on one setting in order to obtain an in-depth student perspective on RE in the classroom.

3.4. Permissions

Permissions required to conduct this research included permission from the instructor of the course for access to his class and time to execute the study, permission

for the use of the PSVT-R, and Human Subjects research approval through the Institutional Review Board (IRB) to conduct this study at Purdue University.

3.4.1. Access and Course Instructor

The instructor for CGT 163 was approached to obtain permission to observe students that were enrolled in the course for the fall semester, to have the instructor lecture about RE methods, include aspects of this research in assignments, and to allow a select number of students to participate in more in-depth RE practices. One such assignment that was given was the PSVT-R in order to examine which students had high levels of spatial ability.

3.4.2. Human Subjects Approval

The application process for Human Subjects approval took place in the fall semester of 2011. Because the research involved surveys and interviews, some concerns with regard to IRB were threats to anonymity and conflict of interest. In order to eliminate any threat to anonymity, their lab division and seat number were coded for the participants. This allowed the researcher to keep track of the participants without using any identifiable information. Students enrolled in the researcher's lab divisions were not approached to participate in the hands on learning environment, which helped to eliminate students feeling compelled to participate due to grade performance.

3.4.3. Use of PSVT-R

Permission was sought for the use of the PSVT-R test because it is the property of the Purdue Research Foundation. There was no cost to administration the test or to grade it. The Purdue Research Foundation was contacted in order to obtain permissions for the use of the test.

3.5. Student Incentive

Once students completed the PSVT-R testing, the five highest and five lowest scoring students from the whole class exclusive of the researcher's lab divisions were given the opportunity to receive extra credit towards their final course grade by completing a hands-on RE learning experience and follow-up interviews. Students that chose to withdraw from the study were not given the extra credit incentive.

Students who were not asked to complete the study were given the opportunity to complete a problem to receive an equivalent extra credit incentive as shown in Appendix J. Any student that did not wish to participate in the study and did not wish to complete the alternative problem received no extra credit.

3.6. Overview of Study Methodology

To assess what factors needed consideration with the implementation of RE methodology in introductory engineering curricula it was important to consider aspects from the instructor's point of view and the student's point of view. The main focus of this study was to obtain insight into the factors students felt were important and that they

perceive would help in their professional development. A secondary focus of this study was to determine which factors were detrimental to the success of the implementation of RE methodology into a higher educational setting from an instructor and industry point of view to provide support to the students' opinions. The information obtained from this study gave insight on what factors should be considered with the implementation of RE into a higher education setting.

3.6.1. Student Perspective

As stated before, the main focus of this study was to obtain a perspective on factors that needed to be considered when incorporating RE methodology into introductory engineering curricula. Motivating students to excel and participate in the classroom can be difficult especially if the class was designed around textbook based learning. One way to improve student learning and retention was to use project based learning styles in courses that gave students a hands on approach to learning thereby getting them more involved and allowing them to use their engineering talents (Dym et al., 2005).

To assess student opinions on RE incorporation, it was necessary to develop surveys and interview protocols that were given to a sample of introductory engineering students once RE methodology was covered within the course. The surveys acted as a general guide to the student perspective by providing a broad view of student reactions to the RE material. The questions were based around the ideas of what were the students' interest in using RE technology and its importance for their professional development,

student motivation in the classroom if given access to this technology, and student likes and dislikes about the information that was presented.

3.6.1.1. Surveys

After the instructor gave instructional lectures about RE methodology, students were given the opportunity to complete a survey. As stated before, in order to eliminate conflict of interest the researcher's lab divisions did not participate in the survey or interview process.

The surveys informed the researcher what this group of students wanted to experience in the classroom and how RE methodology could help them through content analysis. These surveys were also used to determine what factors, from the students' perspective, needed to be taken into consideration if RE methodology was incorporated into their curricula.

3.6.1.2. Interviews

After the surveys were administered, a select number of students were chosen for a hands-on study and follow up interview process. According to Morse (1994) to understand the essence of a certain experience it is important to obtain a sample of at least six participants. Due to time constraints of the researcher, students, and allotted time outside of class, ten students were selected for the hands-on process with an interview following. Those ten students were interviewed at a more in-depth level to obtain specific student ideals on the topic of RE methodology in the classroom.

The process of choosing the ten students to participate in the hands-on study was as follows. Students completed the PSVT-R as a course assignment to determine whether they have high or low spatial ability and the highest and lowest 10 scoring students were selected. PSVT-R scores were averaged with their current course grade for each student and the highest five and lowest five students were given the opportunity to participate in the study, excluding students in the researcher's lab divisions. If a student did not wish to participate then the next highest scoring student or lowest scoring student was given the opportunity to participate. If a student in one of the researcher's lab divisions had one of the highest or lowest scores, he or she was passed over and the next student was chosen.

The reason behind involving the PSVT-R in the selection process was to select students that had high and low spatial ability. By combining the scores it was possible to see students that had high spatial ability and were excelling in class and students that had low spatial ability and were not excelling. The use of 3D scanning technology required the user to manipulate an object or the equipment in a way that required high levels of visualization. Therefore, choosing students with the highest and lowest levels of spatial ability determined if spatial ability was a factor that affected a student's learning of RE methodology that was incorporated in the classroom.

Before the actual interview process could begin it was essential to expose students to RE technology that was used at Purdue University and allow them to complete tasks using the equipment. The hands-on experience allowed students to become more familiar with RE methods and enabled students to give more informed answers during the interview process.

Students were provided with a tutorial for the ZScanner 800 3D scanner that was developed in order to guide them through scanner set-up and the scanning process. The students were given a choice of simple parts and were asked to use the 3D scanner and CAD software to complete the task. The first part choice shown in Figure 3.1 was a bracket support part. The students' second option was a pipe support part that is shown in Figure 3.2. Students were able to ask questions during the scanning process if they found material to be unclear. This gave students an opportunity to use new equipment and also give feedback as to how the tutorial may be improved.

Figure 3.1. Bracket support part from a manual powered scooter.

Figure 3.2. Pipe support part for the handlebars of a manual powered scooter.

Once students completed the required tasks they were given an exit interview designed to assess their performance. As stated by Creswell (1998), interviews typically last one and one-half hours to two hours long, which gave ample time to conduct the interviews. Over the course of the interview students were asked questions about RE methods, their opinions and feelings on the equipment they to used, and what of the RE material they felt should be incorporated into or changed about introductory engineering courses.

Approximately a week after completing the tasks, those 10 students were interviewed again, to give the students an opportunity to examine what they completed over a longer period of time and allow them to formulate answers that may have revealed more information. By doing this it was possible that students may have recalled something they found particularly interesting. It may also be the case that students left

the first interview wishing they had voiced an opinion that may not have crossed their mind. Conducting an immediate interview and an interview following a break period, it was possible to obtain information that would not present itself with solely an interview immediately following the hands-on learning experience.

3.6.2. Instructor Perspective

In addition to determining what factors students felt needed to be considered when incorporating RE methodology into the classroom, it was important to determine what factors needed to be considered from an instructional point of view to provide support for the student opinions.

The instructor used measuring instruments such as dial calipers and the ZScanner 800 3D scanner prior to the student's hands-on experience for many reasons. The first of these reasons was to learn how to operate equipment that had newly been acquired by the university, because without the instructor's knowledge it was difficult for students to learn how to operate it properly. By having more experience with the equipment, the instructor was able to assist the students with hurdles that presented themselves during the hands-on learning experience.

By using this equipment the instructor was given the opportunity to determine whether factors such as accuracy of the equipment, cost of the equipment, and instructor knowledge were important. Giving the instructor this opportunity also gave the chance to look for unknown factors that may have existed while students completed the hands-on portion of this study. The opinions of the instructor were compared to those of the

students to give support to the students' opinions as to what factors they felt needed to be considered when RE methodology was incorporated into engineering curricula.

3.6.3. Industry Perspective

In addition to both the students' and instructor's perspectives, it was also beneficial to gain insight on what items an industry professional felt were important to RE incorporation. To obtain this perspective it was important to approach a company with RE experience. By doing this it was possible to gain an expert opinion on what factors are important to RE as well as what factors were be important to education. This industry opinion gave support to the factors that students felt were important in the incorporation of RE into their engineering curricula.

An interview process was used to gain an industry perspective. Because this research was focusing primarily on the students' perspectives, the interview process was less involved. One interview was given to one of the founders of the company to gain a general idea of what his company, with RE experience, wanted to see from engineering graduates. Rillos Engineering is a company that offers RE services to both large and small companies, which made it the perfect candidate for a single interview process. Due to location and convenience, the interview was conducted by telephone. This interview process helped solidify factors that were found to be important from the students' perspective and also introduced factors that neither the students nor instructor found to be important. This interview gave a professional view that supported the students' perspective.

3.7. Summary

This chapter gave an overview of the framework and the methodology that was used for this study. Using surveys and interviews gave more information from a student perspective that was used to represent the course as whole. The instructor and an industry expert had the opportunity to contribute important factors that students may not have acknowledged. Collecting multiple viewpoints gave more information about RE incorporation. The students' perspective was the most important perspective that was collected. It gave information about the factors that students felt needed to be considered when incorporating RE methodology. Collecting the instructor and industry views gave support to the students' perspective. The support of an instructor and industry expert showed that the factors the students felt were important were factors that needed to be considered with RE incorporation.

CHAPTER 4. PRESENTATION OF DATA

As described in previous chapters, the purpose of this study was to determine what factors students felt would need to be considered prior to incorporating RE methodology into their engineering curricula. To obtain accurate and educated answers it was necessary to introduce students to RE methodology and technology through lectures, hands-on demonstrations, and course projects. By allowing students the opportunity to use RE at some skill level, they were then able to provide more information and if they were new to the subject area they may have learned something new over the course of the study.

Lectures, surveys, hands-on exercises, and interviews were used to gather the student perspective of incorporating RE into curricula. Additional sources of data included scores on the PSVT-R, students' course scores, and recorded times for the student calibration process.

This chapter presents data from student survey responses and the individual sources among the high and low spatial ability levels that participated in the hands-on learning experience involving 3D scanning technology. It begins by providing student responses to survey questions centered on RE lectures given during the study. It follows by providing descriptions of students who participated in the hands-on exercise and the data provided by each participant over the course of the study. Though this chapter

provides the data across the study, a discussion of the data and associated themes will be provided in Chapter 5.

4.1. Participant Descriptions

The following sections introduce the participants of the study. As stated in Chapter 3 the entire course enrollment was provided with the opportunity to complete a survey pertaining to RE and the associated lectures. Also, as explained in Chapter 3, 10 students were to participate in a hands-on learning experience involving 3D scanning technology. These 10 students were separated into two groups. The first group was composed of five students characterized of high spatial ability. The second group consisted of the other five students having characteristics of low spatial ability. Students' PSVT-R scores and course grades were used to determine a students' level of spatial ability. The top five students scored a perfect score of 36 on the PSVT-R. The bottom five students' scores varied. Three students were passed over due to time required for the study or opting to not provide consent.

The reader should consider an important aspect when presented with this chapter. Dividing students into groups of low and high spatial ability was a "relative" measure. Neither group of students was a representative sample of the population as a whole. All students involved in this study were enrolled in engineering or technology curricula.

4.1.1. Survey Participants

As stated prior to this section the entire course enrollment was provided with the opportunity to complete an online survey. Students were 18 years old or older and enrolled in an engineering or technology curriculum as undergraduates. Table 4.1 provides a classification list of the course enrollment according to major. It is important to note that not all students enrolled in the course completed the survey. Also, among the students that did complete the survey not all answered every question completely.

4.1.2. Interview Participants

The following sections provide information describing each participant that completed the hands-on learning experience. The information provided in these sections was collected at the beginning of the student's hands-on exercise. Every student that participated in this study was an undergraduate seeking a technology or engineering degree. Table 4.1 provides a breakdown of the students involved, their major, PSVT-R scores, course grade, and spatial ability classification.

4.1.2.1. Participant 0101

Participant 0101 (P0101) was a 19-year-old male sophomore from India majoring in ME. He said that the reason he chose engineering was because, "basically it is something that tickles your mind and because I have a passion for cars." Being interested in cars is the reason he became interested in engineering. P0101's score on the PSVT-R and his course grade characterized him as low spatial ability.

Table 4.1.

Course Enrollment According to Major

Major	# of Students	% of Total Enrollment
Mechanical Engineering (ME)	202	59.59%
Aeronautical and Astronautical Engineering (AAE)	68	20.06%
Aeronautical Engineering Technology (AET)	27	7.96%
Engineering (Unspecified)	19	5.60%
Mechanical Engineering Technology (MET)	8	2.36%
Electrical Engineering (EE)	3	0.88%
Aviation Technology (AT)	3	0.88%
Civil Engineering (CE)	3	0.88%
Acoustical Engineering (AE)	3	0.88%
Industrial Engineering (IE)	1	0.29%
Agricultural and Biological Engineering (ABE)	1	0.29%
Undecided	1	0.29%
TOTAL	339	100.00%

4.1.2.2. Participant 0124

Participant 0124 (P0124) was a 19-year-old male sophomore from China majoring in ME. He chose engineering because, "I am not very good at science but I like operating stuff and I also want to involve design into my career." He became interested

in engineering because he likes cars and design is a large part of ME. He also likes car engines. P0124's perfect score on the PSVT-R and his course grade characterized him as high spatial ability.

Table 4.2.

Participant Information for the Hands-on Learning Experience

Student	Major	PSVT-R Score	Course Grade	Spatial Ability Classification
0101	ME	6	97	Low
0323	ME	7	66.1	Low
0423	ME	10	62	Low
1020	MET	10	66	Low
0421	ME	12	61.5	Low
0417	AAE	36	93	High
0124	ME	36	97	High
1021	ME	36	97	High
1521	AAE	36	97	High
1524	ME	36	98	High

4.1.2.3. Participant 0323

Participant 0323 (P0323) was a 20-year-old male sophomore from India majoring in ME. He stated that he chose engineering because, "I've always wanted to be an engineer." The reason P0323 became interested in engineering is because, "I thought engineers just built everything." His scores on the PSVT-R and his course grade at the time of the study characterized him as having low spatial ability.

4.1.2.4. Participant 0417

Participant 0417 (P0417) was a 20-year-old Caucasian male from Indiana majoring in AAE. He stated that he, "chose aeronautical engineering because I was always into how planes worked. I wanted to fly for the longest time and planes fascinate me. I felt building was just as good as flying." P0417 said that he became interested in engineering when he was, "about 10 and went to a museum where an old printing press was set up. Visually watching the track and figuring out where everything went and how it did the printing. Figuring out how to track and figure out how it works." By scoring a perfect score on the PSVT-R and his course grade he was characterized as having high spatial ability.

4.1.2.5. Participant 0421

Participant 0423 (P0423) was a 19-year-old sophomore from India majoring in ME. The reason he chose engineering was because he thought he would be best at it because he was not good at biology. He also liked building objects when he was young. P0421 stated, "I was interested in building and designing stuff as well as manufacturing" as the reason he was interested in engineering. His low score on the PSVT-R and his course grade characterized him as having low spatial ability.

4.1.2.6. Participant 0423

Participant 0423 (P0423) was a 20-year-old male sophomore from China majoring in ME. He stated that the reason he chose engineering was, "because I like to

make things and design something so when I finish things I design I feel very happy." P0423 said that he became interested in engineering because, "it's ME. I can learn more things like how the machine operates. I'm interested in that. I am kind of good at operating the machine." His score on the PSVT-R and his course grade characterized him as having low spatial ability.

4.1.2.7. Participant 1020

Participant 1020 (P1020) was an 18-year –old Caucasian female from Tennessee majoring in MET. She said that she chose MET because, "I heard horror stories of engineering and MET is more hands-on. But it is too much hands-on and not enough design so trying to switch to ME." P1020 said she became interested in MET because it is a lot like ME. Her score on the PSVT-R and course grade characterized her as having low spatial ability.

4.1.2.8. Participant 1021

Participant 1021 (P1021) was a 19-year-old male from China majoring in ME. He reason he chose ME was because of the flexibility it gave him after graduation. P1021 stated that he was interested in ME because he was, "interested in anything relative to engineering and interested in programming but not good at it." His score on the PSVT-R and course grade characterized him as having high spatial ability.

4.1.2.9. Participant 1521

Participant 1521 (P1521) was a 20-year-old Caucasian male from Montana majoring in AAE. He stated that he chose to major in engineering because he likes to design stuff. P1521 became interested in engineering because, "my parents told me about being an engineer since I was 12-years-old and I liked playing with legos." His perfect score on the PSVT-R and his course grade characterized him as having high spatial ability.

4.1.2.10. Participant 1524

Participant 1524 (P1524) was a 21-year-old male sophomore from China majoring in ME. He chose engineering because, "I want to be an engineer for Porsche." The reason he became interested in engineering was because of the machines. His perfect score on the PSVT-R and his course grade characterized him as having high spatial ability.

4.2. Responses to Student Survey

As stated in Chapter 3 students were asked to complete an online survey after they were given two lectures pertaining to RE methodology and 3D scanning. The lectures touched the basics of both aspects as to keep them within the 50-minute lecture period. The lecture period following that of the 3D scanning lecture presented students with a real life application of RE. Students were shown and given the opportunity to calibrate a

3D scanner and scan a part from a manual powered scooter. Following the completion of the lectures a website survey link was distributed to all students of the course. Questions that were asked in the survey can be seen in Appendix E. The first question of the survey asked students what major they were enrolled in. Student responses to this question were displayed in Table 4.1 in Section 4.1.1. The following sections outline each of the remaining nine questions and provide detailed student responses.

4.2.1. Student Responses to RE Lectures

This section provides student responses to the following question: "How much did you like the RE lectures?" The responses to this question varied among students. There were students that felt the lectures were very beneficial to their learning while others felt that it was not something that they would be interested in learning more about. Specific answers given by students can be seen below.

The following 10 responses were taken as a sample from the students who found the lectures informative and rewarding:

> The lecture content was very fresh to me and very useful. It explains RE in a very practical way that should be a benefit to any engineer thinking of doing research and development. Although the lecture seem to only cover brief concept and almost in a rush, content is still very much useful.
>
> The lecture was an interesting addition to what I had thought the class would be discussing. Because, yes we are learning to draft and generate technical drawing; but also how different tools can be utilized to do this.
>
> I enjoyed them. I think they could be very useful for future job opportunities. Not something we discuss in other classes.

It was much more interesting than our usual lectures. I took ample notes to back up my sentiments. Reverse Engineering is a very interesting subject, but the actual process seems more tedious and a bit less rewarding than constructing something.

I thought they were very interesting. I liked the change of pace from the typical lecture where we just listen and draw. The PowerPoint was easy to follow and was useful in my understand of RE and why it is a good skill to have.

If the score is out of 10 scale, then I would rated as 8. The reason is I think the lecture covers an important area of engineering and also the information covered during this lecture which I believe will not cover in other courses or not as complete like this lecture.

I liked them. They were interesting to see some of the methods industries use to understand how a competitor's products work. The most interesting parts of the lecture were when the TA's actually demonstrated how to use the 3D scanner.

I liked it a lot. It showed a side of engineering I've never seen before. Normally, you would start from the beginning and finish at the end. It was kind of interesting to see an something engineered from to the end to the start.

I really liked the RE lectures. They were more interesting and informative than many of our previous lectures. I also liked how they allowed students to come up and use the equipment.

The RE lectures were very interesting as this was something very different from what we had been doing all semester for this course. The more application based approach to the material was very refreshing. On a scale of 1-5, 5 being very interesting, I would give them a 4.5.

The following 10 responses were taken as a sample from students who did not enjoy the RE lectures or felt that they needed more information.

I didn't like them because I am not interested in scanning and those things.

They were interesting, but it isn't something i would want to spend my time on.

I liked the lectures. However, I would like them more if we had individual reverse engineering projects to go along with them.

I would have enjoyed them more if it talked more about recreating the functionality of machines as opposed to just how to make the shape, simply because that's what interests me.

They were alright, they didn't hold my attention that much.

> They were interesting but didn't really seem to apply to what we would be doing in class/lab (with the scanner etc.)
>
> Not too much. Kind of dry. Would like to actually use the processes talked about.
>
> I enjoyed them, but I was not necessarily interested.
>
> I don't hate them but it has probably been my least favorite part of this class.
>
> They lectures were ok. I felt like the lectures were too brief and barely went into depth about reverse engineering.

This section has provided responses pertaining to students' feelings on the RE lectures. Only a small sample from each view were provided to give an idea of how students responded to the information they were given in lecture.

4.2.2. Prior RE Knowledge

To determine how much students knew about RE they were asked the following question. "Did you have any knowledge of RE prior to the lectures?" The answers to this question were fairly straightforward. The student had either had experience with RE or they had not. The answers to this question were separated into three categories which were yes they had completed prior RE projects, yes they had heard of RE and knew what it was, or no they had no knowledge prior to lectures in the course. A breakdown of the percentage of students that gave each response is shown in Figure 4.1.

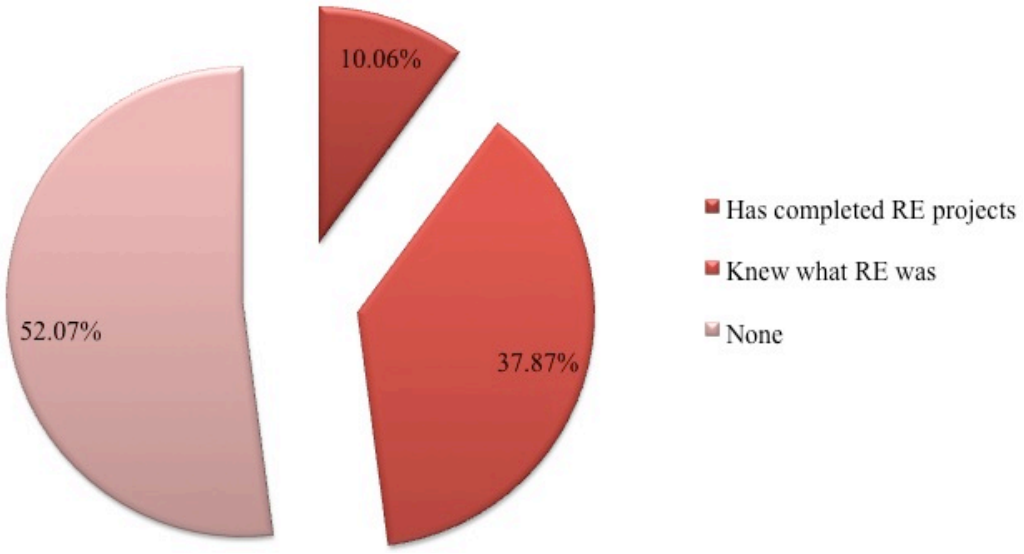

Figure 4.1. Distribution of student knowledge regarding RE.

Out of the 338 students that responded to this question a total of 162 students had some experience with RE. Of those 162 students, 128 had minimum knowledge of what RE was and 34 had completed RE projects in high school through Project Lead the Way. The remaining 176 students had no knowledge of RE and had not heard of it prior to the course. Samples of students' answers in the following categories are given below.

Responses from students who had prior knowledge to RE and had completed RE projects:

> I have experienced reverse engineering, during my co-op at a centrifugal pump company, we refused to sell parts to a certain exporting company. They would reverse engineer the parts and sell them internationally and under cut us. It's a viscous business market.
>
> I had a little bit of knowledge of RE. I had to take apart a camera and draw all the parts in inventor and put it all back to together for an engineering class in high school. I also had to research how each parts works.

> In high school my engineering class had a RE project where we brought something in from home, dismantled it, and drafted the components on the computer in Inventor.
>
> Yeah, in high school, we had to reverse engineer any house hold object, make it on Inventor, and then make improvements on the design or functionality. I also am in the process of taking existing pictures of the Spitfire and recreating it on Inventor with some personal touch-ups.
>
> Yes, I worked for a small engineering firm over the summer and one of my tasks was to draw existing parts in CAD.
>
> Yes, I had to complete a RE project in a high school engineering class. This consisted of measuring a small flashlight and then creating the product in a CAD package.
>
> Yes, I had seen it before in a project lead the way class.
>
> Yes, from PLW, which is a highschool course taken at your highschool but course material comes from Purdue.
>
> Yes i did, i participated in Project Lead The Way in High School.
>
> I had learned about RE in a high school engineering class in which we took apart a pen and created the components in Inventor.

Responses from students who had prior knowledge but had no hands-on experience with RE projects:

> I did have very little knowledge on the subject of RE and it was just enough to allow me to easily follow the presentation.
>
> I did, but it was pretty limited. We touched on the basic ideas in some of my high school courses.
>
> I didn't realize it before the lectures, but I had attempted reverse engineering my model plane so I could use it in a simulator.
>
> I had a little bit of knowledge about Reverse Engineering, my dad uses it at work sometimes and he has been to workshops on it.
>
> I had an idea that sometimes people work backwards to truly understand how a product is made in order to make improvements.

I had an idea, but I didn't know the methodology.

I had heard about it before but I had no idea about the actual process.

I had heard of reverse engineering but did not know a lot about it.

I had basic knowledge of what it was but not on the different methods.

I had known about 3D printers and I had heard about scanners, but I did not know that much about them prior to class.

Responses from students who had no prior knowledge of RE:

I did not have any knowledge of it before hand.

I did not have any knowledge of RE prior to the lectures.

I did not have any significant knowledge of RE before the lectures.

I did not have any specific experience with regards to RE prior to these lectures.

I did not have any substanial knowledge of RE before the lectures.

I had no experience with RE prior to the lectures.

I had no prior knowledge of this amazing tool.

No formal knowledge of RE, but a general understanding of what it is.

No I had no idea it existed until then.

No. I did not. But, I did know that in the real world, companies buy their rival's product, disassemble it and improvise their own product from it.

This section has given details about students' knowledge about RE prior to the in course lectures. The sample answers that were provided above were taken randomly from all answers that were provided. If a student answered simply yes or no they were bypassed in hopes of sampling a more robust answer.

4.2.3. Aspects of RE Lectures Students Found to be the Most Interesting

This section provides data gathered from student responses to the following question. "What was most interesting about the RE methodology lectures?" This question was asked to determine what students felt was helpful in the lectures so that it may be incorporated into future lectures about RE. A random sample of 30 responses was taken and provided below.

> I think the best part is that it shows how learning methods have evolved over time because initially products were made from raw materials but RE employs a counter-intuitive method to understand the construction and operation of products.
>
> I thought that the most interesting part was how useful the methodology actually is. People can learn a lot about products that are already out there. RE can improve anything this world if you understand how it works. I thought taking things and putting them into CAD software was a cool to see how real things were projected into a virtual world.
>
> I think the method of 3D scanning is the most interesting. Wow, technology can do so much! It was interesting to hear all about what methods can be used and how far different technology can help in RE.
>
> Reverse Engineering appeals to me primarily because of how we can reproduce items and things that are long lost. Old things can be re-modeled and then improved upon to make something better in today's world.
>
> The lecture that demonstrated the use of the 3-D scanner was interesting because it actually showed the things we had been discussing in the previous lectures.
>
> I found all of the different methods pros/cons to be interesting because it seemed like there was no method that was the clear best one.
>
> The 3D scanning technology was definitely the most interesting RE methodology. The in class demonstration of the 3D scanner really urged me to look into RE more.
>
> The most interesting part was seeing how many ways there was to Reverse Engineer a product.

The most interesting aspect of the RE methodology was the simplicity of all the processes. It seems to be quite easy to figure things out when you have the product on hand.

I thought it was interesting learning how engineers could work backwards in order to acquire information or parts.

The most interesting part of the lectures was the discussion of the scan technology as it's always interesting to learn about technology I previously knew nothing about.

The most interesting thing about RE to me was the fact at how useful it can be in the real world in order to learn or to re-document something has been lost.

The scanning ability was the most interesting. Although it has its flaws, I can see where a scanner like the one demoed in lecture could make an engineer's job a lot easier and more productive.

I think the most interesting part is the 3D scanning because people will have a chance to see the machine or have the chance of knowing how to use it. However, there is a demonstration in one of the RE lecture.

I was intrigued by how one can come up with a full design and mechanical mock-up of an object, machine, part, etc.. from just a picture or model of the part.

I liked learning about the different methods than can be used for RE. I knew the traditional measuring tools method but did not know about the other techniques that can be used and their advantages and disadvantages.

The most interesting part about the methodology was learning that there were so many ways to interpret reverse engineering. It wasn't just one method, it was using a general idea to implement a bunch of methods.

The fact that there are "middle man" companies devoted to RE for other companies and industries.

The slides with the negatives and positives about RE, as well as the explanation of each one gave me a good understanding of RE and helped me follow lecture and take good notes.

I would say the part discussing about an automobile being broken apart to find places for improvement or repair. It was a very efficient method to make improvements to a car/vehicle.

The ways on how the scanner works. It cost USD40000 and it does an awesome job in scanning. It also shows that through time, reverse engineering had been made easy with all these methodologies.

I thought the most interesting thing was the connection with real life examples, such as companies which are built on reverse engineering other companies' products.

The methods that they use, the scanners looked really cool and also the fact that companies reverse engineer all the time to gain an edge.

The actual process of doing reverse engineering, more than pure theory. It was very interesting to have had the second lecture a demonstration of how to use the 3D scanner.

The most interesting thing that I found about the RE lectures was the scanning and how it can be applied to objects as small as a paperclip, to objects as large as a plane given the proper equipment.

The reverse engineering dealing with the 3-D scanner was pretty neat. I see that being a useful resource in the future with bigger products like vehicles.

I thought it was really interesting to see how the scanner worked and how it identified points on a sheet and that you could get a 3d model just from placing an object on top of that. I just really liked learning about some of the new technology that was out there and liked seeing how it all actually worked.

I found the method of using the high tech scanner to be most interesting. The technology of the scanner is very advanced and I did not know something like that existed.

I liked seeing the different ways to reverse engineer objects. The 3d scanner was cool but i was kind of disappointed by the results that it produced, I expected such a pricey scanner to have cleaner scans.

The most interesting of the RE methodology lectures was the explanation of how objects were scanned and modeled in 3D from those scans.

This section provided responses taken from the survey that students submitted. The reason 30 answers were sampled is because prior sections sampled 10 responses from each category for prior questions giving approximately 20 to 30 answers per questions. Doing this enables consistency among sections.

4.2.4. Aspects of RE Lectures to be improved upon

The previous section outlined aspects that students found to be most interesting. Because of that it was necessary to gather information about what aspects students did not find interesting and suggestions they would make to improve it. The following question seeks to gather that information. "What part of the RE methodology lectures was not interesting and what would you suggest to improve it?" A random sample of 30 responses was taken and the answers provided can be seen below.

> I would have like to know why we were learning this, because being a sophomore is not easy to do this process, because we don't know how to get access to the tools, like the scanner.
>
> I think there was a lack of demonstration or video. It would have been easier to visualize the techniques if there was a video showing someone scanning or the machine working.
>
> Maybe include an example of model someone reverse engineered merely using an obscure photo with little detail. Then it might ALMOST seem cool to use the picture method. Otherwise that section just seems like a no brainer so I shut my brain off during that part. People tend to assume that ANYONE can just look at a picture and figure out what is contained within it graphically.
>
> The lectures were interesting however the slides at times were a bit cluttered and the flow of reading them was somewhat confusing. A professional example such as a short video of something reversed engineered might have allowed the lecture to come full circle. Specifically a video perhaps that shows how something was taken apart scanned/sketched cleaned/ put in a cad program then how from that a physical prototype that was created from this process. You could even create your own video or slides demonstrating this and bring in a product that you reversed engineered and show both yours and the original.
>
> While it is important to talk about the traditional methods of RE, I was not really interested because it emphasized things about drafting that we already knew, and took time. I would suggest mentioning the traditional ways, perhaps a small demonstration of the different ways to use a dial/digital caliper, and then move on to the more advanced ways, such as handheld scanning.
>
> Talking about what to do with the product of a scan seemed a little too general. I would like to see the actual process of dealing with a dumb solid or using

rapidform to create something more manageable. Some examples and a demonstration could fix this problem.

I would suggest improving on maybe feats or accomplishments that people have created by reverse engineering. Maybe show examples of engineers analyzing and creating vehicles or military weapons from competitors.

A little too much time and emphasis was placed on different approaches to reverse engineering. It might be better to focus on a general approach using whatever tools are appropriate for the individual task.

Some parts were a little vague and since it wasn't really a hands-on approach I don't think I will remember a lot of it. I think it would be improved by being able to be a little more hands on if not during the lecture, during the labs that followed.

The section where you gave the students the opportunity to try using the scanner was not helpful to my take-away from the class. i did not feel the students participating in using the device gained much, whilst the rest of the class lost interest bc they weren't directly involved and started to talk amongst themselves.

The length of the 3-D demonstration. You should have done the scanning so that it could have gone at a faster rate than when she did it with what looked like very little experience.

I feel that the overall lectures could have been more interesting if the instructor performed a demonstration of reverse engineering by taking something apart and modeling it.

The lectures that were simply slide shows were a little bit dull; I think that if there was more demonstration or more in depth explanation of the different techniques it would have been more interesting!

Don't teach by slides, actually reverse engineer a small and simple object in front of the class.

The very first lecture on RE was a little dry and too heavy. Instead of just having a simple powerpoint presentation, more demonstrations or small video clips could help make the 7:30 lecture more enjoyable.

None of it was uninteresting, I felt like we need to go more in depth with what we learned because most of what was covered seemed simple.

The content was all relatively interesting, but the slides without pictures were duller. I would add a either some pictures about the successful (or failed) tries with different approaches, or add a quick 2 min video of someone using one of the more advanced methods, just so people not only get the idea about each part for the process, but get a feel of how the process from start to finish flows.

The initial calibration process of the 3d scanning lecture with the scanner was a little prolonged as it was done multiple times. This could've been swapped with some more information about RE.

Just overall watching RE isn't as fun as actually doing it yourself. I don't know how this would work for the lecture, but a project where we have to reverse engineer even something small would be pretty fun.

Adding some examples as what people have actually reverse engineered and how it has improved the world as we know it would make it more interesting.

I think I would try and focus some more on the other methods. However, I understand that the scanner was a method that was accessible and outside the realm of most students' experiences.

The lecture was limited by time so that it had to cover a lot new knowledge really fast, which may confuse some students quite a bit. Maybe it will be better to separate the introduction of RE into more section so that the lecture will cover more in details.

I found most of the lecture interesting although there could have been a few extra demonstrations of using the methods and tools to reverse engineer.

More could have been done to expand on the examples of RE portion because this helps us understand how RE can be used. Also, the slides were kind of repetitive in format.

I found them least interesting because I felt they were insufficient to explain the material. Explaining what they do would suffice. Showing the minor details of how they work wasn't enough for me. Some of that technology was over the $40,000 dollar range and doubtless one slide could cover enough of how the piece of machinery must be used. I just felt that either have a little or a lot.

The slides explaining the process, but using like 4 different models on the same slide was confusing and I would get rid of that.

I didn't dislike any part. The whole lecture was engaging. Maybe more pictures could be included to help visual learners.

The lecture went too fast to cover more details. It may be better to divide the RE methodology into more lectures so that students will have a more comprehensive understanding of how it works.

I actually didn't find any part of the lectures boring. The lecture was interesting and everything presented caught my attention.

> For the sake of this class I dont think it was completely necessary to show in such depth how to use the digital scanner. I think it would be more beneficial to put more emphasis on using hand tools to measure and then mention situations in which the scanner would be appropriate.

This section has outlined suggestions students provided to improve upon RE material introduced in the course. Some of the most common aspects students suggested changing included providing more examples, having students complete a simple reverse engineering project, and learning how to operate traditional measuring tools.

4.2.5. Preferred Method of Learning

There are different methods of learning that students find to help most when learning material. This section provides information students provided to the following question. "In your opinion do you feel that hands-on or theory based textual/visual materials would be more valuable to your learning when incorporating RE into a course?" The answers students submitted could be separated into three groups that can be seen in Figure 4.2. A random sample of 10 from students who felt hands-on learning or a mixture of both and all 10 responses from the students who thought textual material would be the most beneficial are given following Figure 4.2.

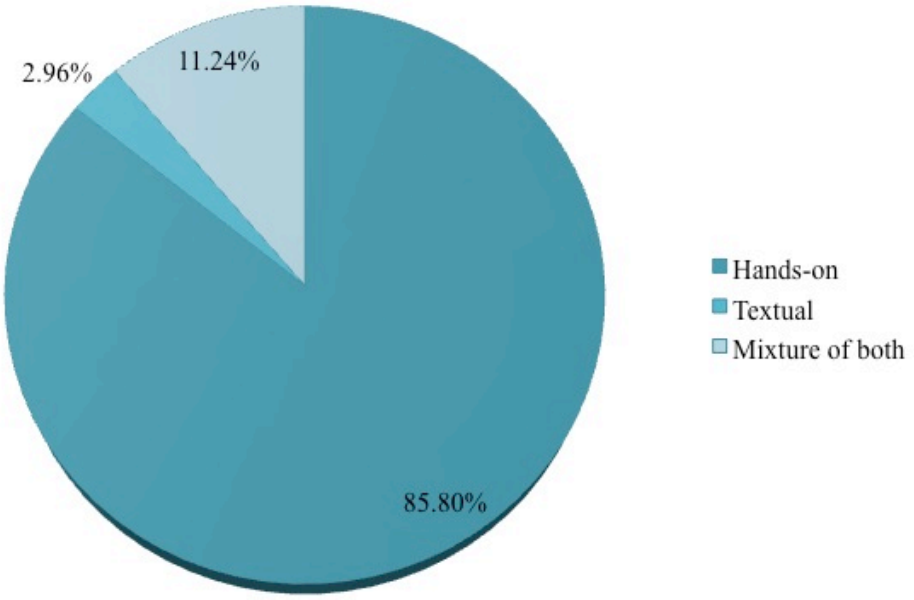

Figure 4.2. Learning methods students found to be most beneficial.

Responses from students who felt the best way to learn RE material would be through hands-on methods.

> Hands on material is much more valuable, because you will actually remember something that you did rather than what you saw in a slide.
>
> Yes, I am a visual learner, so anything more visual will help me.
>
> Hands on. I had no idea what was entailed in calibrating a scanner until I actually saw some students do it in lecture. And I won't ever completely know what it's like until I get a chance to try it. I know it's expensive technology and all, but maybe students could get to try it in lab sometime?
>
> A hands on approach is more beneficial to learning RE. Having a 2D or 3D representation gives a student the opportunity to understand precisely what it is they are working with. Scale can also be more easily understood wit a model.
>
> Hand on would definitely, then you have something to prove for your skill other than just a class in which we learned this theory.
>
> Hands on materials would certainly be more valuable as it would be easier to retain the information as well as understand it better.

> Hands-on by a long shot, because in the end, it doesn't matter how much theory we know if we've never held the machine itself. As was easily visible in the Zscan demo, many students knew how to use the scanner, but none of the students really could, due to complete inexperience.
>
> I think that hands on experience with examples are the easiest way to teach something that can be used later in life. I think lectures are specifically for cramming in alot of information and that is not what CGT and RE are for.
>
> I feel that hands on will be more valuable because from the hands-on experience that a student can understand the detail more clear or even better and also, it is easier to remember the important points.
>
> I liked how you actually brought the scanner in and showed us how it works. Although we ran into some technical difficulties it was good to see the machine in action, as opposed to only talking about it.

Responses from students who felt RE would be better learned through textual material.

> No
>
> Because RE tools can be expensive, I think MOST engineering students would be able to grasp the concept through theory.
>
> I feel like we don't get to many opportunities to learn the theory side of CGT. So I'm going to go with that choice.
>
> I feel that the theory is essential to fully grasp the hands on approach.
>
> No
>
> No.
>
> No. I think field experience is better because we can learn about RE through observing real life examples.
>
> none
>
> In my opinion, theory based textual/visual materials are enough to understand the basics of RE.
>
> Mostly theory, but a little of both would likely be helpful.

Responses from students who felt a mixture of textual and hands-on methods would be the most beneficial way to learn RE.

Both are important I believe. Certain degree of theory based material should companion with hands on material.

Hands on experience definitely trumps theory based but both are not mutually exclusive. A great deal of theory must be understood to grasp the complexity of the techniques and why you use them for reverse engineering.

Both would be necessary, but I would say that hands on would be the best. That's what we did in Project Lead the Way.

Hands on will be much valuable. However, the students should have some theory on how to use it before having hands on experience.

Hands on, but to a point. Theory is fairly easy to learn (at least what was covered in the lecture) Hands on would certainly help, but as i said earlier, spending too much time trying to calibrate the machine would be very frustrating.

No, I think balancing between learning theory based textual/visual materials and actual practicing (drawing) is important and needed. (in other words, both of them are equally important)

Theory based materials are important and necessary to finding out how RE works and methods of using it. However, hands on teaching is important to understanding how RE operates in the business world.

While I probably learned more actual material from the textual presentation, the hands-on approach made it more enjoyable and stuck with me longer.

I feel that hands on would be a more valuable learning technique for a larger class like our CGT 163 class. However, if the class were much smaller, hands on would definitely be the more adequate approach.

I think a mix of both would be best to learn RE. Start with the text/visual aspects to introduce the idea and then give assignments that would incorporate it in a CAD package would be great.

This section has outlined what methods of learning students felt would be most beneficial to use for learning RE methodology. The sample provided is only a small random selection of student responses for the hands-on and mixed method approaches. There were only 10 students who felt primarily using textual materials would be the best method for learning RE methodology.

4.2.6. Professional Development

RE is used in many industries across multiple fields. Therefore, it was important for this study to ask the following question. "Is there an aspect of RE that you feel would be beneficial to your professional development? If so, why?" A random sample of 30 responses is provided below.

> I think having a basic understanding of what is out there is most important. Then when in the workplace, if I reached a problem, I could go back and learn an option more in depth at that point, because I would need to follow company procedures anyways.
>
> It is a great skill to have, but as taught in lecture, RE can involve very detail work that isn't just done by one 3D scanning. So far the lecture had only taught introductory level content, yet it is beneficial for further development in the engineering education.
>
> I think the ability to take something and understand its form and function is very beneficial to professional development. With intense competition in many markets, the ability to understand what your competitors are producing and how to improve on a design are some of the most important abilities for successful company to have.
>
> Over anything else, practice. The more practice I have with RE, the less time I will need to spend on a given RE project, even in the professional world. In fact, some simpler parts might not even need to go through the whole material phase. If someone were to become extremely proficient in RE, they could eventually do most of the workings in their heads. Even when model creation is required, RE comes down to practice. The more practice, the better and faster the final RE come out.
>
> I am unsure because all of my career contents have already been reversed engineered, the only time i can see it aiding me is if a new technology comes into my shop and i have to disassemble it to fix and reassemble it.
>
> Understanding assumptions that can be made about the product during the RE process could certainly benefit my reasoning and provide extra insight into the techniques used by certain distributions of the product market.
>
> Not really, I've done both RE in building of an object, and RE in the Data analysis of competitors trucks.

One part of RE that would be beneficial for me would be the part where you examine the surrounding parts and then can determine what another missing part does just by looking at its connecting pieces.

I personally think that knowing broadly about each of the RE tools and being an expert in specific one could be very helpful. Interoperability of RE is the most important factor since we can create a model that can be used by multiple systems.

Definitely. Lots of times, I am unable to figure out what is in front of me, how it works, what went into making it. By using RE methods, I can completely understand why something works the way it does, instead of just having it in front of me and accepting it for what it is.

Yes the fact that you can take a product and work backwards, this technique can help us in many ways. Even when we work for companies RE can be used to learn things and pick out mistakes which you wouldn't usually find.

I think the overall concept of reverse engineering is extremely beneficial to a future profession. It can teach you many things that can easily apply to any engineering major and skills.

I don't think that a specific aspect of RE would be beneficial to my professional development, but simply the entire concept itself. I don't know exactly what I will be doing in the future so I feel that whatever I have to do in an RE aspect (if anything at all), I will learn to then.

RE will definitely benefit my career as a mechanical engineer because in MechE, a lot of the times new technologies are built on old ones and hence having extensive documentation would help improve the old technology and also create new and more advanced technology based off the revised versions of the old one.

RE is pivotal to my education as a mechanical engineer. One learns about automotive engines, moving gears only when it is seen in action. This basically means taking apart a car engine just to see how the pistons pump and the camshaft moves. For all of this reverse engineering is required to help improve the existing designs and also continuously educate people along the way.

I suppose just knowledge of the processes overall certainly wouldn't hurt anything and it may come in handy depending on the job I get. But since I'm only a sophomore, I don't yet know what sort of career I'm headed towards.

Yes. In my line of work it would be very possible that i would have to recreate a part which has been damaged. So being able to look at a part a RE it to figure out how to make another one would be essential.

I think there is a chance that I might need to have knowledge of RE in the future mostly because technology is becoming obsolete fairly quickly. That being said, I don't think it would be something that's prevalent in my career. I might even venture out to say that it's not even necessary to have extensive knowledge of RE in my career.

Becoming more familiar with the different methods of RE would benefit me because there may be times when I need to use one method for one product and a different method on a different product.

Learning to RE something is very crucial to modern day engineering. I think that we should have to acquire hands on knowledge of the different methods of RE, and be required to apply them to a project.

Yes, having general knowledge of various methods would be sufficient, because reverse engineering could be very important to an employer and having at least a broad understanding of multiple techniques would make yourself look better.

Definitely. Reverse engineering has the word "engineering" in it and thats always a good sign. RE teaches us to use what we've learned about engineering and applying it to real world situations in a way that we haven't been taught before.

I am an avid antique automotive enthusiast, and some of the vehicles I have repaired have no OE manufacturers currently in service. I have always come up with a quick and dirty fix (or a used part) in the past, but I would like to learn how to create accurate replacement parts. I do have access to a CNC mill, and could see lessons in RE as being beneficial on multiple levels.

Yes. in the automobile sector, this might be the most efficient method to come out with "upgraded" version of a car. Rather than starting from scratch, one could just open up a car completely and make necessary changes.

A lot of Aerospace Engineering has to do with 3D visualization either in your mind or by building a CAD model on a computer. The laser machine could really help out those in this field by simplifying their tasks. It could be very beneficial in this major and in many others.

As a mechanical engineer, since I want to work for the automotive industry, creating orthographic and isometric drawings of vehicles would be beneficial for my career. This is because drawings is the best way to represent information about big objects like vehicles. 3D scanning won’t be feasible but the next best alternative would be draw them down to a specific scale.

It would be beneficial from both and engineering standpoint and business standpoint form which you can obtain information on your competitors in this

> manner. Even if they are not your competitor if you could figure out how to take parts from a completely different product and incorporate them into your own product. It would also help if on the job if the team was asked to redesign an old part but they were missing documentation for it.
>
> There are a few things that I can think it would be helpful with, but for the most part not really. Since I am in aviation most of the parts that we need are all specified in reference and part manuals and people still manufacture almost all of the parts that you need. There are probably going to be specialty parts though that you might not have the specs for, in which case, any of the tools for reverse engineering would come in handy.
>
> yes, Aircraft design is where i would like to be heading, so learning Catia and RE things have a great chance to be a part of my career. Just like professor Miller said, sometimes when upgrading from one version of Catia to another old projects wont work.
>
> Learning RE would probably come in handy if I were a part of a design team with not much information about some product that was outdated and had not much information, and working on updating it.

This section has provided insight in to the minds of students and their view of how they will grow as an industry professional. Some students felt that learning RE would play an intricate role in their professional development while others felt RE was out of their professional growth.

4.2.7. Complexity of RE Methodologies

After being introduced to RE methodology and the various methods that it entails, it was essential to determine if students perceived any of the information as to complex. Asking the following question gave students the chance to express any concerns regarding RE methodology. "Is there an aspect of RE that you feel is overwhelming or too complex? If so, why?" A random sample of 30 responses is given below.

RE comes with many detail aspects that should be taken care of when different methodology is adopted. For example the 3D scanning, the scanned object's surface should be treated, but the lecture didn't specified how and the theory behind it. It sort of create gaps in linking up the knowledge.

I think that 3D scanning is a little more than we need to be learning at this point in our graphics careers. I think that the technology is interesting, however not every employer will have an expensive scanner available every time a part needs to be reverse engineered. I think that the basic RE techniques should be mastered prior to getting into 3D scanning and other more advanced RE.

Not really. Obviously, the more complex the product to be reverse engineered, the more complex the process will be, sometimes incorporating multiple methods, but The only real complex part to RE is using the equipment itself.

The scanning seems too complex for a single lecture, but it is also the most interesting aspect. I feel hands on experience with that would be great, but that would take way longer than one lecture.

in the beginning it feels like it is too complex but i think given the right training using a simple approach would make it much better.

A lot of the RE techniques require training, for example 3D scanning, database managements etc. Training will require extra time input which can be a little overwhelming considering that engineering majors are already very demanding. Also, dealing with legacy data such as old isometric and orthographic drawings can be difficult since conventions change over time (the symbology of representing holes) plus the quality of hard copies can be compromised if not preserved properly for long periods of time.

As it was explained there was nothing that struck me as too complex. While I am sure there are finer details which I would find as such, the basic components all seemed straight forward.

There are several methods, and I don't remember them all, to tell you the truth. I remember the demonstrations we had in class and remember them most. I think the methods and their advantages/disadvantages are difficult to recall.

I think that maybe if we were to go and try and use some of the RE methods it might get complex, but the general concept of RE as taught in CGT is fairly simple.

Using the scanner seems pretty complex to me because the scanner itself is complex and you have to put a lot of effort into it in order to get what you're looking for.

Being able to get the best possible scan and then try to retrieve the 3D scan from the data that appears in the program. It seems very complicated to take out what is only needed from that and leave out all of the extra data.

We never touched on how the scanner actually functioned. We just took it for granted. So I guess the mystery of how it works is overwhelming and complex.

No I feel most of the aspects are self-explanatory although it might be difficult to actually draw up complex machines with many moving parts in CAD packages such as Catia or Solidworks.

Some parts might be too dificult to RE with our experience in CAD because of their complex features. As we learn RE we should start with basic parts to get a good foundation. Also, scanning methods seems quite complicated.

Looking at something as a whole and saying "figure out how this is made and how it works" is really overwhelming, but when you break it into parts, and have a process for RE, it makes the task much more manageable.

Learning about the 3-D scanners seemed very complex. The piece being scanned had to be a certain color and stickers have to be placed in some spots. I struggled keeping up with all the details without experiencing any of it.

There isn't much complex stuff. But, I feel that when we 1st did the powerpoint, I found many information to be a little abstract. But when Trevor brought the scanner, most of the things became much much clearer.

From my perspective it looked pretty simple, although I noticed that a lot of volunteers had trouble calibrating the machine before hand. Other than that everything seemed waterdown and easy to understand.

I'm still a little confused on how the 3D scanning works for a large scale object. I feel that perhaps a visual would help to explain this concept.

No I don't think any one aspect is too overwelming, but some objects are much more complicated than others.

No, I understood what was going on the entire lecture, it was just a lot of information at once and I would benefit more from hands on learning by actually reverse engineering a product.

RE, in my opinion is not too complex. However, it can be a very tedious process as there is always bits and pieces of information missing from old technology. Also, sometimes legacy data is not in the most modern format. For example, before CAD softwares were around, everything was drawn by hand. Even though drawings can be scanned, creating 3D parts out of them is still not possible, hence it is equivalent to designing from scratch hence making the process time consuming and tedious.

The 3-D scanning seemed a little arbitrary without valid training and experience. It seemed to take long periods for random students to scan parts of an item and even after scanning there was a lot of "junk" in the scan

> I feel like scanning could be depending on how you look at it. As far as understanding how it works I think most people can grasp that, but I wouldnt mind REing an actual scanner and learn all of the reasons of why it works.
>
> Not especially. The one thing I think that would make everything seem manageable would just be to mess around with some of the tools that we use for RE and get a feel for how they worked and some of the processes you have to go through for specific ways to reverse engineer things.
>
> I feel that the sheer amount of time it takes to reverse engineer something is overwhelming because if you are in a time constraint it would be very stressfull.
>
> Metrology as a method of RE is too complex for me becasue it was not properly explained during the lectures.
>
> Not really, the principal is simple, just different ways of completing it. It may have also helped if you did it in more then 1 lecture, the time period may have been way to short for the amount of information needed to give everything proper depth.
>
> The slide with all of the phases was definitely overwhelming because there were so many different 4 step phases. I think there were about 4 of them with 4 phases and then one with 3 phases. It just confused me why there were so many different options.
>
> no, most things can be learned and understood after sometime working with them

This section has provided information about RE that students felt was too complex or that they found was overwhelming. Because only 10 students were given hands-on experience with RE methodology there may be some bias towards those 10 students. As with a few of the other questions there was a wide range of responses from not complex to very complex.

4.2.8. RE in Engineering Curricula

As stated in Chapter 2, there is great interest in the incorporation of RE methodology in the engineering curricula. One question that had importance in this study was whether students even wanted to learn RE methodology. The interest and

willingness to learn may play a part in students' performance in the classroom. The following question was asked to gather students' opinions on the subject. "Would you like RE methodology incorporated into your engineering curricula? Why or why not?" The responses to this question fell into four categories, which were Yes, No, Maybe, and Not Sure. The distribution of the responses can be seen in Figure 4.3. A random sample of 10 responses to the Yes, No, and Maybe categories and all seven responses from the Not Sure category are given following Figure 4.3.

Responses from students who would like to have RE incorporated into their engineering curricula.

> Absolutely, I feel RE is very important in all engineering fields and especially in ME, where we deal a lot with mechanical devices that sometimes need to be reconstructed. Or sometimes it is necessary to understand how something works.
>
> I would like to see RE methodology incorporated into some of engineering curriculum. This will enhance the ability for engineering students to develop some more user friendly designs and to understand the designs from others.
>
> I would only like it if it gave hands on experience in working with machinery and design. Too many of my classes involve memorizing equations or formulas that i can do off a book or online without having debt in 6 digits.
>
> Yes, definitely. Courses regarding design, sketching, etc should definitely include a component of RE just so that engineers can make sure that while designing anything, to document it as heavily as possible which will make RE an easier process for future generations when they are designing something new or improving on pre-existing technology.
>
> Yes . I feel that in future it will be of huge help in workingh life. As a large number of companies use RE methodology in learning about nature of different objects.
>
> Yes because it's not everyday that you get to work with machines like these, and it's a great way to get hands on experience with machines that I may use on my future job.

Yes I think that it is a beneficial subject that we should learn more about because there is a lot to be learned from the objects that could be reverse engineered.

Yes i would. This way people would get into mindsets very quickly. Lets consider the computer. If i was made to open it up in one of my classes and my professors asked me how to increase the cooling of the overall system. I am sure that even though i might not be able to come up with an answer just that time, the problem would stick in my mind and might eventually find an answer however half correct it might be.

Yes, as engineers it is important to know how to better improve your products and it would be beneficial to understand how other people have made things and it would be nice to have some experience with that before entering the work force.

Yes. I believe using RE in engineering classes would be extremely beneficial in understanding the principles behind why things work, which is what my major is all about really. The fact that over 90% of our curriculum comes from a textbook, to our lecture, and into our heads is rather sad as this is supposed to be about how science applies to the world. Why not incorporate some application in the classroom as well?

Responses from students who did not want RE methodology incorporated into their engineering curricula.

Even though an introduction would be nice, I dont think it should be incorporated too much into the curriculum as it seems rather time consuming.

Honestly, I don't think that I could like it, simply because I don't think everyone will be interested in it or find it 100% relevant to them. I feel that it is more of a special interest thing, than a thing that everyone should learn about.

I think it would be fun to use, but not really necessary. Most of the things we work on in class, we are given all of the tools that we need for installing and taking off things. if we do not have the parts, we have part catalogs and can just get a hold of the manufacturer to give us the parts that we need. I did enjoy learning about it however, but I just do not think it would be that helpful for us based on what we do.
No, because I feel it would be very difficult to do and teach.

No, because it takes a lot of time and as engineers, we already don't have a lot of time. I feel as though RE is something we can learn later on/on the job.

No, because it's not that hard to do.

No, I'm already going to be here for 5 years, don't need more required credit hours.

No, other than in this class. My classes for my major need to focus on getting certified and things that pertain to that.

No. While i find it very interesting I wil not need this for the type of work i want to do when i graduate

Probably not because I feel that RE is something that most engineers won't really have to deal with too much. Although maybe certain fields or industries may find RE more valuable than others.

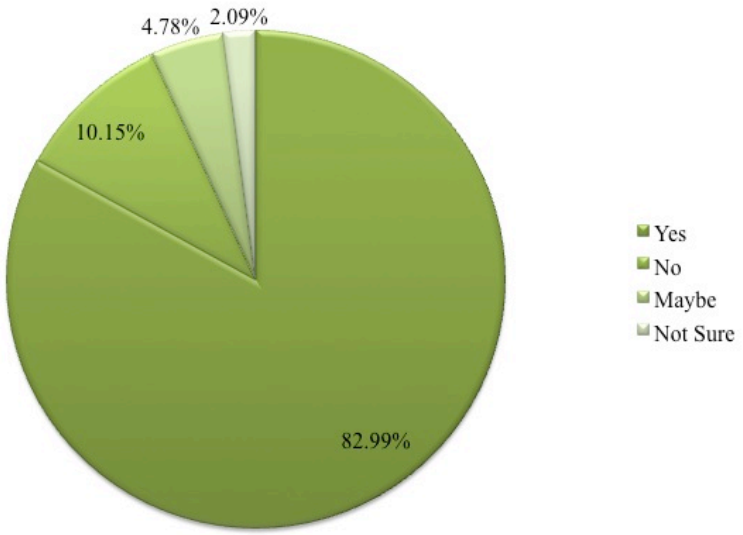

Figure 4.3. Students' willingness to incorporate RE into engineering curricula.

Responses from students who thought they might want RE in their engineering curricula.

At this point I am pretty neutral. I'm sure it would be beneficial to the curriculum.

Depends, I wouldn't want to have to constantly use it, but it would be cool to use it a couple times.

I don't know about the curriculum but it definitely should be included as a significant component in the Computer Graphics design courses.

I don't think it should be applied to the engineering curriculum, but it definitely should be included for CGT majors.

I would like a little reverse engineering incorporated, but I would rather concentrate on design and innovation. I feel it is more beneficial to learn to be creative and create new products.

No, because it's not something that all of us will have to do, and not all of us will need to know how to do it. I do however think it would make a great class if it could be taken as a professional elective.

Only if the homework wasn't too tough...ha ha ,but it seriously depends how it was implemented.

Possibly, not sure in what context though.

Possibly. I would concentrate more so on innovation that RE methodology.

I think it would be neat although I personally don't prefer it.

Responses from students that were unsure about implementing RE.

I am not sure.

idc makes no difference

It would be a good thing to learn. But no, because it would be more work.

Not a separate class in and of itself, however a section of a class would be nice

Not sure

unsure

Not neccesarrily, because it is a relativley obscure area of engineering.

This section has given information to determine if students want RE methodology incorporated into their engineering curricula. As with previous questions opinions varied and not all students felt it should be incorporated due to various reasons. Through elaboration students made their feelings known and provided reasoning behind why they felt that way.

4.2.9. The Role of Visualization in RE Methodology

One aspect the researcher determined might play a role in RE practices it spatial ability and one's ability to visualize. To determine if students felt visualization was a factor to incorporating RE they were asked the following question. "Do you feel that the ability to visualize is important for the use and implementation of RE technology into engineering curricula?" The distribution of responses can be seen in Figure 4.4. There were various responses that fell into the categories of Yes, No, and Not necessarily. A sample of 10 responses from each category is given following Figure 4.4.

Responses from students who felt visualization was important to the use of RE technology.

> Ability to visualize is extremely important to use and implement RE technology so you can understand what exactly is going on.
>
> Absolutely. Visualization is efficiency in RE. A person can draw up all the schematics and write all the words they want, but if they can't get the idea across to their peers, the whole reason for RE is not there anymore.
>
> I feel like it is incredibly important because visualization is, in my mind, one of the most important parts of problem solving, being able to look at a machine or object at all angles and be able to understand what is going on inside is as well as what parts are causing it to work.
>
> I found that there is a fine line between teh ability to visualize and the ability to understand something abstract. When I learned about RE in the powerpoints, it was hard for me to visualize. But, once I get to hold the 3D scanner, the visualization immediately came to me. I feel that visualization is important but only later on once you have learned the theory and basics.
>
> Most of RE requires drawings isometrics and orthographics. Also, its is a given that visual representation of anything is much more useful than having descriptions written out. Therefore, I feel the ability of visualizing is key to being able to successfully implement RE technology.
>
> Visualization is absolutely key when taking anything apart simply because it is now apart and no longer connected to other components. Since we cannot see

physically some of the parts working together, we must be able to visualize how they interacted before they were separated.

Yes this ability is very important for all engineers to become comfortable using. Many of us as future engineers will need to know how to use this process and technology in our normal work routine.

Yes visualization is very important because as you're dimensioned a real part, you need to be aware of how to model this in CAD. This means you have to visualize it in 3 dimensions and understand which dimensions are on which surface. This is an important skill to have to succeed in engineering.

Yes, I never realized that visualization is such a great tool. I always assumed everyone could picture an object oriented in their head. Now that I realize that this is actually a rare trait, I'm REALLY glad I possess it cus I see a lot of kids struggle in CGT with what to me usually seem like easy tasks.

Yes, the ability of visualize isometric views will make it easier to handle the 3D scanning. And we can use this ability to visualize the object more thoroughly and have a better understanding how the object was assembled.

Responses from students who did not feel visualization was important to the operation of RE technology.

Being able to visualize isn't as important in RE because you're working backward. Visualization is key when innovating a new design from scratch.

No, because the engineering courses I have taken are mostly math/science based so far, not visualizing objects.

No.

No.

Nope.

Not really.

No, because the technology is expensive. I'm sure most students can understand the subject through theory.

No, but I think it could help improve visualization skills for some students.

No, i dont think the ability to visualize is that important.

Not really and thats why I like the concept of reverse engineering.

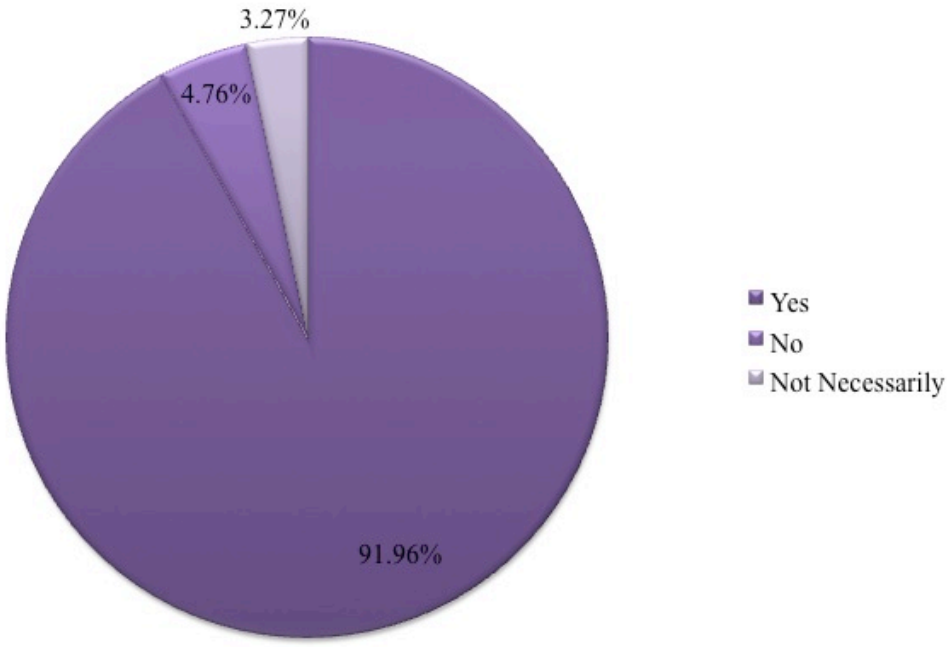

Figure 4.4. Visualization as a factor in RE implementation.

Responses from students who felt visualization is not necessarily a factor in using RE technology.

> I think it could be, and at the same time not necessarily. If the object is hands on then i don't think that visualization is as important compared to if it was strictly theory based material. I've not had this problem so it's hard to speak on it, I seem to have a pretty good sense of visualizing.
>
> I think it is important but not as important as other drawings because you start with the physical object in front of you.
>
> It is to some extent but im a person who is not too good at visualizing and im still able to manage.

> It would certainly help when it comes time to constrain the object, but overall the process does not seem to require it. The computer can do most, if not all, of the 3D visualization for you if you are unable to do so.
>
> It's important for engineering but probably not so much for the engineering coursework we have
>
> Not any more so than it is for a course in computer graphics in general.
>
> Not especially. At least not for the things that we did in lecture. All that really was was making sure that you calibrated the machine correctly and made sure the computer picked up everything that you had. On the other methods you might need more visualization, but for what we talked about I think that there are other things that are more important than visualizing how the part looks and is installed.
>
> Not particularly if you have the proper technology
>
> Not particularly. Some of the technology used will visualize it for you.
>
> Yes and no, or mainly just yes.

This section has given information as to whether students felt visualization played a part in using RE technology. It also gave insight as to visualization possibly being a factor in the incorporation of RE methodology.

4.3. Results from Hands-on Learning Experience

As stated in Chapter 3, 10 students completed a 3D scanning exercise and underwent two interviews. The first interview was conducted immediately following the exercise and the second was conducted following a waiting period of at least 24 hours. The following sections will provide information that was obtained through the student exercises involving 3D scanning technology and interview responses.

4.3.1. Calibration Results

Information regarding the 10 students who participated in the hands-on learning experience, such as PSVT-R score, course grade, and spatial ability classification can be found in Table 4.2 located in section 4.1.2. Each student, during the duration of their scanning exercise, was asked to calibrate the 3D scanner while the researcher recorded their calibration time using an online stopwatch located at www.online-stopwatch.com and the stopwatch on a Samsung Rogue cellular phone. An average of each student's calibration time can be seen in Table 4.3 along with students' spatial ability classifications.

4.3.2. Scanning Results and Primary Interview Responses

Students who participated in the hands-on learning experience scheduled a time to complete the study with the researcher and were in no particular order. Each student was given ample time to complete the study and interview and not all took the allotted time. The following sections will provide information that was obtained from the first interview.

Table 4.3.

Average Calibration Times

Student	Major	Spatial Ability Classification	Calibration Time
0101	ME	Low	1 hour 7 minutes 46.53 seconds
0323	ME	Low	53 minutes 37.37 seconds
0423	ME	Low	34 minutes 5.87 seconds

1020	MET	Low	32 minutes 31.73 seconds
0421	ME	Low	14 minutes 24.71 seconds
0417	AAE	High	4 minutes 46.92 seconds
0124	ME	High	13 minutes 5.62 seconds
1021	ME	High	5 minutes 6.35 seconds
1521	AAE	High	3 minutes 0.34 seconds
1524	ME	High	7 minutes 3.49 seconds

4.3.2.1. Participant 0101

Participant 0101 was classified as having low spatial ability and had the longest calibration time. The participant chose to scan the pipe support part. The results produced by the student through the 3D scanning process can be seen in Figure 4.5.

Prior to the start of the primary interview he said that his hobbies included reading, hiking, and researching about cars. When asked if the scanner tutorial helped him in completing the 3D scanning portion of the hands-on learning experience he said:

> Yes it did. Umm…because it was umm…a step by step right so I found it really easy to follow it and use it to my benefit.

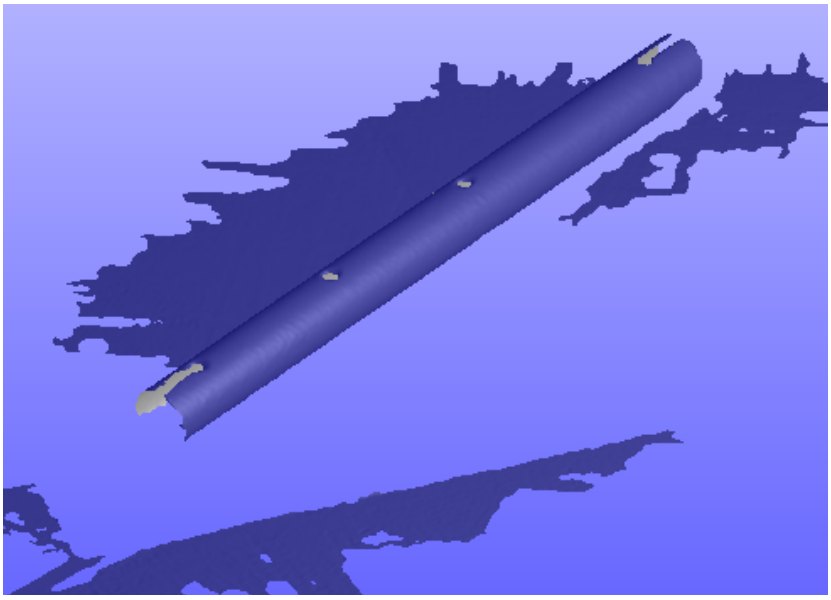

Figure 4.5. Scanning results of pipe support part produced by P0101.

He was then asked if there was anything that he would change about the tutorial to make it friendlier to users and he responded:

> Uh…like some of the information you mentioned was not necessary so…you would like…I mean if it is for general then you should like make…if it's not necessary than it shouldn't be there.

The second set of questions that were asked was about the calibration process of the 3D scanner. He was then asked how he felt he did on the calibration process and to describe anything he found to be easy or difficult. He said:

> Umm…I personally think I did pretty bad on the calibration…uh…process. I found it um…a bit difficult umm…I mean the measurements from 1 to 10 were pretty easy but measurements from 10 to 14 were a bit difficult for me. The tilting ones…and because I was not able to figure out which way to tilt according to the arrows taken.

When asked if he felt his spatial ability was at a sufficient level to complete the scanning calibration or if he felt his spatial ability needed improvement, he said:

> I think my spatial ability uh…has definitely improved by taking this test. But I still think there is much more room for improvement.

The next question he was asked was what he found to be the easiest or most difficult aspect of the scanner calibration process. He said:

> Again the measurements from 10 to 14 were the difficult part and the easy part was the 1…1 to 10 when the calibration were in the X, Y direction.

The set of questions that followed pertained to the scanning process itself. He was asked whether he liked or disliked the 3D scanning process and why. He responded:

> I really like the um…scanning process I found it interesting like uh…I found it really interesting how umm…a part can be uh…scanned and can obtain on the screen and then use it for other purposes. So I really like the concept of reverse engineering.

After he was asked what he thought was easy or difficult about the scanning process, he said:

> The whole process was easy. The way we scan the part was easy. Yea…the weight of the scanner. The scanner's heavy…but again it depends how much time you take to calibrate so…

When asked if there was any supplemental material that was useful in completing the tasks such as his spatial ability or other hands-on activities he said:

> Apart from you no.

He was then asked if he understood what the scooter parts were that he had a choice of scanning and where he thought they belonged on the scooter. He said:

> This particular part…like the handle that part. Where the scooter is it come up where the scooter and the axle is attached so between that.

He was then asked to explain the scanning process as if to someone who had not completed the process such as if he were in a job interview. He gave the following description:

> Uh…I would say that umm…if a particular part has been given to us and we don't have the specifications pertaining to it so the best way to do the um…to get the specifications and then figure out the part and use it for other purposes would be using the 3D scanner. Or basically following the concept of reverse engineering and using one of its methods, which is 3D scanning.

The following question set asked questions about the CGT 163 course he was enrolled in. He was asked if there were any assignments, lectures, or other course activities that helped him to complete the task of creating a model from 3D scan data. He was reminded that he was introduced to how to create a model but did not actually complete the process. He said:

> Well definitely the course has helped me to improve my visualization all the assignments till now and uh…umm…especially the um…uh…the reverse engineering lecture this and the slides according to what's it going to be…or what we're gonna be doing during the study.

For this technology to be implemented into the engineering curricula there are factors that need to be considered. When asked what factors he felt needed to be considered before the implementation could take place, he said:

> First of all like…um…since the scanner is really expensive so and we already know that CGT 163 has so many students…so…mmm…we need to figure out how like…mmm how the scanner would be use like do two people use one scanner or four people use a scanner because it's really expensive. That is one aspect then secondly the weight of the scanner. And then thirdly I would say then…uh…like I personally found the lecture on reverse engineer lecture was too short to explain the whole reverse engineering concept. Dr. Miller like rushed through the one thing so in my personal view I'd place two or three more lectures

> should be con…on that…I mean there should be two or three more lectures before the technology is introduced to the students.

The last set of questions in the primary interview was about the study he had completed. He was asked if he had any prior knowledge of RE before the study and what his opinion of the study was. He said:

> No except from the lecture. It's interesting. Because the…concept of reverse engineering.

He said that he does not tend to leave an interview or meeting wishing he had added additional information. He found the scanning exercise to be enjoyable and when asked about it, he said:

> It was enjoyable but it was tiring at the same time. Again because of the concept of reverse engineering.

To figure out what type of learning method students prefer he was asked what method he learned best from. He said:

> Hands-on. Because then I actually get to feel or see what's going on. But when I try to read the text I sometimes get it and sometimes don't get it. I usually need mmm…some kind of material or practical experience or someone explaining it to me but uh proper…

He was then asked if there was anything about the hands-on learning experience that he would change. He said:

> Because I told you take less time right and if I say that you should reduce the time but again dependent on the person who's taking it.

He said that he was positive he wanted RE methodology into engineering curricula. When asked if he thought RE methodology would be more beneficial as a first year engineering student or as a junior or senior he said, "mmm…I think junior level

course or possible sophomore." Again he was asked what factors he felt must be taken into account if RE technology were incorporated into engineering curricula. He said:

> Cost, uh the way um…students would respond to it whether they would be interested in such type of technology or not.

When asked if he liked or disliked the scanning experience he said:

> I like the whole scanning process. Mmm…the way I scan the way I calibrated it then especially the scanning part. I didn't like the fact that I took so long and…the weight of the scanner was heavy.

He was asked if he felt spatial ability helped him during the process and whether or not he played video games. He said he did not play video games and he did feel spatial ability helped him:

> Especially like when the…the arrows up and down forward back…and trying to figure out.

4.3.2.2. Participant 0124

Participant 0124 was classified as having high spatial ability and had one of the five shortest calibration times among the 10 students who participated in the 3D scanning exercise. He chose to scan the pipe support part of the scooter. The results he produced can be seen in Figure 4.6.

Before the interview began P0124 stated that his hobbies included watching movies, reading novels, listening to music, and swimming. The first set of questions he encountered pertained to the 3D scanning tutorial. The first question he was asked was if the tutorial helped him in completing the 3D scanning portion of the hands-on learning experience. He said:

> Yes, uh to show how the lot it is it is exclusive I was reading it and it tells me how to do all the steps very clearly so it helps lot.

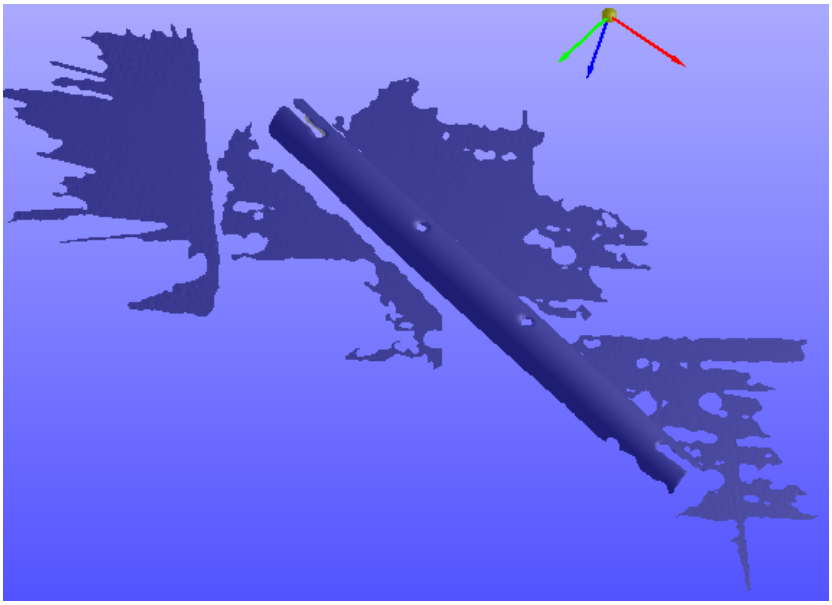

Figure 4.6. Scanning results of pipe support part produced by P0124.

When asked if there was anything he would like to change about the tutorial that he used during the process, he said:

> Uh, one thing I will change is that I…may…um…I will eliminate the…the part the part that I…I'll not use in the calibration or scanning part so it will be more specific and more clear.

He was then asked questions about the calibration process he completed. He was asked how he felt he did on the calibration and was asked to describe anything he felt was particularly easy or difficult. He said:

> Uh, yea during the calibration…the typical parts that I…I start at the beginning I cannot handle the scanner real well. According to the instructions on the screen it sometimes if you are only focused on one part you may miss other parts. After three or four times successing the calibration you will find very easy to follow the

> instructions and you can complete the calibration through uh…overall I think the calibration is umm, not very difficult…

After the explanation of spatial ability was given to him in more depth and the purpose of the PSVT-R described he was then asked if he felt that his spatial ability was advanced enough to complete the calibration task. He said:

> Yea, I think the test is important in this part cause uh the ability to see the isometric pictures can help me to…uh, to the learning the calibration also the scanning part cause uh, I know when I was…I was scanning the objects I knew which part I need to scan which part I already scan.

He was then asked what he felt the easiest and most difficult parts of the calibration process were. He stated that:

> The most difficult aspect…aspect right? Okay…aspect of calibration is…uh, the first time I try to follow…uh, the right arrow instructions I…I always miss…uh, one of the parts when I was focusing…uh, focusing on another one. So… The easiest aspect is, uh after…uh finishing three or four times of calibration and it will be really…easy to finish the rest of the calibration.

The third set of questions was about the 3D scanning process. When asked if he liked or disliked the process and what he thought was easy or difficult about the scanning process he said:

> I kind of like the 3D scanning process cause it can help me to uh use uh program to build other things I already scanned. Which will make…make more easier to uh…to figure out where model in the computer after scanning. Difficult part is its really hard to control the distance for the scanner to the object…during scanning I…I like…I missed…like three or four times…when the scan is to close to objects and I need to restart and scan again. And the easy part is that the scanner is…is really kinda accurate. It can catch um things really very well and can get a good model.

He was asked if there were any materials or activities that helped him to complete the scanning process other than the tutorial. He responded:

No, umm I think the tutorial is pretty much in the…

He said that he did not completely understand what the scooter parts were or where they belonged on the scooter. After having the parts explained to him he was then asked how he would describe the scanning process to someone who had not completed it before. He said:

> Uh…I would tell them while I was doing scanning I used the scanner to scan around the objects and…after doing that I use program to figure out certain model and the lower…the lower file to another program…to…to build another…to build another thing I want to use…and…that's it.

The set of questions that followed was about the CGT 163 course. When asked if there were any assignments, lectures, or other course activities that would help him in creating a model from 3D scan data, he said:

> I using the catia software can help creating of a mode cause we learn a lot of techniques in the softwares such as extrude and revolve…something like that to build all the models which can…which will help a lot. Yea…uh, I…uh, I…I…I can get help from other lectures I take each semester. To build all models cause we learn the isometric sketch and the…and the uh knowledge about dimensions which will help a lot.

He was asked what he felt would need to be considered before the implementation of RE into engineering curricula could be successful. He said:

> Mmm, I say the instructors needs to train certain people to teach students how to use this technology and also they have to consider the…the cost of using…uh, scanner to implement it into a class…and also they have to consider the ability of the students. Uh, who are going to take the classes.

The last set of questions he was presented were about the study he completed involving the 3D scanning exercises. He was asked if he had any prior knowledge of RE before he completed the study and what his opinion of the study was. He said:

> Uh, yes. I…I've done…I've done some knowledge about reverse engineering during the CGT 163 lectures and it is which is about introducing scanning to create a models and…reverse the using process to get the original parts. That's it. I like the…I like this study cause it is kind of fun and I learn how to use this 3D scanner and also I…I know how to figure out the models I wan…I want in better way.

When asked if he leaves interviews wishing he had given more information, he said:

> Okay…I think its pretty much I…I already say what I wanna say about in the interview. That's it.

He was asked if he found the exercises he completed to be enjoyable. He said:

> Yea I think its enjoyable cause I practice myself using a new machine and also it is a new technology for me. I…I think I learn this experience in this scanning process.

To determine what method of learning he preferred he was asked if he learned better from hands-on material or from text-based materials. He said:

> I would say both cause, uh for hands on…exercises I can…I can learn it fast but for um the text books I can learn…learn things more clearly and get more informations.

There was nothing he felt he wanted to change about the study. When asked if there was anything he would like to see he said:

> Mmm, I would like to see the…this scanner practice and being implemented into CGT course…maybe they can set out a spec…specific course just for 3D scanning.

He was asked what he thought about incorporating RE methodology into engineering curricula. He stated that:

> Yea yea I would like it to be my class cause it's fun…I know there is a machine design class for mechanical engineer…engineering students if we can use 3D scanning in the course we can…um, build all our models in a fas…in a fast…faster way to finish our uh…assignments or our umm…our course…and that's it.

For RE methodology to be incorporated into engineering curricula successfully it would be necessary to figure out what courses and what grade level it should be incorporated in to. When asked if he thought it would be more beneficial to learn this information at a first year level or a higher level he said:

> I would say…it would be more suitable for junior or seniors cause…our…our first year engineer students…they just got into college they don't know much about…using scanners and 3D models. Like but for junior and senior students they already learn a lot of mechanical knowledge and they also…they learn how to use…software and they will…they will use uh the scanning better then students who just came into college.

He was asked what factors he thought needed to be considered prior to incorporating RE methodology into engineering curricula. He said that:

> Professors need to uh…mmm…the professors need to setup certain procedures for students uh…to …for…to how to learn uh…and how to use this technology in their study…study plan and such as or they can use this to…to do and…and what they might need…what they might need this scanning technology in the…in the study. And for students they…I think they have to…have to have a basic uh…basic knowledge about the reverse engineering. And that's it.

When asked what he liked or disliked about the 3D scanning experience he said:

> mmm…the thing I like is…I…I can learn something new and knows…knows basic information about scanning technology…uh the only thing I dislike is…is this study makes me kind of tired. Uh…just my hands feel sore and...but is…is getting better.

When he was asked if spatial ability helped him he said, "yes." He said that it was because, "…knowledge I learn in the lecture and also the…basic knowledge about reverse engineering help me to do a scanning better. And that's it."

He was then asked if he played video games and he said that he did a long time ago and it was the Prince of Persia. On the computer he said he also played Warcraft and StarCraft.

4.3.2.3. Participant 0323

Participant 0323 was classified as having low spatial ability and recorded the second longest calibration time of all students that completed the hands-on learning experience. He stated that his hobbies reading novels and any sport. He chose to scan the pipe support part and his results can be seen in Figure 4.7.

P0323 was asked if the tutorial helped him in completing the 3D scanning portion of the hands-on learning experience and if he would change anything about it. He said:

> Yes it did. It uh helps you understand how to like get it and position and how to scan properly cause I remember that …before. Nothing I can think of…it's…just practicing.

He was asked about the calibration process and what he found to be easy or difficult about the process. He said:

> I found it easy to get easier to get the…the pictures right but the X itself took a long time…and I found it to be hard to stabilize the thing while I get the pictures right so I can get X right.

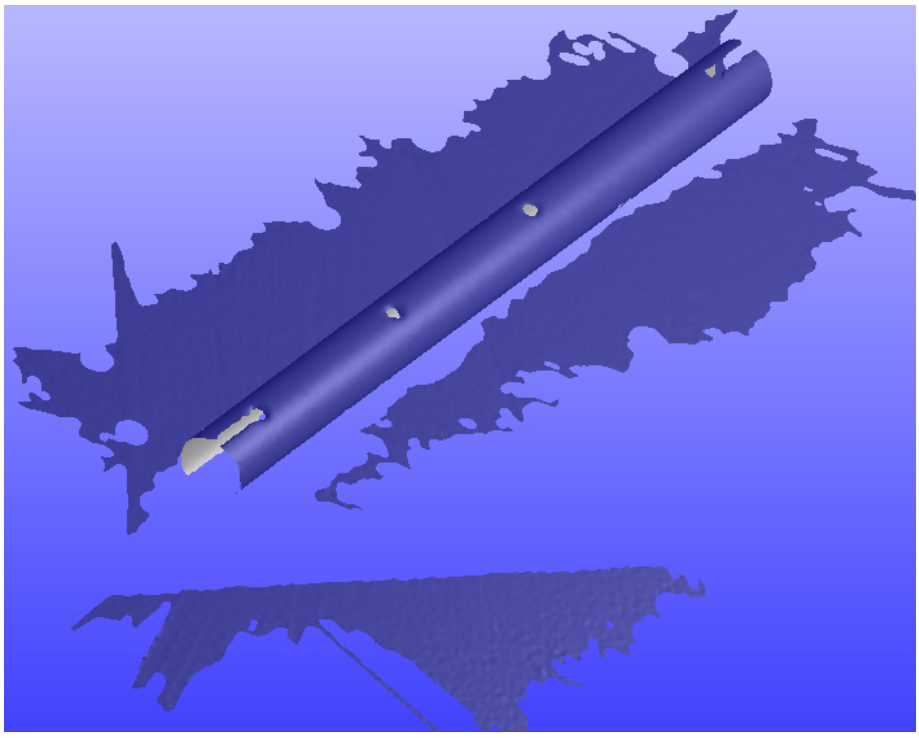

Figure 4.7. Scanning results of pipe support part produced by P0323.

He said that he felt his spatial ability was advanced to a level that was sufficient enough to complete the scanning process. He was asked what he thought was the easiest or most difficult aspect of the calibration process. He said:

> The easiest was getting the…the view…the bottom left view right. And the X was the hardest.

When asked if he liked or disliked the scanning process and what he found to be easy or difficult about the scanning process he said:

> I liked it…it looks really cool and um…I…I think it's really useful. Uh, it was…it was really easy to scan the part itself, but um…getting four dots to gather some times you miss a target when you go…so that's it.

He said that he felt the tutorial was helpful enough and that no other activities helped with the exercises. When he was asked if he understood what the scooter parts were and where they belonged he said:

> Yes I did. The…the bolt shaped thing goes on the bottom of the scooter and the pipe goes to…the scooter bottom frame.

He was asked to describe the scanning process to someone who had never used the technology before. He said:

> You calibrate the uh scanner to…position of uh dot board and X. and then the scanner basically the scanning rays have X and the like little center X and you just scan over the part you do read four dots in the scanning area to get it right to get the position right. And…that's it to use the scanner.

Following scanner questions he was then presented with questions about the course. The first question he was asked was whether there were any activities or materials in CGT 163 that would help in creating a model from the 3D scan data. He said:

> Um…the other CAD assignments that we do especially the last few ones…the ones where we had to make assembly make extrusions make cylinders that would help. And the…the drawings the sketches…drawing the front the bottom and the side view will help.

When asked what factors would need to be considered when incorporating RE methodology into engineering curricula he said:

> The cost and the coordination of the scanning…because it takes just to…3 hours to do one scan of a simple body. The cost. And uh…and the faculty needs to be taught that to learn.

The last set of questions contained in the primary interview were questions about the study he had completed involving 3D scanning technology. He was asked if he had heard about RE prior to the study and what his general opinion of the study was. He said:

> No knowledge I just knew there were companies that actually do reverse engineering. It's interesting.

To determine whether a second interview could be helpful in gathering more information he was asked if he ever leaves interviews or meetings wishing he had given more information. He stated that:

> Yes. Um…the only interview I've ever given was for a BGR team leader. And yea there were questions that I…I could have…I could have…

When asked if he enjoyed the scanning exercise he stated that he did. He added to that by saying that, "the calibration was…took a long time and it took more tries…but the scanning itself was…was fun to look at." He was then asked if he preferred to learn from text-based materials or from hands-on and he said he preferred hands-on. When asked to elaborate he said, "Because I…once…once I actually get to do it I can…it makes it easier to…like understand how I did it…and then I can apply it to do."

He was asked if there was anything about the study that he would change and what his thoughts on incorporating this technology were. He said:

> The number of calibrations but that's not really my choice…It would make things a lot more interesting.

To determine what classes this methodology may be helpful in he was asked if he thought it would be beneficial to learn the technology at a first year engineering course or a higher level course. He said:

> I think a junior or senior level course. Because you have a lot more subject to reverse engineer use the scan for. First year classes don't have much you can scan.

One of the more important questions that was asked was what factors would need to be considered before incorporating RE methodology into engineering curricula. He said:

> Maintenance of the…maintenance of the equipment cause I…and umm the cost time it takes for scan. Was long so because you don't have enough fac…what if you don't have enough time and faculty train...The…hands-on training and how are they going to teach the scanner process. Again training of whoever is going to teach everyone. The cost…how many scans…scanning machines can you really have in your company and…who handles it…

In response to a question about whether he liked or disliked the experience he said, "It really cool. Calibration was frustrating in the start but that's…" He was asked if he liked anything about the study and he responded, "Yea the scanning and the whole concept of scanning and having it made…made to follow…"

Spatial ability helped in the scanning and calibration processes according to P0323. He stated that he does not play video games of any kind. He concluded by stating, "I think everyone in lab should use this. It's really interesting."

4.3.2.4. Participant 0417

Participant 0417 was classified as having high spatial ability and took less than five minutes to calibrate the scanner. When given the choice of parts he could scan he chose to scan the bracket support. A result of his scanning results can be seen in Figure 4.8.

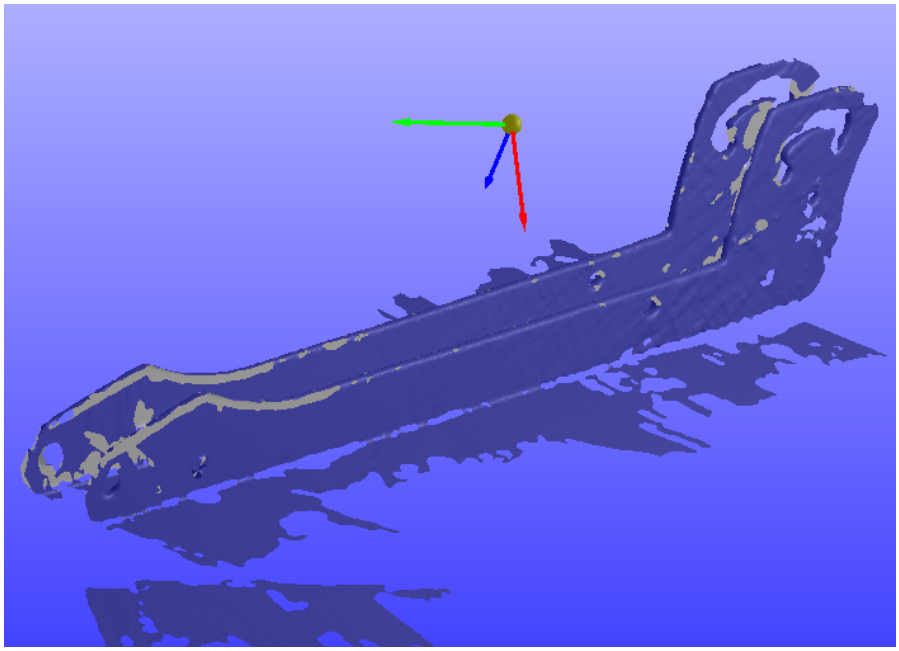

Figure 4.8. Scanning results of bracket support part produced by P0417.

Prior to the beginning of the interview he stated that some of his hobbies were football, playing video games, and using Autodesk Inventor. To determine if the scanner tutorial was helpful during the study he was asked what he thought of the tutorial and if there were anything he would change. He said:

> I think it helped me a little bit. Um, the biggest help in that was we also gone over it in class a little bit so like I remember a lot from there but the tutorial helped refresh in my mind exactly what was going on so…I don't think so it was pretty easy to understand…

When asked about the calibration process, what he thought of his level of spatial ability, and what he thought was easy or difficult about the process, he said:

> I feel like it was definitely advanced enough already to be able to complete it. The easiest was when it was just like right above it where you would be scanning and all of a sudden jerking your hand up a little bit got like five. Um, like I said the hardest part of the calibration test was trying to start in a new area. Just when you

> got off or when you weren't where you needed to be on all four spots all four windows it was hard to get back on track with all four.

For the purposes of the study it was important to figure out if the students enjoyed the scanning process and what they found to be easy or difficult. He stated that:

> I liked it, it was interesting. It definitely was easier than trying to figure something out just like just try to build it on the computer without the help of the scanning process but it was it was fun it was interesting so I enjoyed it. I don't think the weight of the scanner was an issue at least for me like it's pretty easy just to like maneuver around everything. The hardest part was trying to make sure you had enough reference points cause the shape of the object kind of pushed off the edge on the corners and so it was kind of hard to make sure you had the reference points and the…the reference points and the…the ah object all together in order to get the detailed parts in the ends.

Spatial ability and hands-on activities may play a part in the scanning process. He was asked if he felt spatial ability or activities helped him during the scanning activities. He said:

> Uh like I mentioned earlier the in class demonstration last week helped a lot. Just being able to like understand exactly…wha…wha…what I was doing while I was doing it. Um, spatial ability probably just being able to see in my mind like there were points where I knew what I was scanning without even looking at the computer just like I understood where it was pointing and…and where I needed to point to get a certain feature. So, spatial ability definitely helped to.

He was asked if he knew what the parts of the scooter were and how he thought the scooter would go together. He stated that:

> Yea I think I can figure out where it would go on the scooter to…to build the scooter from these parts, yea…the bracket part would be underneath the foot base. And the pipe would be in the uh ha going up in the handlebars.

Part of working in a career is the ability to communicate. To determine how one might describe the scanning process to someone he was asked how he would describe the scanning process to someone who had never used the technology before. He said:

> I'd explain it as a tool to help create something on the computer. Where you're using lasers to bounce off the object and by moving it around and having the different angles of lasers you are able to read depth and shape of an object and with enough readings of each square millimeter of the object that you'll be able the computer will be able to render the part.

Part of the RE process is to create a 3D model from scan data. When asked if there were any course activities he felt could help with the model creation process he said:

> Like I said the lecture last week. The Thursday lecture for week 12 or Tuesday lecture for week 12. Uh, just like showing us basically how to do a quick scan like it helped me to just to understand what exactly what was going on when I was scanning and what I needed to be doing like it showed like the problem with the distances and like being to close or to far away. And, the refle reflectivity which we didn't have to deal with in this but like it kinda it showed different difficulties we'd have which definitely obviously helped in this because I didn't have to worry about those I knew what was going on. At least some of the difficulties I was having.

To determine what factors students felt needed to be considered for RE implementation he was asked what he thought needed to be considered. He said:

> I think people the students would need to understand um reverse engineering like the like what goes into reverse engineering before just messing around with this cause yea this is cool I can make a part and and put it on the computer but what does that do like for engineers. Like how would this help engineers because in real life this is used to scan a part so they can put it in figure out how it fits with other parts so they need to understand like the basics of reverse engineering before they can really understand what this is used for.

The last set of questions that was covered was about the study and what he thought of the experience. When asked if he knew about RE prior to the study he said:

> Yes. I spent two years in project lead the way in high school, which is largely based around reverse engineering for a year and a half.

His general opinion of the study was found to be positive overall and does not leave interviews wishing he had added any other information. He said:

> I thought it was an interesting study um it's asking some interesting questions about students and how things outside of the uh their work and school might effect their ability to do something such as this. Uh, scanning so I thought I thought it was really interesting. That's why I signed up for it.

He found the exercise to be enjoyable and when asked to elaborate he stated:

> Yea, it was it was fun. Like getting to play with the technology was interesting, I…I like learning new technology and stuff like that so…getting to play with the scanner actually doing the scanning was it was definitely enjoyable.

The best method of learning for P0417 was through hands-on activities. He stated that he can read something multiple times and not pick-up on subtle details. When it comes to hands-on exercises he claimed he knew what was going on better because he was actually doing something. When asked if there was anything he would change about the study he said:

> No, I feel like we get a good chance to…to figure out what's going on hands on wise with the scanner so. Hands on wise its very good.

When considering the incorporation of RE methodology, he stated:

> I think reverse engineering is a major part of a lot of engineering. Just…just because you have an idea for something doesn't mean you're changing the entire product you need to understand how other parts of the product work as well which is reverse engineering and its basics taking something that exists and figuring

> how…how it works. You need, so reverse engineering…yea I just completely turned myself around there. Embarrassing, but yea…like that answers the question I guess. I…I feel I feel it's important to do that. Like I said that's part of being an engineer is you might have like I said you might have a small part you want to change but you need to understand how it works with the whole…so it…it I feel that it's definitely needs to be it should be uh, major part of engineering.

The course level at which this methodology is incorporated could play an important role. When asked what course level he thought would receive the most benefit. He said:

> I think older the, ah older students the higher level students junior or senior level courses would benefit from it more. Because the freshman students are still most of them at least are still figuring out what it means to engineer something and the scanner would just...I…I feel that the meaning of the scanner would be lost on them…It would just be a toy to play with and the higher level students would actually understand what...what it stands for, how it can be used in the job later on. So they'll definitely get more out of it. Cost obviously, you can't you can't have every …every group in engineering 131 or 132 class using a 3D scanner such as this such…such it would be ridiculous for the cost. Um, so I guess also the…the ability for every group to be able to work on it…just we have so many freshman engineering…engineering students here that my…my 132 class had 30some teams just the whatever you're doing whether it be in that course or be in the course with 5 groups in the 400 level class are all the groups going to be able to work on it or is it going to be one group at a time or is the project that they're doing…can…is revere engineering really helping that project. So some groups might be doing one thing that reverse engineering isn't needed for while another group under the same project title is doing something going a different direction where it's not needed. So you need to make sure that if reverse engineering is supposed to be used that the groups are doing something to use it.

To determine if this experience would be helpful in the future he was asked what he liked or disliked about the experience. He said:

> I don't think I disliked…But uh, I…I enjoyed just the overall like getting to play with the scanner and seeing what would come out of it. Um, the entire experience was really good for me. I didn't dislike anything about it.

Spatial ability and video games may play a role in the scanning process. Therefore, he was asked if he thought spatial ability helped him and if he did play video games. He said:

> I do. The ability to see what I was doing without actually seeing myself do it I guess. Like, I could…I could like I mentioned earlier there were sometimes I wasn't even looking at the…at the computer to see where my scanner was. Like I understood what was going on at all times with the part…through spatial ability. I play a lot of video games. Um, I play on PC I play some RPG's and RGS's. I play a lot of first person shooters when it comes to my XBOX. O play a lot of Halo, a lot of call of duty, a lot of third person shooters like gears. Stuff like that. I play a lot of Ha…Halo. Lot of Call of Duty.

He added that he thought the process would take him longer than it did. When asked to elaborate he said:

> Just when they were talking about it in the lecture a couple weeks ago like they were doing the part in lecture. It took a long time for a very simple part. So I expected to come in like have…even in…an easier part I expected to take longer just to have to have to go over more times. But…it wasn't as hard as I expected it to be I guess.

4.3.2.5. Participant 0421

Participant 0421 was classified as having low spatial ability and had the shortest time of the low spatial ability students. Some of his hobbies included playing cricket and reading. He chose to scan the bracket support part and his scanning results can be seen in Figure 4.9.

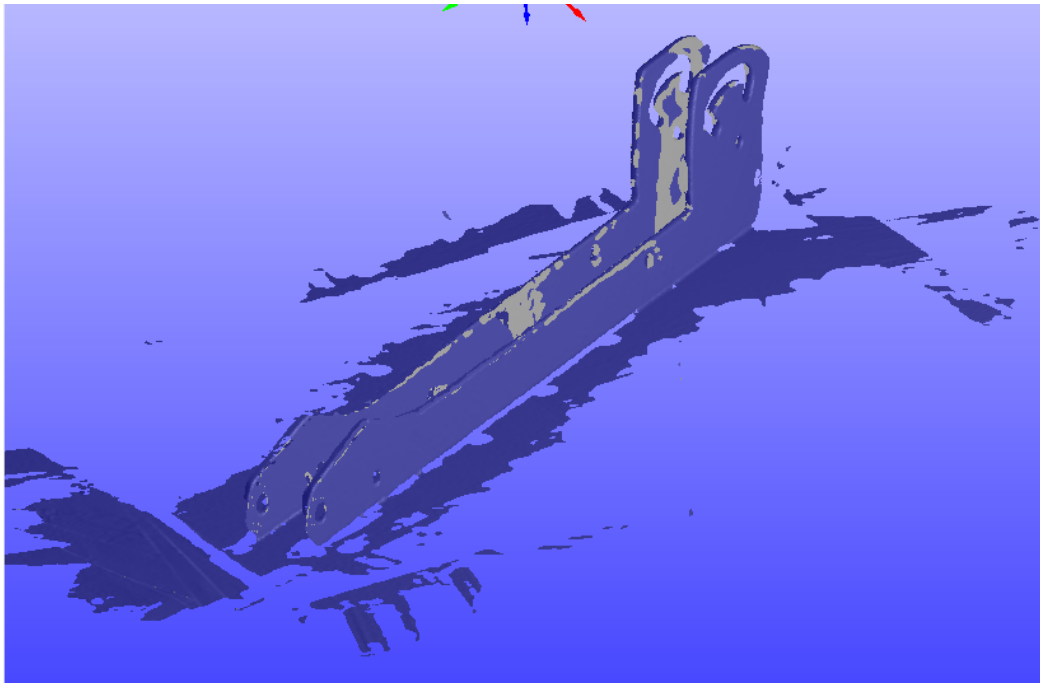

Figure 4.9. Scanning results of bracket support part produced by P0421.

He said that he found the scanner tutorial to be helpful. He stated that:

> …the procedure was explained very clearly and uh, and it was also very simple language that was used and uh…uh…it was a step wise process so I didn't find uh any problem understanding the procedure at anytime.

Some of his thoughts on the tutorial included wanting more steps to elaborate the process. He felt that adding those steps could make the tutorial easier for users to understand and use. When asked about the calibration process and details as to what he thought was easy or difficult about the calibration he said:

> Uh…I think uh…I think it good…it was my first time. I cannot say really much about how I did. But still, uh…one thing I would like to say is that thing was pretty heavy…

He was asked if he felt his level of spatial ability was advanced enough to complete the process and what he found to be easy or difficult about calibration. He said:

> It...it was average I mean my spatial ability is pretty average. It isn't very advanced but…um with this type of ability I…did pretty goo…good as far as I'm concerned. So…I don't think someone needs to have very advanced spatial ability to uh do the calibration or scanning. I think. Uh…at some points uh while doing the calibration…um…used to…um…get calibrated pretty fast but at...at some time…at some points it was like…um you had to go from one place to…it was distant two points were just the calibration points were distant. At that time I found it difficult to maneuver the…the machine the scanner. And that's where I found that its difficult. And some times you had …I mean…make a…I mean I was looking at the screen and…um…keeping my eye on all the thr…all the four parts. That was very difficult at some point…the scanning which I did later on. I think it was very easy in comparison to the calibration part. Because you just had to take the thing the scanner and uh…and rotate around several circle… circle point so scanning… scanning was pretty easy than calibration I'd say.

He was asked if he liked or disliked the 3D scanning process and what he thought was easy or difficult. He said:

> …I liked it I won't say that I disliked it because um…uh…as I was using it the first time I didn't expect this machine to work so efficiently… and the scan which was solid later on was uh…it was very good so…I think uh…this uh…this very good process scanning…the scanner is pretty heavy so if you had to scan like big parts…and…that can get messy sometimes. Because you're human not a super human…otherwise when I was scanning and it was making those sounds…uh…that was also bet…it was um baffling sometimes. But other than that it was good.

He was not able to tell the researcher what the scooter parts were or where they would go on the scooter that was used. After the researcher explained what the parts were and where they would be located on the scooter he was then asked how he would describe the scanning process to someone in a job interview. He said:

> Okay. Uh…like uh…picked up the scanner and uh…uh…placed it o…over the part. And…I…uh…rotated my wrist in a circular motion a…making small circles and going very slow. And at some points …like three to four times just to make sure that sound doesn't come up that you have missed a point or something…error has been made…so…uh…I made sure I go like three to four times and continue till the end of the part and then I umm…did the sides …both

> the sides and the inside of the part using the same method and some times…I zig…zigzagged the scanner…

The set of questions that followed was about the CGT 163 course. He was asked if there were any assignments or activities from the course that he felt would be helpful in creating a 3D model from the scan data. He said:

> …I think the first time uh…when I was given the sheet to fill out the like…which is the profile which is the frontal surface now…so by that I can…when I am…I get that scan data I can figure out which is the profile or frontal surface…in this…and then uh…by looking at the data like I've made the views and umm…and all that in CGT 163. And um…I can thin…I think that by looking at the scan data I can figure out that how to actually make it in catia or…the program we have used in CGT 163.

The implementation of RE methodology would require research and planning before it could be put into a course. He was asked what he thought would need to be considered in the incorporation. He said:

> …this machine is I thin…I think its pretty easy to use so…uh…I don't think a student will need any before hand before hand experience or explanation bout how to use this machine…so uh…mm…but I still think that if this idea is implemented or…umm…the university wants to implement this idea they'll have to uh…mm…like…mm…make the students practice uh…more and more because more we practice we'll get better.

He had no prior knowledge of RE and said that it was the first time he had heard of the phrase. When asked what he thought about the study in general, he stated:

> …it's good…I mean its helping you out so…I wont say its bad but…it's time consuming sometimes and uh…I did it in 14…14 minutes but those who did it in more than 14 minutes I can imagine what their han…hand situation would be after doing that 53 or 1 hour scanning. It's uh…but it's alright. As long as we're getting grades for this.

He found the scanning exercise to be enjoyable and when asked why he felt that way, he said:

> Because uh…when I came I thought it would be like very difficult to use because I saw it in lecture hall…uh…it was uh…it was pretty difficult to calibrate all the four points the same time…but when I actually used it I found it pretty easy and everything sounded the machine made the com…laptop made…made me happy. So…an…that was all…it was good.

Hands-on activities and textual material are two ways that people learn from. He was asked what method he felt was more beneficial to him. He said:

> Uh…I think uh…hands-on is the best procedure to learn about new things. But, uh…we should also have the…mm…mm…text books and the…the literature to understand that how the process works…it's not that…its not that a person can be given a machine and start working on it right away...they'll just mess things up.

There was nothing he wanted to change about the study but thought it may be helpful to scan more than just one part. He felt that RE methodology would be of great use in his career.

> …as I'm in mechanical engineering…uh…I think that later on I'll have to deal with the design of machines and uh…um…the aerodynamics…uh so I think that if I'm using the reverse engineering process in this designing…3D designing scanning…uh…it would be a….of great use to me because then I can figure out where the machine does not working properly and where the design needs to be perfect so I can minimize the drag of the car or something…designing.

The technology, according to him, was not very complicated and was easy enough to use that freshman or sophomore level students could use it. He believed that students who recently entered the engineering curricula would receive more benefit out of using the equipment. There were factors that he thought would be important to consider. He said:

> …I mean the students ah…should be taught about this process I mean the literature part at least. Umm…that should be um…before they could use this machine. So…they should be given pri…prior knowledge and uh…a procedure on how to use the machine…so that should be…that should be added to the curricula.

There were aspects that he did liked and disliked. He told the researcher:

> …I like most the part because I was learning something new and something, which can be beneficial to me in future…so I like most of it. Only thing, which I disliked as when I had to hold this machine for 14 minutes. That was uh…that was messy because…uh for the last 2 or 3 minutes I was just going to give up this things not going to calibrate I'm just taking time…Most of the part is very interesting and uh nice.

Spatial ability is not something that he felt was helpful during the process. When asked why he felt this way he said:

> The scanning I don't think you need spatial ability. I…I could see..I could see the image right on my computer screen I knew where to go. It was pretty clear so I don't think someone with ah…a high spatial ability can do it better than I can or someone with a lower spatial ability would be able to do worse than I did. It doesn't dep…I don't think it depends on the spatial ability it's just on how well you handle the machine and how well you can see the things going in front or back or something. Simple arrow directions there were so…

The last time he played video games was when he was around 10 years old. The games he played were Mario and other games he felt were simple.

4.3.2.6. Participant 0423

Participant 0423 was found to have a low level of spatial ability. He recorded one of the three slowest calibration times out of all 10 participants. Hobbies he enjoyed included reading and going to the gym. The bracket support part was what he chose to scan during his exercise. A result of his scan can be seen in Figure 4.10.

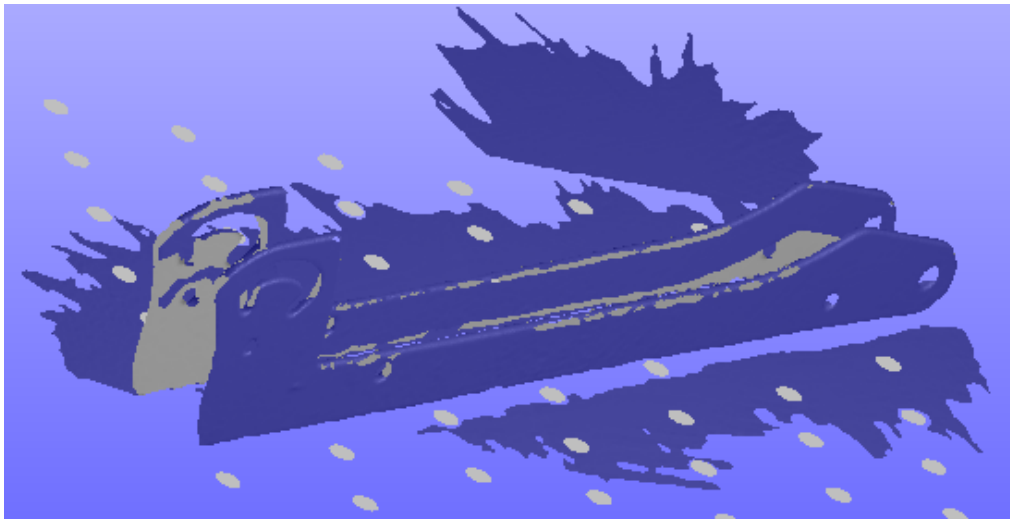

Figure 4.10. Scanning results of bracket support part produced by P0423.

The first question he was asked was whether he thought the tutorial was helpful in completing the scanning exercise. He said:

> Oh it…it can help understand how it works and to scan part and the scan part and also the calibration part um but uh the tutorial material I feel confused about how to connect the parts. Some words are not very familiar I don't know what it they should connect…

One suggestion he had to improve the scanner tutorial was to increase the number of pictures. English was not his primary language and stated that he did not understand the words and that pictures were better for him. There were things he found to be difficult with the calibration process. When asked what he found to be difficult he said:

> Oh uh I think that because I first this is my first time to use It I feel the difficult to particular thing is that uh…uh when I want to move in a certain direction but I cannot control a little bit in other directions so…so that uh so that makes it difficult to match the pattern so that's the most difficult thing for me.

When asked about his level of spatial ability he felt that it was not sufficient. When asked why that was he expressed that he needs help on occasion to imagine the

shape and how to move the scanner. The easiest part of the calibration process for him was the completion of the task. After completing the case he felt that it would be more familiar and he would know how to match the screens more efficiently. He said:

> Also its difficult for me to uh imagine how to move it to match the picture for example I need to rotate it or lift up or move forward or backward so I can not imagine how to move to correspond to correspond to uh the scanner to match it match the pictures.

The scanning process was also difficult for him. When asked what he found to be easy or difficult about the process, he said:

> For the difficult for the difficulty of the process uh sometimes I I easily miss some parts of the object so…I cannot catch all the parts in the object think that's the most difficult thing.

He was asked if there was anything other than the provided tutorial that helped him to complete the study. He said:

> Uh I think your demo helped me when you showed me how to do that so I can get basic idea how to operate it. Also, also from the cgt class its enhanced my ability to imagine object so also not all my spatial ability still not good but its improves because of this class uh yea…

The scooter parts were not familiar to him and he was not sure where they belonged or what the function of each part was. He was asked how he would describe the scanning process to someone who had never used the technology. He stated that:

> I would tell them that first I identify the X point the X part in the scanner for the scanner then I identified the location based on the X on the object and then move to scan anything I need and uh to also I need to move slowly to to get any as many parts as I can and I think that the process for just one side so I need to turn around and turn so I can get the other side and do the same process until I finish scan of the object.

He was asked whether there was any material he encountered in the course that would be helpful in creating a 3D model from the data. He said:

> Oh yea last Tuesday you show us in the pre lab lecture how to use the scanner and so first is how to use a scan to do the calibration part and several classmates tried and I didn't. and then you showed us how to do the scan part yea. And it helped me to get the big picture of how to use about how to use the scanner…I begin to be familiar with it.

When incorporating RE methodology into the engineering curricula there are some factors that need to be considered. He felt there were some factors that were important.

> …I think first the instructors need to demo how to use it and then make students together big picture how it operates also I think also for the tasks that we need to use the scanner its better to give us some process step by step how to use it…also its better to…to talk about some series about…about the purpose of the scanner so we can we can understand why we need to use it. How to understand the scanner… Oh also uh how many equipments can we use in the classroom…such that how many student can use one equipment or how each student can use it… it's the instructors can assign some tasks to do some research about it so students can uh get familiar with it before hand.

He had no prior knowledge of RE and had trouble recalling what it was at the time of the interview. He said he liked the second part of the study. When asked what he meant by the second part, he said:

> The second part is the scan part the scanning part because, because I can I can use it to get each part of the object to make a whole thing that I created I like that. I feel successful when I see it see the whole thing i created by scanning and uh the first part the calibration I also like it but not much as the second part because I felt tired when I do it when I do it and also I need to much force to hold it for me to keep it a certain direction so that's kind of difficult I don't like that much as the second part.

There were no instances he could recall wanting to add more information during an interview or meeting. When asked if he found the process enjoyable he said:

> Oh yea its enjoyable because its completely new thing for me. I never I never touch a scanner before this. So it's exciting for me. And uh so I can learn new equipment I can learn new equipment so…so that broaden my knowledge and uh also and also uh and so I enjoy the process.

Spatial ability was an aspect that he felt played a part in the study. The calibration process was a part he felt benefited from spatial because:

> … for example in the calibration part when we need to imagine how the relation between the moves the move of my hand and the image how to how it moves. I think that.

He felt he learned best from hands-on material. When asked why he felt this way, he said:

> … because when I read a book all the instructions I can only imagine how to do it if its an actual practice I can I can I can know how to operate actually. In practice. So that make me familiar with the object I learn. Also, in the extra practice I can know some mistakes when I do the task by this object I can only guess on theory and that I don't know anything about how to operate it.

There were items he felt could be changed to make the process more user friendly. When asked what he felt could be more user friendly, he said:

> Uh I think uh for the first part maybe for the directions for direction to hold scanner and just once to match just to one time one time of that how you say. We can only uh match the picture once by each direction so its better to uh like twice or third time to hold it in one direction to match the pictures. So its I can get more practice in this direction.

When asked if he would like RE methodology incorporated into the engineering curricula he said that he would because it could, "…make me do some projects more logically." He was asked what course level it would be most beneficial at and he said:

> I think its better to study junior or senior course. Because uh in those courses we feel a push more complex projects. So we need have a clear direction and uh and uh logically to make the project so the RE can so it the RE can become practice how to make the entire thing.

There were factors he felt would be important to consider when incorporating RE into the classroom. He said:

> Oh I think the classroom before you use the scanners the instructors should give clear instruction about how to safely use it. To avoid damage the equipment like how to put it back into the box and something like that. So…yea it's a thing its important equipment…We think teachers need to demo how to use it… I think the cost I think the instructors can get information for the students whether they want to have more scanners or just a few of them or if students wants more the students all the students should be in charge of some cost of the scanner it just the students wants to few scanners they can be in charge of the costs in charge of the last of the cost.

Finally, when asked about what he liked or disliked about the process and whether or not he played video games he said:

> Oh I like that because the same like it's a new thing for me so uh I am really excited to do it because it is so I can I can get new knowledge about how to use it and how to learn the scanner. I say it's a completely different way from catia the way we do it because on this I can we don't need to set the lens or length of the part. Just cause we scan it it will be exactly the same thing. We scan it.

4.3.2.7. Participant 1020

Participant 1020 was classified as having low spatial ability. Some of her hobbies included playing tennis, reading, running, swimming, and cars. She chose to scan the pipe support part during her exercise. The results she produced can be seen in Figure 4.11.

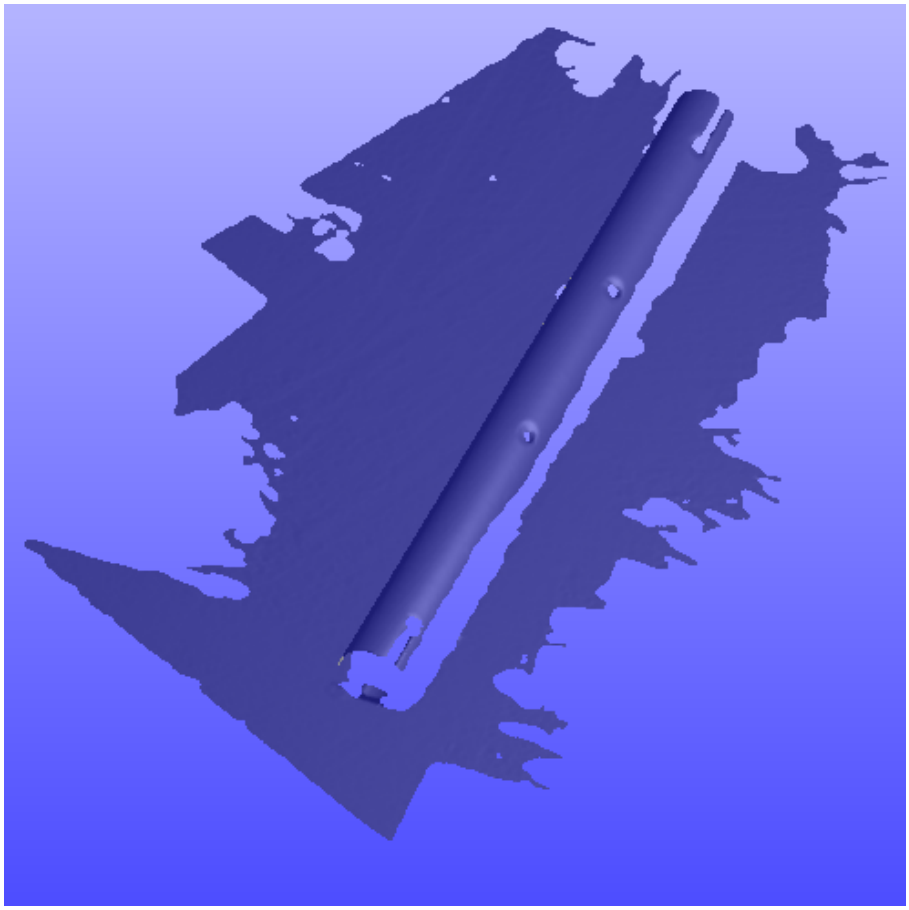

Figure 4.11. Scanning results of pipe support part produced by P1020.

She was asked if she felt the tutorial was helpful and if there was anything that she would change about it to make it easier to understand. She said:

> Um to visualize about through a lot of processes setups after a while you just got a hang of it… Probably not make it look less sensitive I would make the arrow kind of tell you which ways to go. Understand that a little bit better.

She found that trying to line up the different parts on the calibration screen was the most difficult part of the calibration process. Matching up the X on the plate to the X on the screen was the easiest part for her. She also felt her spatial ability needed

improvement to use the scanner. When asked if she liked or disliked the scanning process she said:

> I liked it…A lot easier than the calibration…Very easy to do.

When asked what she thought was easy or difficult about the scanning such as the weight of the scanner she said:

> Yes because of wider you can stand over it a lot easier than have to do that much movement…The weight of the scanner.

She was asked if there was anything she did that helped her to complete the scanning process besides the tutorial. Playing the older Nintendo video games was helpful to her in the process. The scooter parts were understandable and when asked to describe where they went on the scooter she said:

> The one I just scanned would probably be the part where the handle goes where it connects to the thing. That one is obviously the footrest.

When asked to describe the process to someone who had not completed the process before she said:

> Try to line them all up try to visualize how they would look… I sufficiently used advanced technology to be able to visualize to use spatial abilities in order to scan particular objects.

She felt activities that could have helped her in creating a 3D model were drawings that she encountered in class because they helped her visualize. When asked what she felt would need to be considered with RE implementation she said:

> Guess just practice on it. Do examples before you lecture through it…training people.

The concept of RE was familiar to her. She said that she had encountered it before:

> For intro to engineering design we had to take apart a pen design the parts and putting it back together.

Her general opinion of the study was that she liked it. When asked to describe why she liked it she said:

> Um it brought a new viewpoint um computer graphics a little insight into the different parts of engineering.

She found the scanning exercise to be difficult as far as calibration but felt that the scanning process was easy. When asked what she found enjoyable about the scanning process she said:

> Just had to make sure you scan the entire part didn't have to worry about lining up anything together just trying to get it all scanned.

Hands-on material was the best way she felt she learned material. When asked why this was she said:

> Someone actually doing it with me showing me how to do it. Just reading it was confusing.

She did not feel anything needed to be changed in the study and her thoughts were "very favorable" when considering the incorporation of RE methodology. She said:

> Because its part of engineering you have to take stud apart and learn how it looks and still be able to put it back together.

The technology, she felt, would be best implemented into a junior or senior level course. She said:

> Because I have very little experience in this type of thing and I'm pretty sure by the time I'm a junior or senior ill have more knowledge thus more skill on it.

There were only two factors she felt needed to be considered. When asked what she thought should be considered she said:

> Making sure the students know. Making sure the professors actually have background in it so they'll actually be able to help the students.

The researcher asked her if she liked or disliked the experience and she said:

> I was confused at first. Especially with calibration but then toward the end it started to make more sense.

The scanning part is one she found to be enjoyable. She also felt that spatial ability helped her. When asked why she said:

> Just thinking about when you are holding the scanner kind of puts things in perspective.

4.3.2.8. Participant 1021

Participant 1021 was classified as having high spatial ability and had one of the three fastest calibration times of the 10 students who completed the scanning exercise. Swimming was one of his hobbies. The bracket support was the part that he chose to scan during the exercise. The result he produced can be seen in Figure 4.12.

The first question that was asked was whether he felt the scanner tutorial was helpful to him in completing the scanning process. He found the tutorial to be unclear at first because it was not easy to understand. The researcher had to help him in understanding the tutorial and what certain terms meant. The main reason it was hard for him was because there were a lot of words and he claimed to just be too lazy to read

them. When asked if there was anything he would change about the tutorial to make it more understandable he said:

> …I would say…I would…get more screenshots…more pictures for each step so…I know where…where I need to take the …so the tutorial read to much stuff. I can be more quick to um...move forward.

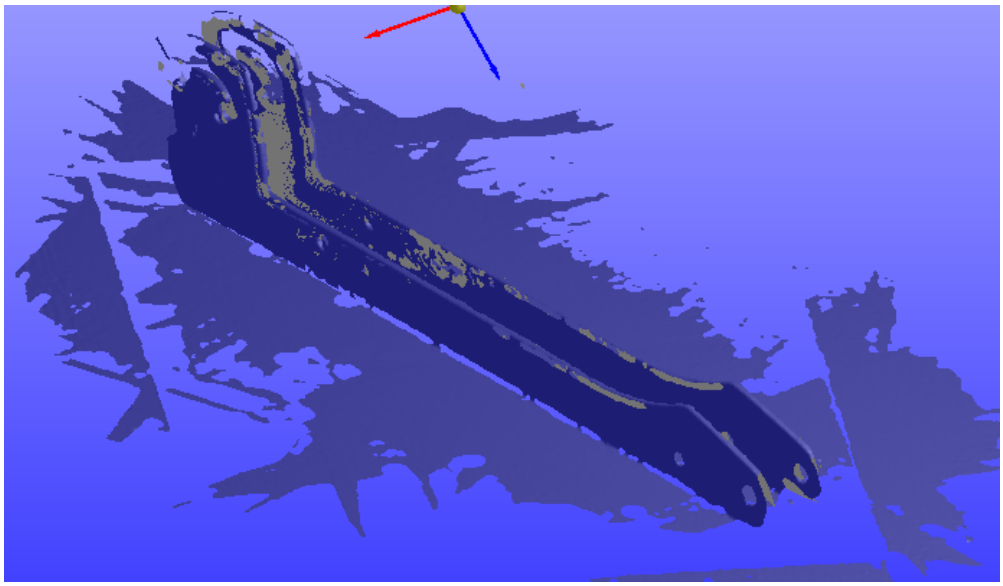

Figure 4.12. Scanning results of bracket support part produced by P1021.

Calibrating the scanner came fairly easy to him. At first he confused the idea of calibration with the idea of scanning but finished by saying he found it to be pretty easy to do. His level of spatial ability, in his mind, needed to be more advanced. When asked to elaborate as to why, he said:

> …in the first time I….do the stuff…for the fist time I do this stuff…and…so I need to learn to know more stuff. It's…for this time…uh…it's like I scan something…simple parts like the…like that…like the model that…if I give me a really complex part it'd be…really tim…time consuming.

The easiest part for P1021 was moving the scanner into the correct position. The hardest part was the weight of the scanner. His arm started to hurt from holding the scanner. He liked the 3D scanning and said:

> I like it…because it's like…new stuff for me and…I can actually…generate some knowledge about the…the scanning. So…after this…after this time I…I know how to move the scanner. Actually…cause I really did.

There was nothing that was found to be helpful other than the tutorial in the scanning process. He understood the scooter parts and their placement in the assembly of the scooter. When asked to describe the scanning process to some new to the technology he said:

> …I would just take the scanner and show…cause it…it is effective. Take the scanner show the person. So I can make the ra…it's like the ra...uh…tutorial.

The researcher asked him if there were activities in class that could help in creating a 3D model form the collected data. He said:

> …I am taking the CGT 163…That class is more about 3D drawing umm…the…I don't think that class teaches how to mo…teaches much stuff about the…real scanning. So…mmm…that class is helpful for uh…draw…drawing from a…three dimensional wheel…gra..but not the scanner…scan not the 3D model.

The implementation of RE was not something that he was sure about and he had no knowledge of RE prior to being introduced to it through the CGT 163 course. His general opinion of the study was unclear. When asked if he found the experience to be enjoyable he said:

> Yes it is enjoyable and…the reason…I'd say is that…umm…I can learn from…I can…learn from stuff by learning to do it right.

Hands-on learning was the preferred method for him and said if he can do it he understands it better. His one suggestion for changing the study was to add more screenshots of examples to the tutorial. When asked his thoughts on implementing RE into engineering curricula he said:

> …I'm mechanical engineering and…for mechanical engin…engin…it's like this kind of stuff…is for mechanical engineering technology. So…ummm…but for me this kind of major should be…should have attain certain knowledge about the…I don't nee…I don't think I need to learn it that deeply.

First year engineering is the level at which he felt RE would bring the most benefit in education. He claimed that it was not very hard and that it was time consuming which is why he felt it would be better in first year engineering. When asked what factors he felt needed to be considered he became confused and did not understand the question after elaboration was given but he did feel spatial ability helped him. When asked how it helped he said:

> …how the reverse engineering do…and…ho…how to take the scanner and take it into the software as a model.

Video games were something he did enjoy playing. The games he enjoyed included StartCraft 2 and Call of Duty Black Ops.

4.3.2.9. Participant 1521

Participant 1521 was classified as having high levels of spatial ability and had the fastest calibration of all 10 participants. Hobbies he had included playing sports and playing guitar. The pipe support part was what he chose to scan and the results from his scanning process can be seen in Figure 4.13.

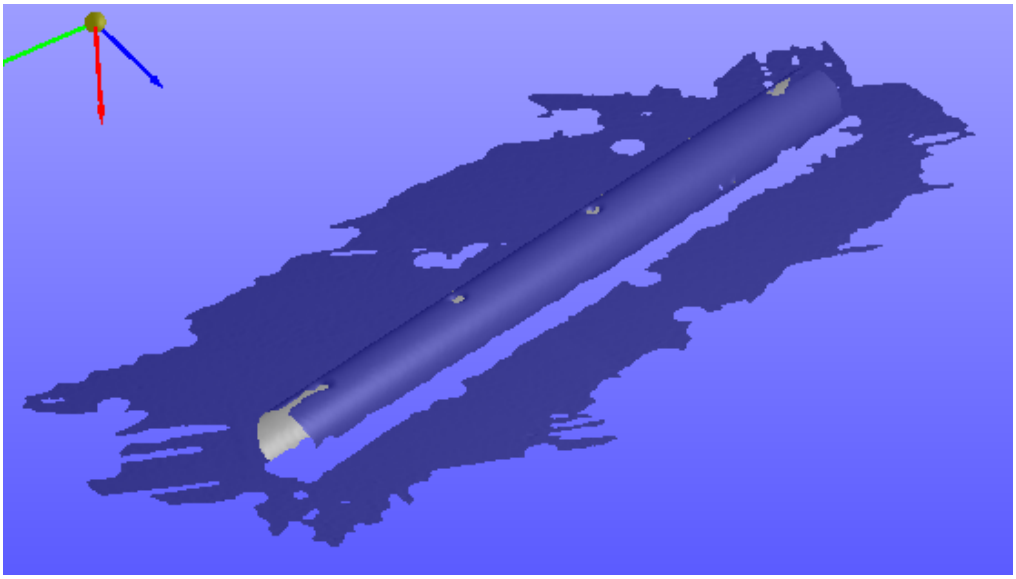

Figure 4.13. Scanning results of pipe support part produced by P1521.

P1521 read the tutorial that was provided to him prior to coming in for the study. Reading the tutorial ahead of time helped him to eliminate confusion when he began the study. He felt the tutorial was pretty good overall and said:

> Uh overall it was…uh pretty good. I think it would be nice to have a little more detail on the scanning of the object part. Umm…it mentions circular motions and then also mentions zigzag motions but not a lot of clarification on what they mean or how to…proceed with that.

The calibration process came pretty easy to him. His spatial ability was advanced enough for the exercise. When asked what he liked or disliked and about spatial ability level he stated:

> …I feel I did well. It didn't take very long. I didn't really have any uh…issues that were tough to overcome…I think it was definitely sufficient. Umm…I was able…to kind of look at all three screens at the same time. I know the tutorial says like…recommends going like looking at one matching the one matching one then trying the…the…the X I guess but I was able to view all three screens and get all those lined up simultaneously while watching the target move so I think that

> helped things a lot…figuring out exactly what the…the screens meant as far as the arrows and objects moving on the screen umm…once I was able to figure out what uh…how the arrows were oriented and what they were umm…indicating uh…it was pretty straight forward from there.

The scanning process was enjoyable for him and he did voice a concern he felt could be a drawback to the experience.

> I liked it. I guess only one of the drawbacks I found to it was that at least for me it…it felt like the we…like hold the handle and pulling the trigger that where it was actually targeting was not exactly lined up as…only thing to say like if it was a gun I felt like it would be shooting low…and that also could be just the…the heavy weight of the head pulling down so I felt as if it were shooting low rather than it actually doing that but a little bit of struggle with that. Yea like I said the weight was uh…a little bit of a factor. It's not a very balanced uh…weight distribution through the object so you constantly having to exert a force to pull uh…to rotate it backwards just to keep it level since the head is the heaviest part.

There were some aspects that he felt could have helped him during the scanning process. When asked to elaborate on these factors he said:

> …I've been told I have really good hand eye coordination. I've done a lot of work in a…like wood shops umm…on various projects so I've used different power tools. I feel like that helped a lot with the keeping my hands steady or being able to orient objects the way I wanted them to.

He fully understood the scooter parts that were involved and knew where they belonged in the scooter assembly. He said:

> …the pipe would be the shaft going up to the handle bars. And then the other object would be the main support secured to the eh…I don't know where you call it the place where you put your feet to stand on. The attachment point to where it would pivot when you close it.

His explanation of how he completed the process, as if he were explaining it to someone new to the technology, was detailed. He explained:

> I would just start off by explain exactly what it was a small hand held device with a trigger it was a target the object umm…plug it…plug it in the computer the wall outlet. Go…go over all the just physical connections then calibration process with the different targeting platform. And umm…then what's involved there as far as the orientation on each of the screens and what they show. And then any tips or tricks that I've learned through doing it. Umm…and then cal…the actual scanning o…it's just basically uh…you just going over in the slow steady motion the object that you want to scan. Um…obviously having to rotate move around to get all or as many sides and views as possible. And as many data points as possible to make the clean-up process easier. Then as far as the clean-up process goes just uh…saving the stl file and then importing it into RapidForm program. I believe that's what it's called and then using a…the various tools in the program to find any of the geometry recognizable parts and remove any of the features that aren't needed.

There were activities he felt would help in the creation of a 3D model. When asked to elaborate he said:

> …obviously the lecture where we got to see the 3D scanner helped a lot. Umm…reading the tutorial helps for sure but it…it definitely is a benefit to actually see the object in action it looked cool in action. Umm…as far as the…the assignments go it's helpful seeing the objects before and be familiar with what I will be scanning. Is that? What's the next part of the question that have everything…well we just have a…reverse engineering pencil project. And that's helpful because up until that point all the assignments have been umm…the object was already known all the dimensions were known and with the pencil there's a lot of unknown going into it so you have to be able to see the object and kind of uhh…comprehend how it all goes together. Umm so that would help with being able to find the primitive objects within the object you scanned and figure out the best ways to take your cloud point scan and turn it into an actual object.

He was asked what factors he felt would be important to consider with RE incorporation. He said:

> …well honestly I don't know if everyone would be able to use this tool just because of the hand eye coordination involved with it. It's a skill that not everyone possesses so…while they may be talented in the model part the scanning part might need to be done by another individual. But as far as implementing into the curriculum I guess uh…I think maybe in…interactive tutorial might help. Maybe just the same tutorial umm…just in electronic form and maybe a video. Similar to just being able to watch it in lecture as we talked about.

When mentioning a video he was asked what material should be covered in the video and what could make that video successful.

> …the calibration process. I think if there's only one thing you could see that would be the most umm…beneficial in my opinion. Just because it goes through all the different rotations and movements of the scanner and then how the computer picks up what you're actually doing do I feel like once you're able to complete the calibration process that you have enough experience to be able to get through the scanning of the object process.

Reverse engineering was unfamiliar to him other than what he learned in lectures and other simple tasks. He elaborated by saying:

> Well through the CGT course umm…I was exposed to that through the various lectures. Prior to that course never really knew of any reverse engineering processes other than just drawing a picture from what you see. Actually didn't even know if 3D scanning was a technology that was available. I actually wa…thought it might have been more of like a sci fi thing or something they talked about as naïve as that sounds. But yea…so I guess just over the past few weeks or month I guess I've been exposed to this. I think in a little bit of experience in that concept.

His overall opinion of the study was favorable. It was "an opportunity that not everyone gets to have. It's why I agreed to do this." The experience was valuable to him and gave him an experience he could talk about in an interview to a future employer, which he thought was "…pretty awesome." In an interview situation he said he tends to feel good about everything he says and does not feel he leaves anything out. The experience was positive for him and felt it was enjoyable. When learning methods are

considered, he tended to learn well from both hands-on and text based material. When asked why that was he said:

> …that's actually something I'm not quite sure about I do learn with both. I have somewhat uh…photographic memory so I can read over text and then recall information from it. Umm…A completely later point in time so I do learn from text but…but I also the hands on is very well and doesn't require as much strenuous brain activity cause I …I feel like through all the sports that I've done and all the various activities hands on I'm pretty good with my hands.

There was nothing about the study he felt needed to be altered. When he was asked about his thoughts on incorporating RE and what grade level he felt would receive the most benefit he said:

> I'm not sure if there's any courses that do it all but…it would be cool to have maybe smaller CGT classes since it would be hard to get so many to use it. Have uh various assignments where they had to go through the entire process of scanning an object and then doing the clean-up and then have that clean-up object they created be the assignment they have to turn in and have various times maybe a lab set up where they can go and scan the objects and then all the projects be based on an object that was already in existence. As far as this basic level of going over the process I think it would be fine to implement in the first year. Maybe not get too far into the uh…RapidForm part of that or any of the…the clean-up process the details. But as far as them just being familiar with the calibration and the scanning part those are relatively basic and it's nice to have exposure to things before you're thrown really far and in depth into the topic so I think first year would be fine.

There are multiple factors that could play a part when placing RE methodology into a course. When asked what factors he felt were important he said:

> Biggest factor I would see would be expense of the equipment and then also a…safety of the equipment. Isn't exactly something that you want being tossed around a classroom it should be taken care of very well. And obviously the more people that use it the higher risk you run of it being damaged or broken so that's where the cost would come in. There would have to be a way to heavily monitor what's happening to the scanner. I think that would be probably the biggest obstacle.

He was asked what he liked and what he disliked about the scanning experience and if he felt spatial ability helped him in the process. He replied:

> Well I guess that I like the opportunity and experience that I get from it. Now I'm able to say that I have used a 3D scanner before. Even though it might be very limited experience as far as the…the time that I spent doing it goes. Umm…I am familiar with the process and I wouldn't be completely in the dark if I was ever asked to do it again. Uh yes 100%. Spatial ability was…what allowed me to calibrate it umm…in such a short amount of time. That was how I was able to look at the…the various calibration screens and judge what I was doing and how it translated onto the computer screen and what the computer thought I was doing. And then like I said, I feel like that if you have the skills to calibrate it then that generally translates over to the skills to scan an object.

When he came to college he stopped playing video games but he had played them in the past. He concluded by offering additional comments:

> Well I mean I guess since you asked the video game obviously trying to see if that correlates to skills in the calibration scanning. I do feel like my sports experiences really helped I play football, basketball, and track all four years in high school so umm…a lot of various motor skills that required through sports I think helped a lot.

4.3.2.10. Participant 1524

Participant 1524 was classified as having high spatial ability. Reading and sports were two of his main hobbies. When given the choice of which part he waned to scan he chose to scan the pipe support. The results he produced can be seen in Figure 4.14.

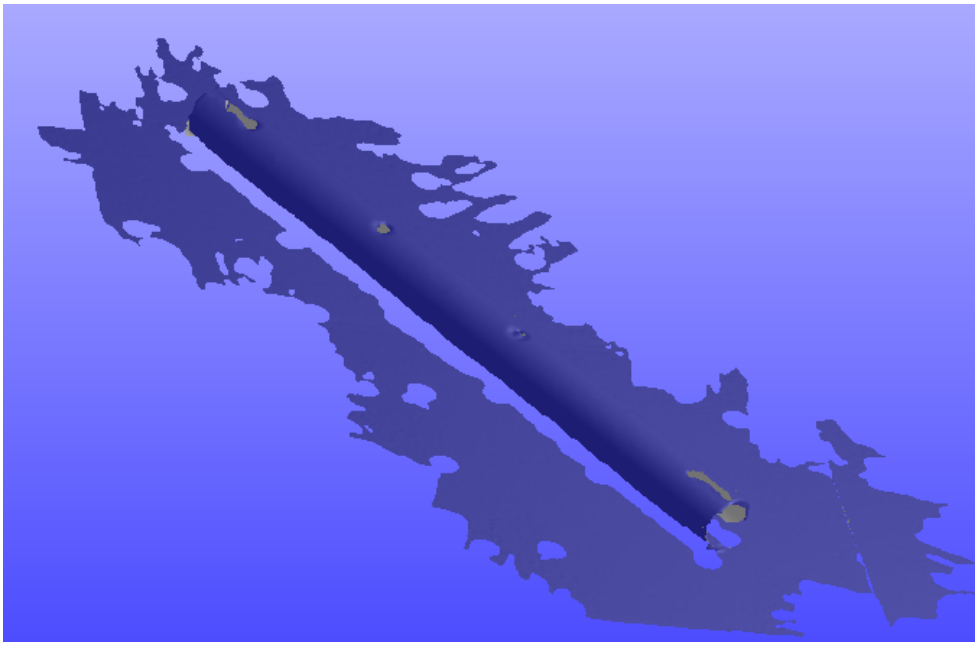

Figure 4.14. Scanning results of pipe support part produced by P1521.

The scanner tutorial was helpful to P1521. When asked why he felt this way he said:

> …It shows me how to use the scanner and…how to use the software to start…to start scan things will want and…yes…I think that's it.

There was one thing he felt would help in the tutorial and that was to add pictures to make it clearer. The scanner felt heavy to him, which made it hard to complete the calibration process. The level of spatial ability he had was something he felt needed to be more advanced to complete the exercise.

> During the calibration I feel really terrible when using the scanner. The scanner can…can be much lighter that would be better for using for long time when scanning the easiest one I think is the scan…figure out…after figure out how…how to scan it. It…it is really fast to use the scan...uh…object that you want…I mean the part the thing you want to scan.

The scanning process was something that he enjoyed. When asked to elaborate on why he felt that way he said:

> …it's like use a gun to shoot stuff…it's umm how to say…uh…when I do it I'm interested in that…I think umm…it's not just like use the software to draw something you just use the scanner and scan the parts and then you can see a part is showing on the screen. It's really interesting.

When asked to describe what the scooter parts were and he became confused. It is unsure what the reason was but he was not able to explain the parts or how they could be assembled. He felt that there were items that could help in creating a 3D CAD model. He said:

> …so what would I use is the…the RapidForm…yea the RapidForm…uh…so…by that software when you finish a scan a part it will create the…the umm…the parts you completed automatically so uh…it's really easy and it…convenient it's not like Autodesk or catia cause these two softwares you need to uh sketch in 2D…in 2D model first and then create it to a 3D model. Mmm…so uh…compared with those two softwares the RapidForm is really coun…intended with processing. And also…ah…we'll us…if you use the scanner to scan something you don't need to change the uh…the type of the …ments hat you scan with RapidForm you can just open it but if you want to use other software you have to change it.

There were factors that he felt would play a part in RE implementation. He felt the university would need to buy multiple machines and that students would need to use them regularly. Other than lecture material that was covered during the study he had never heard of RE before. He did enjoy the experience. He said:

> Entire study…mmm…it's really interesting and learn a new thing in a wa…and it would helps me with future I think and also I know a new software for creating 3D model.

Hands-on exercises were the way in which he learned material the best. There was nothing he felt needed to be changed about the study and liked the idea of having RE in the classroom. First year engineering is the level at which he felt the technology would be most beneficial. When asked why he said:

> …cause I think freshman they have a lot of…lot of time to do some uh…extra…extra works and then when they just come in to the college and see some new things they will interested in that and they can use it for a long time in school cause…cause they still have uh…other three years to use that one…if you just know that in junior senior the…the time is too short to…to like…to use the new…new thing.

Training was the factor he felt was important in the incorporation. He did play video games that involved racing, sports, and first person shooter scenarios.

4.3.3. Secondary Interview Responses

The second interview was given as a chance for participants to provide any information they felt they did not provide in the primary interview. The majority of the questions are very similar to those of the first interview. The following sections give specific information provided by students involved in the 3D scanning experience. Only information that was not given during the primary interview will be given.

4.3.3.1. Participant 0101

Participant 0101 felt that the scanner tutorial was helpful to him and that it was effective in learning the technology. Spatial ability did contribute to the calibration

process that he completed. The 3D scanning technology was something that he enjoyed and found interesting. One thing he thought would be interesting in the future would be to scan something larger. When asked if he would recommend the study to other students he said:

> Yes. Because um…I personally believe um…that students would learn um…more if they used this technology and like they use it hands-on rather than just uh learning it through lecture slides. Because uh…because whatever you're taught about this it actually turned out to be quite different.

He determined that the process was relevant to CGT 163. When asked why he felt this way he said:

> Because CGT 163 is basically a class which is…which it teaches you the basic concepts of computer graphics technology such as now we have been drawing sketches and using software such as ProE or Inventor or CATIA. So…I would say this is also another good aspect, which can be taught to students.

Where CAD software is concerned he felt that RapidForm was more difficult than the software that was used in the CGT 163 course. This was because the software was new and unfamiliar. He was asked if he would like to take a course involving RE methodology and RapidForm software. He said:

> Yes I would like to. Because I find this concept really interesting and this is something, which I have never done before.

There were factors that he felt would need to be considered. When asked what factors he felt were important he said:

> The first one I think the cost would be a major factor. Secondly um…making technology available to each and every student would be uh…a huge task. But at

> the same time the benefits of in…um…incorporating this technology I think are a lot.

The secondary interview was found to be beneficial for him. He asked why he felt this way and he responded by saying:

> Because it…it allowed me to think about the aspects which I was not able to …think about right after the study so I think it helped me give you a better an …that's what I think.

An important thing to consider when creating any course is to ensure the information covered in the course is relevant to a student's future career. To determine if he felt he would benefit from RE methodology he was asked if he felt RE would help in his professional growth. He said:

> Yes definitely I think it would help um…make if uh…if Purdue comes up with a class in this particular technology and then I see myself taking this class and um…getting to know more in detail about the technology and then applying it uh…during my uh industry career.

Materials and information that is covered in a course can come from a variety of places. When asked what he would like to have in the course he said:

> …I would like to like…more in detail about 3D scanning but at the same time I would also uh…like to learn about the other methodologies…I would say first of all uh…having all the car parts scanned and then making a car from them.

There were two factors that he felt would be important in RE incorporation. When asked to reveal those factors he said:

> Cost, first of all whether better uh…students would like to use this technology or not cause classes like CGT 163 are huge.

4.3.3.2. Participant 0124

Participant 0124 felt the scanning tutorial was helpful and recommended small changes such as eliminating sections that may not be used and spelling errors. He felt that spatial ability did contribute to the process. The scanning experience was enjoyable to him overall because he learned something that was new that helped him gain experience with the technology. When asked if there were any products that should be used in future 3D scanning exercises he said:

> Maybe we can scan a wheel or parts we…we use uh CAD software to produce in the…in the class.

His recommendation was that other students participate in the experience to learn a technology that they could use in their futures. The RapidForm software received a positive review and when asked why he liked it he said that it would be helpful in creating the model that he wanted. The experience involves processes that are introduced in the CGT 163 course. He was asked if he felt the process was relevant to the course and he replied:

> Yes it is cause in CGT 163 we build up the sketch model we want and the scanning can…the scanning technology can help us to get the models of the…of the…of an actual part which saves time and help us to make the part more specific.

The RapidForm software that was introduced during the study, he felt, was similar to those used in the course. When asked how he compared them he said:

> I think that it's pretty different cause RapidForm is used after we uh…scan a part we want but for the software we use in class is…is the software we use to build up the parts that we…we thin…we think in our head.

A course involving RE methodology and RapidForm software was something that he was interested in pursuing if the opportunity were to arise. He felt that it was relevant to his ME background and could help him when creating models. When asked what factors he felt needed to be considered when creating such as course he said:

> I think the…the first important thing you should consider is the cost cause the scanner seems kind of expensive so it…an…there are lot of students in Purdue so if they're gonna involve a classroom with the scanner they should consider cost and also they should take the students ability into uh…consideration because the scanner is not that easy to use they should have ability to view the isometric tops and they have to have a basic ability of the calibration.

The knowledge he obtained throughout the duration of the course was helpful to his completion of the process when it came to sketching and creating a model using 3D CAD software. The experience was something that he enjoyed because he had an opportunity to use a new technology and gain experience in a new field. The secondary interview helped him to gather his thoughts and better answer questions that were presented in the second interview. His professional growth is another aspect he felt gained benefit from the experience. When asked why he felt that way he said:

> Yes it will help that goes in my major cause reverse engineering was…uh…the…production process of a specific products or part and in my major I…I'm a get involved in producing a…a machine or a design process by learning about reverse engineering it will help by having…in studying my major.

A course involving RE could entail countless amounts of resources, references, and materials. He was asked if he would enroll in such a course and what projects he would like to see. He replied:

> Oh involving a course that has umm…several methods cause. Reverse engineerings can be one part and lets do something else would need to learn about the…the reverse engineering not just the reverse engineering. I think a project of

> 3D scanning is really enjoyable cause I'll…I learn a how to use it and how to scan a real parts by using this type of technology. So…I think I…it is really enjoyable cause I got a new experience.

During the interview he was asked what aspects he felt needed to be considered which were similar to the factors he mentioned before. He said:

> …an aspect that need to be considered is the cost of the…of involving this technology into a class and also the instructors need to consider the ability of…of the students that taking…that take the class. And…also they need to find other materials to uh…technology that students can also learn about…

4.3.3.3. Participant 0323

Participant 0323 found the tutorial to be helpful and felt that nothing needed to be changed. Spatial ability was an aspect that he felt helped with the calibration process and said the hardest part was lining the picture views. The scanning portion of the study was something he found to be enjoyable and said, "…the scan…itself was very cool to look at and very innovative…" and felt there was nothing that would help that the study did not cover.

Determining assignments and projects for a course can be an important aspect. When asked what type of projects he would like to see he said:

> Something a little more complex maybe like a toy or some sort of…or something a little more complex that can let me see a shape or a body form.

He had an interest in taking a course involving RE methodology. His reasoning behind wanting to take an RE course was because:

> …reverse the concept of reverse engineering itself is very interesting and plus we take courses like CGT and machine design because we need to learn how to make

> stuff…design stuff so reverse engineering can come into that and if we can practically use latest technologies it's…better.

When asked what factors he felt would need to be considered in RE incorporation he was given examples such as cost, time and experience of the students. He said:

> I think all three of them. It takes a long time to get the calibration right and then scanning and if you have a lot of students doing the same thing it's gonna take a long…long time to get everybody done with the scanning…and uh…I know the…the machine itself is very expensive so you need to have multiple machines to get all the students the experience. And the students' skills if someone doesn't handle it right or if somebody doesn't get the concept right it's going to be a huge hassle.

There was knowledge that was obtained through the CGT 163 course that he felt was helpful during this experience. He felt the study was very interesting and helped with visualization. The second interview was helpful to him because he was able to give more input when questions from the first interview were repeated. Growing as a professional is very important while completing a college degree. When asked if he felt this experience helped with that growth he said:

> Yes it will, we're all engineers and I'm doing mechanical engineering and yes it will. Because if after I design something I will generally design something to make it better so I need to know what mistakes the previous people did so I can make it better.

There were projects and aspects he felt were important to incorporate into an RE course. When asked to elaborate he said:

> Maybe umm…you give a complex machinery and over the semester you reverse engineer parts of it and finally a project is to put it together. Time, cost, maintenance and use, faculty training again. And umm…I also think that umm…not…not all courses really need reverse engineering.

4.3.3.4. Participant 0417

Participant 0417 had a positive experience with the tutorial and felt it was easy to follow and covered all necessary material. The tutorial, he said, made it easy to understand the scanning technology at a basic level. Measurements four through 10 were the easiest for him, which involved simple X, Y, and Z coordinate movements with no tilting involved. The experience was something new and different for him, which he enjoyed and he did not dislike anything about the process. When asked if there were any products he would like to see in future scanning exercises he said:

> …not sure. I really can't think of anything like the scooter…scooter was really interesting and cause it's pretty simple overall but it has some intricate parts to it that so its like you can see quickly which close to see detail on sorry can't really think of anything off the top of my head that would be much better than the scooter.

The experience was something he would recommend to other students and when asked why he felt this way he said:

> I would definitely recommend this to my friends. I talked to one of my friends about what I did in the study he's not in the study so it was like just what I did and everything like that and he…he was kind of jealous that he didn't sign up for it so uh I definitely recommend to the people it's a fun thing to do and it was interesting giving you a new experience within a class that I'm taking right now…

RapidForm interested him and he had the desire to research it more so that he could learn the software. The process was relevant to the course in his opinion and felt that the RapidForm software was more complicated than what they used during the course. Because it was related he had an interest in taking an RE course. When asked why he felt this way he said:

> I definitely would I think that it would be really interesting, be fun to take, and it would really pertain to like I'm going into engineering so it would really pertain to what I'm trying to do cause not everything made out…out of someone's mind it's improving on something that's already been made so…it…it would really pertain to what I'm doing…what I want to do too so…

After expressing interest in the course he was asked what factors faculty would have to consider when implementing RE into the course. He stated:

> Well it's an expensive piece of equipment to use scanning or anything like that. Uh…so I would…and you'd want to be careful that every group got to participate so I mean there are a lot of students in engineering and even the higher level engineering courses there's quite a few students. So if you only have one scanner to go around it would be hard to every group to really get full benefit out of it and if every group can get a full benefit out of it you're gonna tend to have every group get an equal share which means no one gets a full benefit of learning about this. You want to make sure you have whether you're doing it in a freshman level course or higher level course you want to make sure you have enough that everyone can use it equally and get everything that they can out of it which I mean the cost of these things would make hard for us engineering school as big as Purdue to get enough for…

In general he enjoyed the study and had previous experience with RE while attending high school. Having the second interview allowed him to give more information and really think about what he wanted to say in response to each question. He expressed in the second interview that he would have liked to complete more scanning exercises to learn more about the technology. He felt the experience was beneficial to his professional growth. When asked to elaborate he said:

> I think it'll help me…uh…I directly want to go into engineering and portion of the engineering that I'm really interested in is…really t…taking what other groups have done and trying to make it better in this…like I want to go into proportion for aeronautical engineering and there's only so much you can do with a jet engine so I'd like to try tearing apart like what I would be doing would be tearing apart others and like figuring out how there's worked better than ours so

> we can do it better than them so like reverse engineering is directly what I want to do so…this has helped me a lot with my professional development.

The idea of taking a course involving RE was something he was very interested in. He said:

> I would definitely that'd be very fun course to take I think. It would be directly pertaining to what I wanna do and something that I enjoy doing so…I would definitely take a class like that.

There was a project he felt would be really interesting to complete using RE methodology and aspects that would be important with RE incorporation. When asked what those were he said:

> I think trying to figure out how something new works umm…take for example there's a uh…a technology it's a water jet pack that uses a jet ski to uh…force water up a hose and shoots out a jet pack and a guy can go tooling around a lake 30 feet above the water 40 miles an hour…I think using uh…pictures of possibly even getting your hands on one trying to figure out how that works because it's a new technology they only people who know exactly how it works are the people building it. I think that would be something that would be very interesting to reverse engineer as a class kind of thing just separate the parts like you…have this group work on backpack and this group…group work on the jet ski itself kind of thing. The cost that it would take to make sure every student got everything out of it…like I said earlier you can't just use one scanner like even for a higher level course that only has 20…30 people on it you…so you…gonna need to think about how many scanners you're gonna need and what's the cost of that gonna be…because the amount of scanners is gonna be important to whether the students really take away everything from the experience.

4.3.3.5. Participant 0421

Participant 0421 found the tutorial to be helpful while completing the scanning exercise but felt there were certain sections that needed elaboration and more steps.

Spatial ability was not something he felt helped with the experience very much because with what he considered to be average to low spatial ability he was able to figure out what to do with what he was given on the screen. He did like how efficient the machine was but did not like when it tilted down slightly and made a warning sound saying he was too close or too far away. The study was something he felt was very good and when asked what other products he would like to use in the process he said:

> …I mean it will uh…a machine which is like complex to uh…design in CGT uh…uh…I would say. Mm…mm…like um…engine parts or something which are like complex to uh design in CGT…I mean CATIA or something…

When asked if he would recommend this study to others he said, "Yes I would. I certainly would." He also said:

> Uh…because later on when uh…when they are like in their junior or senior…I mean junior senior in uh…or when they're working they might come across uh something like this when they…when they have to scan it to…to design a model or something so this will be a very good first time experience and can help the future. They're future.

The software was something he thought was easy to use and understand and wanted to take a course involving RE. He said he felt this way because:

> …first thing I would say is that it's easy and it's not much time consuming. Like when we use…the CGT…the CGT software like CATIA autocad…autocad something they like…uh…I almost had to spend more than like 2 hours to do the…the scooter part that I did in like less than 10…15 minutes when I was using the software so I would say it consumes less time and gives almost the same result.

There were factors he felt were important with this type of methodology incorporation. He said:

> …cost is also important factor and I would say not time because the machine is easy to use I mean uh the time we spend outside lab to make…create all the CGT assignments we are given and its pretty high and uh we can learn this machine in almost no time so umm...first thing I think that is cost the machine is expensive and uh…like more than 200 students take CGT 163 every semester so…uh…to with that amount of people we have…we have to have machine for every 5 or 10 people to uh…for them to uh…I mean to work in lab simultaneously so I think cost will be important factor.

There were activities from the course that did help him with the activities and felt there was a lot of benefit to the students in completing the study. The second interview helped him to understand the exercise better because he had more time to think over what he completed and analyze it in a more detailed manner. Some items he expressed a concern about were the size of items you could scan and the time it would take to scan something that was larger. Even with the concerns he felt that the process was beneficial to his professional development. When asked to elaborate he said:

> Uh…I think so…it…it's uh nice to it will certainly come to use uh in…in my future when I'm doing some modeling stuff because I'm in mechanical engineering I'll be …I'll have to design certainly say like cars, engines that I …I have to look at the drag it has or something so…I think yea it will be helpful.

Enrollment in an RE course was something he was interested in taking part in and wanted to see more complex parts being used. Aspects he felt were important were:

> …the students uh should be given a basic idea of what this is like uh like we were given lecture…uh…in CGT 163 so basic idea what reverse engineering is…uh what machines to use and how this is…helpful and uh…stuff just like that…stuff such as that so…uh…so that we could get a basic idea of reverse engineering before using this uh machine or something.

4.3.3.6. Participant 0423

The tutorial was something P0423 found to be helpful during the process. Adding pictures was a suggestion he voiced should be considered with regards to the tutorial. Having a step-by-step process was something he liked about the structure of the information he was provided. Spatial ability was another aspect he felt helped with the scanning exercise.

The 3D scanning technology was something new that he enjoyed using and felt he got more information from the process to help in visualization. The materials provided covered everything that was needed to complete the process, he felt. He did suggest that the objects used in the process could be more complex to understand a more complex structure. The experience was something he recommended other students have the chance to participate in as well because he felt the spatial ability could help with learning involved in CGT 163.

The software used in the course was more complex in his opinion than the RapidForm software that was used. His opinion of the software was positive and he enjoyed using it. The idea of taking an RE course was appealing to him and he felt he could learn a logical way for him to complete methods. When asked what factors he felt were important to implementing RE into a course he said:

> …the first thing would be the cost because it's…it is exp…expensive so it's important uh…uh…so it's important to get some opinion from students that want how many sets they want for the…for the scanner and if…if they want more they need to be in charge of some of the expense. So…and the second it will be the methods the instructor teaches so for my perspective I think it's better for instructors to demo it so and so…it's the best way for students to get familiar with it and know exactly how to do it…it's the most direct way.

Completing the study helped him to complete a project in a logical way through a step-by-step process. Knowledge from the CGT course played a part for him in the scanning process. The second opportunity allowed him to express feelings he was not able to recall in the primary interview. The feeling about adding pictures to the tutorial was one such item he was not able to recall immediately following the exercise. When asked if he felt the process helped with his professional growth he said:

> Yea…uh because in the future…in the future uh I need to do some more complex projects so for the reverse engineer…engineering I…so to do the complex project I need to analyze a which point or which step should I start and uh…and uh…and…think of a more…efficient method do the project so the reverse engineer…neering help me do that. So…I…I can do it step by step more logically.

He wanted to learn more about RE to enhance his abilities and be able to process methods in a more logical manner. Taking a course in RE was one way he felt he could accomplish what he wanted to learn. A project involving several small parts was an activity he felt would help him finish projects more efficiently. There were factors he felt would be important and when asked what those factors may be he said:

> Oh first uh…it's important to estimate the cost of the technology and uh decide whether the students should be in charge of part…part of the expense. Also…also, uh it's better to give some background that want information about reverse engineering and some general objective of it…so students uh can get familiar with it before it is implemented.

4.3.3.7. Participant 1020

The tutorial was helpful for P1020 to complete the process but she did feel that adding more hints on how to position the scanner would be a change that could benefit other students. She felt spatial ability did help her complete the exercise when trying to

put the different views together but she did think positioning the scanner was difficult overall. She said:

> Well it was confusing sometimes to see how high you should move the scanner or how low you should hold it and exactly how far over if it were a curved object how far over you should move the scanner in order to scan the entire thing because even though you thought you did well a lot of the parts were missing so…maybe knowing exactly how far to rotate it about it and also how slow and how fast to move and also how high.

Learning about the technology was not sufficient enough to convey to her through the lecture notes. The hands-on experience was more helpful to her when learning the technology. She felt that experience is something other students should get to have as well because it was relevant, in her opinion, to the CGT 163 course. She stated:

> Yes because you can understand products a lot more when you reverse engineer it you take it apart and then kind of…draw the objects and then you actually have to put it back together and that way you actually understand how the product works a lot better and then that way you can apply it to other types of industries and businesses that you might get involved with.

There are many engineering courses that have requirements that need to be met before a student can enroll in the course. She felt a course involving RE should have a prerequisite for students to obtain knowledge that is needed in the various methodologies. She said:

> I think depending on the level try to have a prerequisite to the course if you're going straight into reverse engineering have students actually have somewhat of a knowledge of what it is before that. If it's just introducing it I guess have…make sure the professors and whoever is teaching it knows what they're doing and that the students…so that they can help the students and also…do a lot of examples in class and then make them actually do examples so they know what they're doing and kind of maybe describe the process and how each part functions when reverse engineering a particular product.

She expressed that she wanted more knowledge about RE and felt the study could have been more in depth. Having the second interview gave her the opportunity to express that concern and helped her formulate answers to the interview questions. She did feel that it was important to stress the importance of having students read the tutorial because after reading over it after the study to give them more detail. When asked if she felt the exercise was important to her professional growth and if she would enroll in an RE course she said:

> Yes it would because I want to go into the engineering field and engineering just basically take a product and try to either make it better or invent a product and in order to do that you need to take existin…existing material take it apart see what's wrong with it put it back together and change how you…put them back together and what you would add to it. Yes because it would be really helpful when you go out into the real world and trying to find a career. That way you have a little bit more knowledge over the others who just read about it instead of just having a hands-on experience with it.

A car or remote control objects were projects she felt could contribute to her professional growth as well. By breaking down objects such as those she felt it would help us to appreciate them on a deeper level. When asked what aspects she felt were important other then project selection she said:

> Whether or not the person who's teaching it has the knowledge to teach it. The materials because if it's reverse engineering you're gonna need products and depending what kind of products you're gonna use are they gonna be expensive like cars are they gonna be simple objects like just a scooter. Those kind of factors, how expensive.

4.3.3.8. Participant 1021

There were some changes P1021 felt could help when made to the tutorial. More explanation was something that could explain things better but overall he found the tutorial to be helpful when attempting to learn the technology. He enjoyed the study and he felt he did learn something new but did feel the scanner was too heavy to hold for a long time. Some of the questions in the second interview were hard for him to understand and his answers, at times, were not clear. He was unsure what the researcher meant when he asked what projects he would like to see but felt that a car or a building would be an interesting product to scan.

The study was something he felt other students should participate in and that the information covered in the process was relevant to CGT 163. When asked what factors he felt might be necessary to consider he only felt there was one. He said:

> I would…I would say um…just makes uh…uh like make a video show how to move the scanner to apply the re…reverse process.

Hands-on learning was the way he learned material the best. When asked if the hands-on exercise and knowledge about RE helped him in his professional growth he said:

> Yes…cause uh…uh…the sca…the 3D scanning work uh is a part of could be a part of uh mechanical engineering technology. I mean…fre…frequent to operate it to the technology and mechanical engineering…so…I think it will help. Doesn't it. Not help much cause it's just…some research…

The idea of taking an RE course was favorable to him. He felt the number of credit hours the course would have was more important than the level at which they

would be implemented. He was asked what aspects he felt would be necessary to the incorporation. He said:

> …so if I draw the…3D product from the…scan model…solid model. I ca…I could know where that…where the may…uh…it's like from the colors how to scan so there may…might have a based…based a little bit on this part so if I draw the product from the model I…I will know that.

4.3.3.9. Participant 1521

Participant 1521 felt that the tutorial "did a good job of detailing uh…the processes that you need to go through as far as the set up and the scanning." A suggestion that was made was to make a video of the scanning process or an electronic version of the tutorial to clarify the process. Spatial ability was something he felt contributed to the exercise because he was able to look at the multiple views at one time and calibrate the scanner more efficiently.

Once he realized how to manipulate the scanner to match the views on the computer he was able to calibrate the machine more easily. He enjoyed using the technology and said:

> Uh yes I did…um I think it is a very helpful tool I…like the experience that I got to be able to use that right now it's an expensive piece of equipment and there's not a lot of people that get to use uh…something like that but I…I enjoyed the process of scanning also just the…because it's very helpful and then I guess the only drawback I would see was obviously it's not 100% accurate of a…of process there's you know the clean-up process which is where you get rid of all those errors. But uh…I still enjoyed it overall.

There were some aspects he liked and other aspects he disliked. When asked to elaborate he said:

> Well I mean I guess there's a lot of errors involved…uh…with the scanning as it's not um…100% exact I guess uh…the thing that bugged me the most was that I couldn't get the underside of the object. I was trying to move the scanner very very low till the beam was almost parallel with the surface that it was on and then it would lose its position I'd have to start searching so I was trying to get very close down to the edge as possible but then keeping in mind that I could actually it was actually impossible for me to get the entire object anyway…so…a little frustration in that but um…the other parts went pretty uh…seamless and um…it went rather well so I enjoyed scanning.

The materials covered in the study were beneficial. He said, "I was adequately prepared just by reading the tutorial." When asked what types of products he would like to see used in the future he said:

> Um…I mean any other mechanical parts make sense to scan I guess…being an aero engineer maybe some like uh…various attachments that might go onto an aircrafts wing…wingtip…uh…or see devices and any little parts that might go into the building of aircraft would be very helpful for me to see and then scan and then maybe work with a CAD model and be able to modify even and create my own if possible…

He felt that the experience would be beneficial for other students to complete. He said:

> Yes definitely if…if people have the opportunity to do it it's a really cool thing to a experience um…and like I said not a whole lot of people get the opportunity to work with something of that nature and…and obviously the expense involved is probably a big factor in that and…so if an opportunity comes along where you can use a cool piece of equipment like that then I say go for it.

The process was something he thought was relevant to the CGT course. The RapidForm software was something that he said seemed good at getting the job done when creating a 3D model from scan data. The thought of taking an RE course was favorable to him. He said:

> Yes um…I really like pretty much anything having to do with uh…3D modeling. And…adding in the extra factor of the 3D scanning just makes it that much more interest…interesting it gives you that much more that you can do with it. Um…rather than just you know following instructions on a piece of paper day after day and modeling the same thing there's a lot more variability and a lot more uh…design uh…choices per say I guess.

There were factors he thought would be important when implementing RE methodology. When asked what the factors were he said:

> Well I mean as far as incorporating it is to give a…hands-on experience obviously um…the cost of the equipment or even the availability of the equipment, which is a part of the cost would be an issue. There's not going to be you know 200 3D scanners for one class. You have to figure out um…a way that um…as many students as possible can get access to the equipment to use…and then also the…liability that comes with using any kind of equipment and then…you know as far as any students maybe doing something that might harm themselves in some way or harm the equipment I say would be a factor. Um…yea you don't exactly want your thousands of dollar equipment to be destroyed so…that'd be uh…probably my biggest concern.

Being exposed to the parts that were in the scanning exercise was something he felt was beneficial to the learning experience. Through the course he was able to visualize things better and he felt the study was a "cool opportunity."

The second interview gave him a chance to add information to the primary interview. He found the process enjoyable and said, "…I'm grateful for the opportunity." When asked if he would enroll in a course based on RE methods he said:

> Yes I would. Um…there is obviously a lot of different methods used um…besides the 3D scanning and so it would be interesting to…try to test out some of those other methods and see uh…maybe a comparison of which ones I feel fit my personality better or more capable of doing.

The technology was something he felt could be incorporated into first year engineering courses. Projects that gave variation to current CGT 163 assignments were projects he felt would be enjoyable in the future. When asked what other aspects would be necessary he stated:

> Well…as far as the 3D scanner goes specifically I'd say…obviously that um there was the cost and liability involved but then the ability of the students to be able to use a 3D scanner might end up being a factor not all students are as coordinated as others so…um…I know different people struggle a lot more with something like that um…but the…at least in my opinion the other methodologies would probably a little bit more basic um…and more accessible to students of a wider range of uh skill sets. I suppose um…but yea besides that and any other thing would work out.

4.3.3.10. Participant 1524

Participant 1524 felt the tutorial was helpful in learning the 3D scanning technology and software. There were no changes that needed to be made as far as he was concerned. He found the experience to be enjoyable and the scanning to be interesting. When asked what other products would be interesting to use in the process he said:

> Well…maybe…an engine cause an engine has a lot of parts and…we…we want to build it I think it is not easy to use…just use the software to sketch. But if you use uh…scanner to scan it…it…it's a really fast and sometime…

The experience was something he suggested other students participate in. The software was easy for him to use and said it was convenient to be able to just scan a part rather than build it from scratch through sketches. The idea of a course involving RE interested him and when asked what factors would play a role in RE implementation he said:

> …I think it yea…the students' experience cause uh…after the professor and TA's know the…feeling from the…the students they will know how to uh…they develop the course and make it better.

Because the university only had one 3D scanner it was an opportunity he felt was really good for him. The experience was enjoyable and hands-on which was the method he learned information the best. The second interview helped him to relax and think about exercises from the study. When asked if he felt the secondary interview was beneficial he said:

> I think yes…cause umm…after the first interview uh…I just umm…cause it's first one I would feel nervous and for the second…second time I feel relaxed and it…and I have time to think about things at home and then I …I think the second time we'll have a lot of uh...differently from…mmm…for the interview I think.

First year engineering courses were at the level he felt students could use this technology because:

> …just for the first year engineering will have more time to spend on it and figure out how to do that…and…after that we…we'll be getting to junior or senior will be maybe an expert on that one.

There were no other projects he could think of that would be interesting to complete in the exercise. When asked if there were any other aspects he felt were important to RE incorporation he said:

> I think it be…is the experience. That you need to…mmm…learn it and try…and try and try to figure out how to use that and…get more experience than you can scan things real fast…and then build 3D model in short time.

4.4. Instructor Interview Response

The researcher conducted an interview with the course instructor for CGT 163. His thoughts and opinions on the implementation of RE were gathered to add information and support students' thoughts on what factors need to be considered when incorporating RE into engineering curricula. When asked to introduce himself, the department he worked for, and the courses he instructs he said:

> My name is Craig Miller. I teach in the department of computer graphics technology at Purdue University in the college of technology. I teach computer graphics 163, which is an entry-level course for in mostly engineering students. I teach CGT 426, which is a 400 level class that's focused on PLM and simulation visualization. I teach visualization graduate classes and the major…and a variety of other courses in the department.

Reverse engineering caught his attention around 1982 or 1983 in a senior level course he was enrolled in at Bowling Green State University in Ohio. He was asked what interest he had regarding RE and what he did not like about it. He replied:

> The interests I have are varied. Um…if you reverse engineer products you can use these products to show students in educational setting how they're built it helps the students to visualize individual parts and as the products go together. Um…it shows how processes are used for putting together and taking apart parts. What process had been used um…what I don't like about that's the general theory about what I don't like about some of reverse engineering is um…the equipment can be cumbersome so you need space to store it. It can…it is expensive at the high end. Um…at the low end actually you can do a lot of things cheaply with just measurement tools, calipers, etc. at the high end ther…there's issues with cost and…and space.

Students should learn RE skills, according to him, because they may need the skills when entering industry. When asked why he felt this way he said:

> Yes I do feel they should learn the theories and the applications of reverse engineering. Um…one because when they go out in industry they may have to work on a product that no longer has current or valid specifications in drawings or

> models so they may actually have to use some type of reverse engineering technology to get size, location of parts and pieces and assemblies. Um…it's important for them to know how to use these technologies from the low end to the high end. And that was some of the reasons why um…because they'll probably have to use that in their professional um careers. Now how deep they get into it um…can be debated but I think at some point or multiple points in their engineering curriculum that they should have exposure to both the theories and the applications of reverse engineering.

Majors such as ME, MET, AAE, and other majors involving mechanical skills are the fields he felt should have exposure to RE methodology. Teaching a variety of methods was what he felt would be the most beneficial. When asked what methods he felt would be necessary he said:

> Any kind of mechanical related um…major. ME, mechanical engineering technology, um…any of those are related to that mechanical caree… I think should…should be expos…should be exposed to it. Aeronautical engineering is another just a specific application mechanical engineering.

Much like the students, Dr. Miller was asked what factors he felt had to be considered for RE incorporation coming from a teacher's perspective. He stated:

> …some of the logistical factors are cost, you know if you get one of these systems can you maintain it because there's a lot of times contracts with it. Space…do you physically have the space to do it? Um…how do you im…implement it into the different courses of the curriculum so it's not just a one shot deal then it disappears. Um…the development of exercises that…that are appropriate for the different levels the students may have exposure to this and I think also feedback from um…business and industries that actually use this technology to validate that what you're putting into your curriculum in RE is actually something that they do and use in industry.

When creating a course it may be difficult to gather and create course materials, create a course outline, and have it pass through an approval process to be incorporated

into curricula. When asked what steps would need to be taken for an instructor to create a course he said:

> Well first off you'd have to have a genuine interest in it. Second you'd have to do research into the area to determine what could be covered or what should be covered and what should not be covered. And determine what from a…from a financial standpoint as far as equipment you could afford and if there's space to afford it. Um…once that is in place then you would have to review your curriculum and I'm talking all the way from freshman to se…senior year and identify courses that it would fit in that would be valid. Um…develop a progression from simple to advanced applications of RE and then placing these things in the correct courses in the correct parts of the courses. And then finally um…if you get the equipment if it's higher end equipment um…you get the people who are going to be using the equipment trained in it so it's used correctly.

Along with getting a course through the approval process or adding RE to a course already existent in curricula it is important to have a plan of what materials the course will cover. In regards to what an RE course should cover he said:

> Applications, tools, and processes. Where it's applied, why it's applied, how it's applied. What tools are allowed…that what tools are used that allow for these applications that were identified and finally what processes need to be done so that one you can correctly implement it and two once implemented you're actually using the correct processes with the technology involved. Without these three I don't see how you can successfully implement it. If you can identify a current text-book that would be helpful. Um... I think what's more valid now is identification of…of websites that are focused in this area and there's a couple reasons why I feel this is important. One from a cost factor it would typically be cheaper and two probably which is in my opinion is even more important they are more relevant and up to date um…then once that is implemented or those areas are identified then basically um…you could use videos, manuals or whatever to…to allow the development and the explanation of the use of the technology, the applications of the technology. Um…implementation of the technology in specific areas.

As stated in Chapter 2 in section 2.3 an effective way of teaching RE methods is through PBL. He was asked what learning methods the course should be based upon. He said:

> It should be a theory/project-based course. One theory you have to know why it…how it works…what are the good and the negative and the positives about it's implementation the cost all of the things that…that somebody should know before they ever even touch a tool. But because of the way this technology functions you have to have hands-on application of it without a hands-on application of it I don't think you could really give the students a…a valid representation of what it's capable of and…and…allowing them to actually just experience it.

Exposure to RE was something he considered to be important for engineering students. When asked why he felt that way and how students and professors could prepare for the course he said:

> Yea I think you know at least exposure to it. Should be incorporated throughout the engineering curricula. Again, people coming out of undergraduate engineering programs such as Purdue, um…should know at least know about technologies they may run into or may have to recommend for use and reverse engineering falls into this category. Then tying it into specific courses where it applies um would be the challenge of you know putting it in so again its not just a one shot deal but it's brought in sev…at several points throughout several courses. The professors would have to have the tools in place. The lectures in place from a basic theory and application standpoint and know how to use the technology. You know that…that's a given from the instructor's standpoint. The student standpoint would be basically have an interest in it you know which I think they would want to have an interest in learning anything anyways but basically um…come prepared to…to…utilize it to understand why its' important and just have fun with it.

There are a variety of RE tools that can be used such as metrology, hand tools, and 3D scanners. When asked what tools he felt should be used he said:

> First off from a very basic level I'd like to see them use um…measuring tools um…that could be calipers, micrometers, um…gauge blocks to understand what

> you're actually measuring and why then you get into metrology equipment you know whatever you…that might be available to them and then finally into some kind of laser scanning equipment that could be available with…within a…a um…lab.

Creating a course based solely on RE was an idea he was not fully in favor of. He was asked how he would approach Purdue University with a proposal for a course involving RE methodology. He stated:

> This would be a challenge to try to basically justify a reverse engineering course per say. As a standalone course and I wouldn't do that. I would propose to implement reverse engineering into several courses over their curriculum. Um…I would give them examples of why it's important. I would have letters both from industry with major donors and major employers showing why it would be important and then finally allow it to happen it would be you know you'd have to have the release time to develop it. You'd have to have the time for training of the equipment. You'd have to have the budget to actually buy the equipment and you'd have to have the space to place the equipment.

Technology such as 3D scanning is new to the university. He felt students needed to be exposed to the technology. When asked his feelings on 3D scanning he said:

> I think it's important they're exposed to it but I think the reality is it's a…with the at least with the I'm familiar with it's an expensive technology it is a…delicate technology form the standpoint of handling. Um…maybe to a select few in a select class this would be important but for the all the students I don't know if I'd…I'd have the scanning technology available. Um…it's time consuming um…you know from our experiences here some students have a difficult time using it just from their spatial ability standpoint and calibrating it. You know at the 100 level I would not use it you know to maybe 3 or 400 level in smaller class scenarios I would probably recommend the use of it.

Retention rates are a subject that schools may feel is important in many cases. Dr. Miller did not think it would have any effect on retention rates and said:

> I think it's important they're exposed to it but I think the reality is it's a…with the at least with the I'm familiar with it's an expensive technology it is a…delicate

> technology form the standpoint of handling. Um…maybe to a select few in a select class this would be important but for the all the students I don't know if I'd…I'd have the scanning technology available. Um…it's time consuming um…you know from our experiences here some students have a difficult time using it just from their spatial ability standpoint and calibrating it. You know at the 100 level I would not use it you know to maybe 3 or 400 level in smaller class scenarios I would probably recommend the use of it.

He felt students would become more interested in RE if they were introduced to the different methodologies in more detail. If the technology could be demonstrated to students and examples given it may spark students' interest in the subject. Along with student interest, professional growth may be a factor students consider when registering for a course. When asked if he felt RE methodology could help students to grow professionally and improve design skills he said:

> I think it would help in their professional growth from the standpoint of recognizing the technology, understanding it's utilization and importance. If they actually got exposure at the 300, 400 level courses where they actually used the equipment enough that they understood how to use it…yes I think this would be helpful for them in their professional growth. I'm not sure if it would improve them or not. Um…I think it would show them how things are …put together and give them more…real world examples of this through reverse engineering of products. Um…but for them to improve their design skills I think a lot of that is innate. Either people have a…they just have it in them to be able to design things and have unique solutions or two just actual time on the job through co-op internships and permanent employment is where they're really gonna get the application or design set…or design set of skills in there. Reverse engineering won't hurt any but I'm not sure how much it would really help.

Having products to practice RE skills on is necessary. He was asked what types of products he would have students use:

> …beginning would be something very simple. Um…to allow them to basically use the technology. With um…planar surfaces you know with a big enough space so it's easy to be scanned if you're using a laser scanner for example. Um…that I…basically gradually move them up to a more complex type of product um…the

simple product you might be able to use with metrology tools or even with hands tools. As you get into more complex products that have complex curves and curved surfaces in them then you could basically allow them to use such technology as scanning technology which you may not be able to do with the other type of technologies. And you go through a progression and so students would have a very good understanding of all the tools and where one should be applied and not the other and the reasons why…they'd be hands-on projects again kind of like I answered before where they would start out with a simple project or a simple part or parts and then gradually work from that once they have um…an understanding of how to use the tools to into more of products, simple assemblies then into more complex assemblies and step them through that progression. And the different tools to show which is app…which would be more app…applic…applicable at a certain you know…to get on a complex part.

When asked if he had anything to add to the interview he said:

…I think reverse engineering has potential. In curriculum I mean all the way from elementary school up through higher ed I mean elementary school students should be the…should know how to use measuring tools and I mean simply rulers you know tape measures…um…they should really know the metric system better than what they do and then you know as you progress through into high school these people want to be in technology or engineering fields then they should be exposed to micrometers and other um…simple tools and then step them up through this I think it's important. The challenge is…is basically how do you get people to buy into this and if you do get them to buy into it how do you cut things out of the curriculum to allow this happen how to find…how do you train people but I do think it is important and um…the limiting factor's probably the cost at the high end anyways.

4.5. Industry Professional Interview Response

The industry interview, much like the instructor interview, was conducted to gather an industry opinion of RE implementation to support the students' perspective. It was important to choose an industry professional that worked with a company that specialized in RE and had years of experience. Kaae Rillos from Rillos Engineering, who was the president of the company, was chosen for the interview. To get some

background information he was asked what computer software his company uses most often. He said:

> …most often it'd be uh…CATIA there's a verification program where we use for NC programming called Veritech um…uh…adobe acrobat 3D quite a lot that's primary means for communication, data translation uh…all the Microsoft office products um…uh…filezilla for FTP transfers uh…dropbox to synchronize data with various people in the organization uh…we have our own um…product data manager on the web called MBD central which we use to uh…distribute data and define work for people that are doing work for me. That's about it. Well here's the thing…each software has it's own specific purpose and you just really just can't say you know one piece of software's gonna solve everything for you.

Because the company does reverse engineering work, they practice RE methods often. When asked how often they use RE methodology he said:

> Quite a lot just got a contract uh…probably today to do some reverse engineering uh…right now the main use for it is uh…uh legacy data like old programs if you got mylars or uh…the last week we did a reverse engineering job on a CATIA version 4 data set it was really complicated because they couldn't get fastner locations to work in 3D states. First …first question is do you know what a fastner is for aircraft parts? Fastner is just a generic term for any kind of rivet, nut, bolt, high lock okay…basically allowed like a…an aircraft assembly…so there's sheetmetal parts that held together who knows what maybe by rivets. Bu that little crosshair that's on a piece of paper problem is getting is…is…is…morphing all paper manufacturing tape pieces and no organization digital manufacturing techniques so we kind of fill this really tiny little gap in…in that need. In the case of last weeks job I just use every trick I could think of but finally we got it to merge uh…merge uh…a file that had the fastener points and a file that had the 3D data morphed them together and identify the ones the customer needed and send back to the customer.

Kaae Rillos presented on RE methods at the CATIA Operator's Exchange in Las Vegas, Nevada in 2010. Best-fit methods were used during his presentation. When asked what methods his company uses most frequently he said:

> Uh…3D scanning did an interesting job on that but…that's kind of rare uh…it is fraught with peril um…the easier kind of…of reverse engineering we do is…like flat mylar drawings uh…or uh…I think in the Las Vegas presentation I gave we showed some antique car parts we reverse engineered. Sometimes it's just a matter of just scaling it and uh…making it from that. Reverse engineering we can do it we have done that there was a…company in Tacoma called CCR the thing they did is if you give them a…a modern day corvette they would put a 1962 body on it and of course because they want to use a digital manufacturing method they needed that done. The data was actually very hard to handle cause there was so much of it it's like 300 megs of a points so the thing you have to do is write a routine and I used python to uh…give me like every 10th point and it was still too much and then I had to rewrite the routine and give me every 100th point it was still too much. Sweet spot was about 300 points now I had something I could work with again it's just too much data. So uh…yes we do 3D scanning too.

Engineering skills are something he felt students should be exposed to. He was asked why he replied:

> I think yes. I think it's good because…it's kinda like uh…riding a bicycle then going to motorcycles then going to cars it's…it's how we use to do engineering. How to get from there to here it's kind of like the history of engineering in a way and it…it gives you down and dirty with the manufacturing process too. Like in the case of the corvette body I learned some new insight on how somebody else used you know new carbon fiber technology and how to make it cheaper…they had a really cheap way of making molds. But uh…I think reverse engineering is great for understanding the whole engineering/manufacturing process cause…to make…to engineer is useless unless you finally make it right…I mean that's why we have 3D CAD is not for pretty pictures it's to make something.

There may be many factors to consider when incorporating RE into curricula. Kaae was asked what factors he felt should be considered to compare them to the factors students felt were important. He said:

> Mm…well you can make it as…simple as possible it could just be project based that's an easy way to do it. How to get the data uh…we used to teach a reverse engineering class as part of our 10 week CATIA class and what I did was I purchased a Sony digitizer for about $4,000. Didn't break the bank and essentially had a bunch of airplane parts that we had the students…we made them first of all come up with a coordinate system uh…inspect the parts, gave them a routine that

> they used to read it into CATIA and then we showed them techniques on uh…how to reverse engineer it. Uh…the one I showcased in the uh…Las Vegas COE was uh…basic just using those points not to define the surfaces that's suicidal cause things bend, birds hit things, whatever…uh…we taught them to uh…use those points of more of like a go no-go you know kind of come up with your best guess for a smooth surface, a smooth plane, a smooth cylinder and then use those points to decide you know how far can they deviate. What can I make my master surfaces expand or contract to uh…best fit those points but the whole cost wasn't all that much considering what it…what it made the students do it really got them uh…thinking of the overall picture and it improved their CAD skills ultimately too.

Skills are needed to perform RE tasks much like any profession. When asked what skills are needed for performing RE methods he said:

> Spatial visualization if you're a 2D thinker if just using Photoshop all day long you may have the talent but your basically it's a different part of the brain um…I remember when I was a kid my dad gave me this…he showed me a picture of a…3D picture of a triangle, a circle, and a square he said think of a shape that will go through all those items and you really need to think about it you know basically it looked like Hershey kisses right you pull the ends out so that it was vertical then from this view it would be a rectangle, from that one it would be a triangle, if you rotate it it'd be a cylinder. That'd be an example of visualization and the kids that play video games today. Halo's a good example of it they understand visualization. They understand…they can see…the 3D because if they go around corners they don't know uh…what to expect. I think that's a critical skill to have for reverse engineering. So let them video games is my advice. Um…next thing you should point to is XBOX Kinect. We got one for Christmas shh…but um…they reverse engineered that within like a couple of weeks to uh use it for reverse engineering. I think that's…that's the next thing is a low cost…I mean cause here's the thing its 100 bucks it's hard to beat the cost. So really just looking at your constant coding and a lot of the coding is already there so it's just taking that…morphing that the inputs into whatever you want to uh…control but I think that's a huge…I think it's gonna be huge the XBOX Kinect I really do for reverse engineering.

As stated before it is important to have materials and exercises for the course. He was asked what the course should cover and why he felt that way. He said:

> Um…well the gamut I mean think of as many ways you can do it for instance there's a huge need to just reverse engineer dimension drawings into 3D…CAD. So let's…let's look at the goal the goal is to get everything into 3D CAD because then it conforms to the…digital manufacturing process. So that's our goal. So what are our inputs? First input could be a uh…2D dimension drawing. We do a lot of that basically customers give us a drawing and they say we need a solid. So we give that to them. Sometimes it's undimensioned in which case it's a little more tricky because it'd be like 36 inch mylar that might be 10 feet long but it has a 10 inch grid pattern on it. Basically you can control…use it for quality control checks to see if the expansion and contraction is uh…what the mylar too much to where it couldn't be used. In that case what we do is we take a tiff file of that we use adobe Photoshop. Basically to fit within that 10 inch grid. Some times there's multiple sheets and then you have to have multiple CAD parts. So where was I uh…yes…back to mylars that's never been for manufacturing to use machine shop or mylar tape…make something that fits on top of that so they use it for they would reverse engineer the um…um…you know students scale they would just measure everything make the parts put them back on this mylar for QC check and then put the whole assembly on the mylar for QC check. That might be uh…option number two. Option number three definitely want to use some kind of 3D scanner uh…there's a lot of cheap alternatives for that. There's sonic digitizers there are uh…someone at a…west tech it's like a turntable. But anyways it's like a…it's like a turntable that rotates and his camera just takes a bunch of pictures of the…turns the whole thing out in 3D uh…that's pretty inexpensive. Uh…they also have these uh…laser wands you just you know drag over a surface and it just uh…it takes pictures of all the laser contour changes and quickly gives you 3D uh…and the…you get from that all three methods are different types of skills to put it into 3D. So I think it would really exercise the students brain as far as you know how do you use the CAD and really stretch the limits of uh what they're learning.

Along with determining what the course should cover, it is important to consider how the materials should be presented and what should be presented. He stated:

> Uh…see PowerPoints are very good because they…they pace you. Um…textbooks…not so much uh…I've got a…I've got a library thing upstairs with all my engineering textbooks. I don't think I've ever open them you know. I don't think books are the way to go anymore. I…I think uh…videos like posting Youtube videos or internal videos. Uh…I think that's a quicker way to learn uh…plus you just give them a couple steps and make them recreate it because

> there's I mean a lot of this stuff is only going to be done hands-on alright. A book cannot adequately describe it uh…the best way to…to show the frustration of a book is uh…back in the 70's I'm kind of old. There's a…a book called the Chilton Manual and you bought it…we had this '69 Cougar and you bought the Chilton Manual for the '69 cougar and show everybody how to repair everything. And it would show you these pictures and you look at the picture you sit down…I wish this thing wasn't in the way so I could you know see the thing on the other side. Um…that's the way I look at books is their static. Um…I do…firm believer in…in Adobe PDF's… to buy like for instance Acrobat…we used to have Acrobat Pro extended version 9. That had their reverse…simulation package with it too. Now you'd use um…tetra 4D. T…E…T…R…A…4D. Fairly inexpensive it's like 600 dollars with Acrobat uh…10. What you can do with that is you can take whatever it is you're reverse engineering but you can also you know um…animate the blowups. You can basically leave the things together and take it apart. I think that'd be great for any kind of reverse engineering tutorial. Cause that's you know single step through it say step three they would animate your startup view plus you could rotate at the same time so look at well…what it is you are uh…uh trying to see. Uh…so that's your question PowerPoints, Acrobat 3D, and videos.

The best way he felt students would learn information was through a hands-on setting but thought that some theory is needed. When asked how the class should be implemented and how students can prepare he said:

> Project based uh…because there's an actual sense of accomplishment at the end of it. You actually do something and it's also an obvious thing for pass-fail. It should be a project I mean a simple a way of verifying if they reverse engineer correctly is just the center of gravity at the very end. And only allow a certain amount of deviation from it and that's the passing point in fact you can even give the students the center of gravity too because you ultimately want them to get the thing right. So project based I think is better than…than theory. The theory can probably cover you know in a…in a one two hour lecture in the beginning of class um…um…So uh…I think project based.
>
> Um…play a lot of video games you can read on that. Okay. Uh…must be proficient in a CAD system. Alright. SolidWorks, Uni…NX, CATIA, PRO/E. I would definitely do one of the higher level ones. Uh…rather than the low level like AutoCAD. Um…reason being is uh…a little bit more powerful. Even though they're more expensive they're a lot more powerful and uh they give you a lot

> more tools to get where you want to go. So uh…definitely 3D CAD experience is…is uh…necessary thing to get the thing to work.

Not only should students prepare but professors would also need to prepare to teach the course. In regards to what he felt professors needed to do to prepare he stated:

> Do it themselves. Understand the pitfalls of it cause it…then you'll understand where the questions are going to come also. Definitely do it first and constantly think of you know as you walk around the house, as you walk around industry. Constantly think of new things and new applications. Uh…for instance uh…when I was at the Las Vegas COE there was a big buzz that week about reverse engineering the B-52 because they still fly. They still need to make spare parts for them and there's no blueprints on them. So in that context a…a team by professor could actually contract with some company that needed to reverse engineer lets say a B-52. Have all these students that uh…understood the theory and went through a basic drill that ultimately get thrown a whole bunch of B-52 parts at them would make them all experts to engineer I mean. And now you get…some people that then go out and start their own reverse engineer…

Proposing the implementation of RE to an engineering department might be difficult and there could be resistance to the idea. He was asked what he would tell the department was important and what needed to happen. He replied:

> What was important? I would first of all sell that uh it's critical for the understanding of the manufacturing process current and past. Um…it would also build up critical skills where I mean the whole point of getting students degreed is to get them out there where industry can use them and it would make them familiar with a lot of the uh…processes. Lot of terminology for instance you didn't know what a fastener was alright. Um…didn't take you long to find out what one was right. Be nice ahead of time when you go to an interview place that you knew what a fastener was. So it would…it would uh…they would have been seeing real life engineering drawings rather than just something in a picture in a book alright. So it gives practical use to make something that happened in the past or present. Um…so I'm sold on that as far as the overall curriculum goes. It would make them more marketable once they got their degree. I mean uh…friend of mine went to…she was…work source job fair and like the first thing they asked everybody in the classroom. About 40 people in the classroom cause they finally based on someone getting jobs with Boeing. The first thing she said…the

> counselor she said is anybody here know CATIA? And the girl I knew put up her hand and said I know CATIA. Well that's the thing Boeing needs is people to understand CATIA. So uh…they didn't ask does anybody know thermodynamics, does anybody know stress analysis. They asked something very specific do you know this CAD package and a great vehicle to get to be familiar with a CAD package is a project through that and a project would be a reverse engineering project.

For the implementation to be accepted and become successful it might be important to consider other factors. He said:

> Uh…success well obviously some people are not going to get it. I think well first of all it's fun and trust me it's a really fun thing people look I have do it for me. Once you get them…cause we have to train our people on reverse engineering. Once you get the involved in it it's a lot of fun they enjoy it. We did the uh…we did start we did ribs five through 35 on the 737. And then…no 767. We also did a bunch of a…a flight controls. Uh…reverse engineered for uh…767 and one of the guys that um…enjoyed it never did…two of the guys that did it never done reverse engineering before. Uh…so I had to explain why we did it how we did it and you know coached them while they were doing it. But uh…eventually we got through it. There are some people that will not get it but that's the case with any class you know you always have you know D's to A's right for that very reason. Um…success well like I said before whatever the…the end products are you know CG measurement to see if it's…if it's accurate. That's one measure of it but the fact that they got there indicates success because A, they…they understood. They got to see how the part was made. They got to analyze it to get dimensions off it. They got to put that in a 3D CAD and then they conformed to a final…what do you call it um…acceptance. Acceptance model okay. So think about things that they had to go through and there's also a feeling of success because they can see it. They can see start to finish so uh…I think it would be successful in that regard.

There is a variety of equipment that can be used in learning RE methods. When asked what equipment those involved in the course should be familiar with and what he thought of 3D scanning technology, he said:

> Well obviously the CAD package that's number one. Uh…they have to learn whatever it is they're using to do the reverse engineering. They for instance very

inexpensively you could get a broken arm like a roamer arm that they make some really small ones for reverse engineering like…like an iPod or something like that a thousand dollars. There's Sony digitizer that took a while to understand how that worked. We had to write some software to get you know the raw part data, scale it to put it back into CATIA, um…tell the students how to calibrate it cause there basically based on we were like uh…there was one, two…two sources of sound on it it's like uh the thing that lights up a cigarette lighter you know. And then there were…there were five sound sensors that depending where they're placed uh…triangulated where the location of the end of it was. It took a while for students to understand that and for us to understand it to explain to students um…you also have you know laser wands you have uh that thing I told you that will rotate it in a circle on a turntable but whatever method you use to get to your reverse engineer data into the system the students would have to become familiar with that which I think is a valuable exercise in problem solving too.

Excitement it's…it's amazing what they've been able to do in a short amount of time uh…for instance I mentioned that uh…we did the 767 reverse engineering right. The company that gave us the work they use the old method. They had scales and magnifying glasses and they tried okay 1.265 then they go and enter 1.265. Much slicker method of using it where we could crank them out faster than they could give them to us almost. Um…I've seen where at Lockheed in '88 they had a digitizer with like a crouching board and they could go and punch something on a mylar and come over here and punch something in and it would measure the 2D. It would give the coordinates every time we punched it. Um…and then the sonic digitizer that I saw back in 2003 the broken arms that I've seen you can now get broken arms roamer arms that are accurate to like a thousandths of an inch which is incredible. Um…for somewhere like $20,000. I mean the cost of everything is just dropping so much where it's…it's way more affordable and then I just told you with the Kinects. That's gonna be amazing too the things that we're gonna get out of the Kinects remember all that can happen is that it gets better. We can get…right now the Kinects might only be accurate to plus or minus a hundred thousands right but that's this years Kinect. You know give it a couple more years and we'll be down to the thousandths too and we'll be able to measure all sorts of other things like the amount of heat that you…you emanate the amount of reflectiveness that you emanate um… there'll be so man y other metrics it'll be able to grasp from it. I'm just excited about the future of reverse engineering I think it gets cheaper and more accurate.

Lastly it was important to consider any other factors that might be important to the incorporation. When asked if there were any others he felt could play a role in the implementation of RE he said:

> Uh…overcoming the inertia of the faculty typically it's new um…certainly some faculty members won't embrace it…for the simple reason is they're not experts at it. It's kind of like John Claude Killy going down the slope and you say now you have to do it on a snowboard. And he resists because it's even though it's the way of the future he resists because it's something he's not an expert on and a lot of your professors are experts in what they do. Reverse engineering is not their expertise because it's typically not taught so I think the biggest thing is to overcome resistance from the faculty.

4.6. Summary

This chapter has presented data that was collected over the course of the study from the variety of sources that were used. Through the surveys presented to the entire course enrollment, students were able to provide their opinions on their interest in RE methodology and to determine if students would enjoy learning RE as part of their engineering curricula. The hands-on study gave a select group of students the opportunity to use 3D scanning technology newly acquired by Purdue University.

The first interview, given immediately following the study, obtained students immediate opinions on the technology. The second interview, given after a waiting period of at least 24 hours, was given to allow students to think about what they completed in a more detailed manner and provide more information that they may not have expressed during the first interview. The instructor for the course, Dr. Craig Miller, was interviewed to determine how he felt about implementing RE and support what the students felt. Lastly interviewing the industry professional, from Rillos Engineering,

gave insight from an industry perspective to determine how implementing RE could benefit students as well as industry.

Data from this chapter will be drawn upon in the following chapter to examine themes that emerged among the data. It will summarize the data and provide recommendations for future studies that can be derived from the study conducted.

CHAPTER 5. THEMES, CONCLUSIONS, AND RECOMMENDATIONS

The purpose of this study was to determine what factors students felt must be considered when implementing RE methodology into engineering curricula. The findings given in Chapter 4 provide details that will be discussed in this chapter as well as hypotheses that can be used for future research.

5.1. Themes

Qualitative data collected during the study was interpreted to determine themes that emerged among the data. The following sections will provide themes discovered among survey and interview data.

5.1.1. Survey Data Themes

Among over 360 students that were provided the opportunity to contribute to the online survey, 339 chose to complete it. Of the 339 students that did complete the survey, not all answered every question in its entirety. Surveys that were not completed properly, honestly, or that consisted of inappropriate answers were discarded, as they did not provide any relevant data. Also, only one survey per student was collected. If a student submitted more than one survey the most complete survey was taken to avoid the collection of incomplete answers.

Among those enrolled in the CGT 163 course who completed the survey, 59.59% were majoring in ME. Those majoring in AAE and ME made up 79.65% of those that responded. It stands to reason that those two majors make up the majority of the entire class enrollment and would require visualization skills the most. If RE methodology were incorporated into engineering curricula, the AAE and ME curriculums would be those most likely to benefit from RE implementation.

The majority of students found the RE and 3D scanning lectures to be interesting and enjoyed having a different topic covered during their lecture period. Specific examples can be seen in Chapter 4 in section 4.2.1. There were also students who did not enjoy the lectures because they were not interested in the subject, they felt they didn't apply to the course, or felt the lectures were not in depth enough to teach the concepts. If RE were implemented, the majority of students would enjoy the content according to the surveys collected.

The fact that many students had never heard of RE could have played a role in why students found it to be interesting purely because it was new to them. As shown in Figure 4.1 over 60% of students knew what RE was, some of whom completed RE projects. With RE being a new concept to less than 40% of the students taking the course it shows that not all students found it to be an interesting subject because it was new content. There were many aspects of the lectures that students found to be interesting regardless of whether it was new or familiar to them.

Aspects that students found to be interesting included the different RE methods, 3D scanning technology, the simplicity of some of the processes, learning how to work

backwards from a product, the real world applications, and that there are companies dedicated to RE. Those are only aspects that were taken from the sample given in section 4.2.3. Along with aspects students found to be interesting there were also aspects students did not like or felt needed improvement.

Many students wondered why they were learning the material in a freshman level course where they had no knowledge of how to access RE equipment. Other students felt having a video of a RE process and a list of accomplishments obtained through RE. Others wanted to spend less time on methods and more on examples and felt that slides were a poor way to teach the material. A few students also felt there needed to be more emphasis on using hand tools. There were some students who felt the lectures were too early or that there should have been more hands-on practice for students but these factors were uncontrollable due to school policies and the number of students enrolled in the course. It is impossible to have over 350 students use the 3D scanner in a 50-minute lecture period. Therefore only a few students were able to use the equipment. Many students felt that PowerPoint presentations were an ineffective way to learn the material.

When students were asked whether they preferred hands-on or text based learning, over 85% would prefer to learn the material in a hands-on setting. Many students felt that learning from PowerPoint presentations or textbooks was uninteresting. They also felt that they would remember more of what they learned if they were able to do themselves. From this data it can be concluded that RE methodology would be most successful if it were implemented in a hands-on setting.

Not only must students be able to learn and retain the information that is presented to them, they must also benefit from it in their professional career. Many students felt learning RE methodology would benefit them in their professional growth. Learning RE methods, having a basic understanding of technology that is used in industry, using RE to determine what part is missing from an assembly, and being able to work backwards to determine how a product was made were just a few aspects that students felt would contribute to their professional development.

Certain aspects of the RE lectures were found to be overwhelming or too complex. These included the 3D scanning technology, metrology, and scanning large objects. According to students, these aspects would need more elaboration. Determining what concepts need elaboration is an important factor to consider when incorporating RE into engineering curricula.

Only 10.15% of students did not want RE incorporated into their curricula while 82.99% wanted RE incorporated. This comparison proves that students are interested in RE and would like it incorporated into their curricula at some level. The survey showed that quite a few students felt that it would just be something else they would have to learn and did not want the added work. This shows that some students lack motivation and interest and feel adding new methodology would just be adding more work to their course load. Even though they may not have wanted the added work, some of them felt the visualization skills needed by RE were important.

More than 91% of students felt that visualization was important when using RE methodology. One student said, “I feel the ability to visualize is very important for the

use and implementation of RE technology into engineering courses." The CGT 163 course involves many assignments that require visualization skills and learning RE could help improve a student's spatial ability. The fact that over 91% of students feel visualization is important shows that spatial ability would play a factor in the implementation of RE methodology.

5.1.2. Hands-on Learning Themes

As stated in Chapter 3 there were a total of 10 students that participated in a hands-on learning experience involving 3D scanning. Five of the students were classified as having high spatial ability and five students were classified as having low spatial ability. Of the students that participated seven were majoring in ME, two were AAE, and one student was MET. Each student completed the 3D scanning process and underwent two interviews to determine their thoughts on 3D scanning technology and what they felt was important to RE incorporation.

As shown in Table 4.3, calibration times for the students varied anywhere from three minutes to over one hour. What was interesting about the calibration times was that the five students classified as having high spatial ability had the five fastest calibration times. This shows that there is a high probability that spatial ability is important in the 3D calibration process. Every student that completed the calibration process felt that spatial ability did play some part in the process but did not necessarily feel that it was absolutely essential to complete the process. The process can be completed by anyone

that attempts it but it may take a lot longer for students whose level of spatial ability is not considered to be high.

When given the opportunity to choose which part they would like to scan, students made their choice based on different reasons. Complexity of the part was one of the main reasons for students' decisions. Of the six students that chose to scan the pipe support part, all six said they chose it because it looked easier to scan and would take them less time and therefore the process would be faster for them to complete. The four that chose the bracket support part chose it because of the complexity and were interested to see the final scan of a complex part. All students that participated attempted to complete the process as swiftly as possible to simply get it done so they could move on to other activities. Every student enjoyed the technology and the process but not all of them seemed to appreciate the technology as much as they would if they took their time.

Prior to attending their dedicated slot for the process, students were given a copy of the 3D scanner tutorial that can be found in Appendix K and asked to read through it before coming in for the process. Only two students did as was asked and read the tutorial. Those two students completed the process in a more accurate and more efficient manner. During the interviews students were asked if they found the 3D tutorial to be helpful. In the second interview one of the students who read the tutorial said, "I remember a lot of the stuff from in class when we went over it but looking over the tutorial before hand definitely gave me a leg up. I didn't have to read through it like try to figure out while I was doing it so having it before hand was nice." Though there are

aspects of the tutorial that need to be updated and modified every student felt that it was helpful during the process.

There were mixed feelings on whether spatial ability helped with the process or not. Some students felt that spatial ability was not necessary. Participant 0421 said, "I don't think someone needs to have very advanced spatial ability to uh do the calibration or scanning." It is yet to be determined whether spatial ability is a factor that plays a role in 3D calibration but as P0421 felt spatial ability was not needed he was also had the sixth fastest calibration time. Therefore, it stands to reason that spatial ability may play a larger role than some students realized.

As stated before all students who participated in the study found it to be enjoyable. There were aspects that students liked such as the actual scanning process and there were aspects that students did not like such as the weight of the scanner. One student felt there was a drawback that needed to be voiced. He said, "…it felt like the we…like hold the handle and pulling the trigger that where it was actually targeting was not exactly lined up as…" Though there were aspects students liked and disliked about the process all 10 students said that they would recommend that other students participate in the 3D scanning process.

To recommend that other students complete the process it would be necessary for them to communicate what the process was about and what it entailed. When asked how they would describe the process to an interviewer, students gave a description as if they were in an interview being conducted by an industry professional. There was a variety of descriptions from as simple as using a handheld device to create a scan to a very complex

description entailing every small detail of the scanning and calibration process. Descriptions that were given can be observed within the subsections of section 4.3.2.

Communication is just as important to understanding the material as it is informing others about the experience. English was not the primary language for all of the students involved. For those whom English was a second language, they found it difficult to understand certain interview questions and sections of the tutorial. Misunderstanding information presented in the tutorial was one of the main reasons students felt pictures would be more helpful in learning the technology. Not everyone was able to understand certain phrases, abbreviations, or sentence structure when reading the material. Also, all students knew what the parts of the scooter were but were not able to understand the questions they were asked and consequently, claimed to not understand the parts. Therefore, finding a common ground on which all students can understand and communicate processes would be a key factor in RE incorporation.

Though communication was an issue in certain circumstances, students felt that the study was beneficial. As stated earlier there were aspects that students felt needed to be changed or areas where information needed to be updated. According to P010, "Dr. Miller like rushed through the one thing so in my personal view I'd place two or three more lectures should be con…on that…I mean there should be two or three more lectures before the technology is introduced to the students." Along with needing more lectures to portray the information, students felt that the documentation needed to be more visual and less text based, that the objects being scanned needed to be more complex, and the number of calibration measurements needed to be changed. The number of

measurements and some other suggestions are aspects that cannot be controlled by those instructing the course and were therefore omitted from the list of factors that need to be taken into consideration.

Keeping in mind the factors students felt needed to be changed, there is also the matter of what course levels RE should be implemented in. The researcher received mixed reviews when asking students whether they felt RE would be more beneficial in a higher-level course or a course upon entering the university. A few of the students who participated in the study felt that RE should be implemented into lower level courses because it is not that difficult to learn.

One reason RE should be implemented into freshman engineering was, "…cause I think freshman they have a lot of…lot of time to do some uh…extra…extra works and then when they just come in to the college and see some new things they will interested in." On the other hand, as stated before, some students felt the technology should be limited to higher-level courses. One student said, "I think a junior or senior level course. Because you have a lot more subject to reverse engineer use the scan for. First year classes don't have much you can scan." It is hard to determine at which level RE should be implemented but it can be incorporated into engineering curricula at all levels as long as it is structured according to the level of students being taught.

The main focus of this study, as stated in prior chapters, was to determine what factors students felt must be considered when implementing RE methodology into their engineering curricula. The 10 students who participated in the 3D scanning exercise were asked this question on more than one occasion and it was also portrayed in other

words in case students had difficulty understanding the question as it was given the first time. The following is a list of factors and other aspects students felt were necessary to consider when incorporating RE methodology into engineering curricula:

- Cost of the equipment
- The number of people that can use the scanner at one time if in a group
- The weight of the scanner
- More lectures given before students are introduced to 3D scanning technology
- Whether students are interested in the technology
- Professors need to set up procedures and study plans for students to learn the technology
- Coordination of the scanning process
- Faculty training
- Maintenance of the equipment
- The time involved in scanning
- How the scanning information would be taught
- The number of machines that would be necessary for large classes
- Students need to understand the basics of RE
- Students should be taught the theory of RE
- Step by step processes for scanning exercises
- Research tasks into RE and scanning
- Safety of the students and the equipment
- Professors have proper knowledge to train students
- Spatial ability

- Students' ability
- Making interactive learning material
- Monitoring the use of the scanner
- The types of projects that would be involved
- The RE methods that are taught
- Liability in regards to equipment

Going into the study cost, time, and experience were hypothesized to be factors students would feel to be important. Students gave a variety of factors they felt would be important. There were more factors that were thought to be important than the researcher predicted the students would consider. Overall the students covered and surpassed the factors the researcher felt would be important.

5.2. Instructor Supporting Data

As stated in Chapter 3 the instructor for the course, Dr. Craig Miller, was interviewed to provide support for the students perspective. Of the questions he was asked, his answers to which are provided in Chapter 4, the most important question was what factors he felt were important. The factors he felt would be important and necessary to incorporating RE methodology were:

- Cost
- Maintenance of the equipment
- Physical space to store equipment
- How it is implemented

- Development of exercises and appropriateness for each level
- Feedback from industry and businesses that use the technology to validate what is put into curricula.

Of the above factors, two of them were factors that were not mentioned by students. Even though they are important to consider, they are not necessarily factors that students would have thought of. The reason is because they are primarily factors regarding structure of course curriculum and storage of equipment. Of the six factors Dr. Miller proposed, four provided support for student factors.

5.3. Industry Supporting Data

Much like the instructor data, the industry data was gathered to support the factors proposed by students. The questions presented to the industry professional, the answers to which can be seen in Chapter 4, were asked to provide insight into what his company would like to see taught in education. The factors he felt would have to be considered are as follows:

- Project based
- How it is implemented which can be as simple as possible
- That students have skills in modeling
- Spatial ability
- Have professors complete exercises so they know what questions to expect
- Be familiar with the equipment
- Acceptance of RE by faculty

Of the factors that he felt were necessary to consider, five of the factors were thought to be important according to students. His opinions provide support for the students' perspective. The ability to obtain an industry opinion helped provide factors that neither the students nor professor had considered. The insight he provided into what his company did and his opinion of the best way to teach the material was invaluable.

5.4. Conclusions

The study that was conducted provided students with an opportunity to voice their opinions on RE. It is not often that students are able to provide their insight into what they would enjoy learning and what types of exercises and assignments should be included in their course work. Students gave valuable comments on exercises they would like to complete, equipment they would like to use, methods they would enjoy learning, and the best way they learn material. The experience also gave students a chance to use a technology that was new to the university and had only been used by two people prior to the study.

The factors that the students provided would be very helpful if RE was implemented into engineering curricula. Both the instructor and industry professional supported factors that the students proposed to be important and added others that the students may not have considered. If RE methodology is incorporated into engineering curricula more data would have to be gathered from instructors and industry to solidify a course structure that would not only be successful but could be translated to other universities as well.

5.5. Recommendations

Many avenues for future research have emerged from the completion of this study. Some areas that could benefit from further research include spatial ability, industry, and education. Studies on the effect of the 3D scanning process on spatial ability, the effect that incorporating RE has on engineering curricula, and the effect that RE has on education as a whole can be based off this study. Future research study details are given in the following sections.

5.5.1. Effect of 3D Scanning on Spatial Ability

During the study students were asked if they played video games and if so what types of video games. According to Dorval and Pépin (1986), spatial ability can be improved through playing video games. Therefore, it may be possible that certain types of video games have more of an effect than others. Students, from the study, who played video games involving 3D maneuvers such as the Call of Duty series and the Halo series performed the calibration process faster then those students who played 2D games such as Mario and World of Warcraft. In addition, students who played any type of video game calibrated the scanner faster than students who played no video games at all. Future research can be done to determine if certain types of video games, such as first person shooters, have more of an effect on spatial ability than others.

Characteristics such as age, gender, and race are some reasons why spatial ability levels differ. Athletes in sports such as basketball, football, and baseball may have higher levels of spatial ability than those who play no sports at all. A study can be

conducted using the 3D scanner calibration process to determine if there is a significant difference between athletes and non-athletes when comparing calibration times. Completing that type of study could add support to spatial ability playing a role in the calibration process of a handheld 3D scanner.

As stated above students that played video games were able to calibrate the scanner faster than those who did not. It may be possible that spatial ability plays a role in the scanning calibration process. With a sample study of only 10 students it is hard to determine if spatial ability does play a factor in the 3D scanning process. A future study can be conducted with 3D handheld scanning technology to determine if spatial ability is important when calibrating and operating 3D scanning technology.

Many studies have been done regarding spatial ability and those studies have provided reasons for why spatial ability levels differ. There are many studies that can be conducted from the work provided in this research. Some questions that can be answered through further research are, "Do athletes perform better on 3D scanning exercises than non athletes?" and "Do people who have only been exposed to items such as Legos or Erector sets perform better or worse than people who have only been exposed to video games?" In the latter question, the first group would be people who have never played video games, but have played with Legos or similar items. The second group would be comprised of people who only play video games and have never used Legos and other hands-on items.

5.5.2. Industrial Applications

Within industry there are many jobs where spatial ability is helpful to performance. These include careers such as unmanned aerial vehicle (UAV) pilot, crane operator, and microsurgery to name just a few. According to Chen (2010), participants that had high spatial ability levels performed tasks better when using video streamed from a UAV to guide a ground robot to target locations. It may be possible that using a handheld 3D scanner could have an effect on one's job performance with jobs having similar movements regarding spatial orientation and spatial relation as the 3D scanner. A future study regarding this would be to have two participant groups. The first group would use the 3D scanner to complete the calibration process and the other group would be the control group and complete no training. Both groups would then complete a task, such as the UAV task mentioned above, to determine if completing the 3D calibration process has an effect on job performance. Other studies can also be conducted with crane operators and micro surgeons to determine if the calibration process of a 3D scanner has an effect on job performance.

5.5.3. Educational Applications

The factors discovered in the study give good insight into what needs to be considered before RE implementation can become a reality. There have been studies involving RE courses as stated in Chapter 2. Further research can be conducted to determine if the factors discovered in this study play a part in RE incorporation. By

incorporating RE into a test course it can be determined what factors are important to the implementation.

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APPENDICES

Appendix A. Reverse Engineering Methodology Lecture

What is Reverse Engineering (RE)?

RE is the, " the process of starting with a finished product and working backwards to analyze how the product operates or how it was made " (United States District Court, 1989).

RE is "the general process of analyzing a technology specifically to ascertain how it was designed or how it operates" (Tang, Zhu, & Xu, 2010, p. 723)

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Phases of RE

PHASES	SOURCE
1. Data evaluation 2. Data generation 3. Design verification 4. Design implementation	(Ingle, 1994, p. 9)
1. Data capture 2. Preprocessing 3. Segmentation and surface fitting 4. CAD model creation	(Várady, Martin, & Cox, 1997, p. 256)
1. Digitizing 2. Data segmentation 3. Data fitting	(Sokovic & Kopac, 2005, p. 3)
1. Scanning – Digitizing 2. Processing captured data 3. Surface creation 4. CAM/technical documentation	(Sokovic, Cedilnik, & Kopac 2005, p. 602)
1. Prescreening 2. Observation 3. Dissection 4. Analysis	(Younis & Tutunji, 2010, p. 3)

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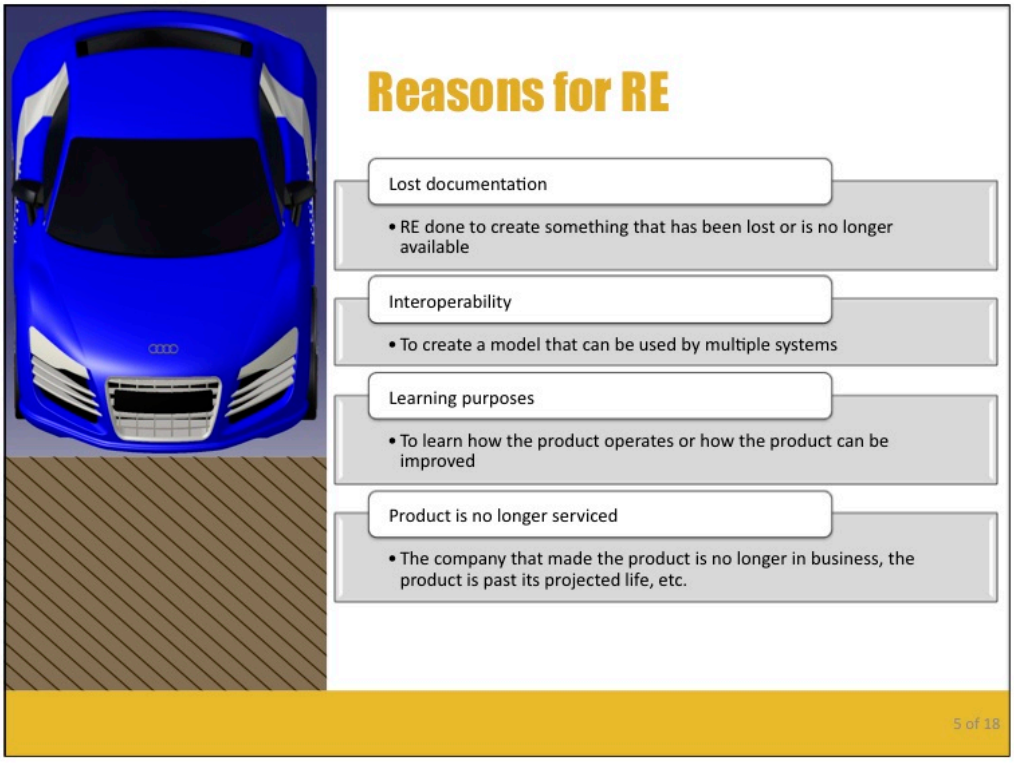
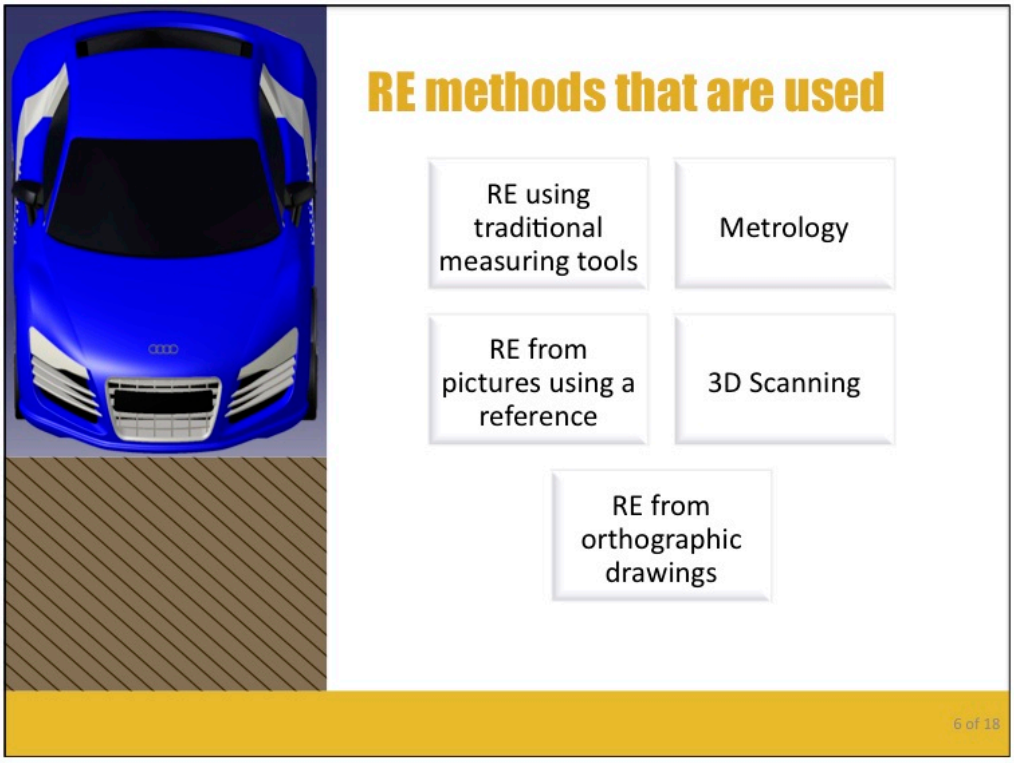
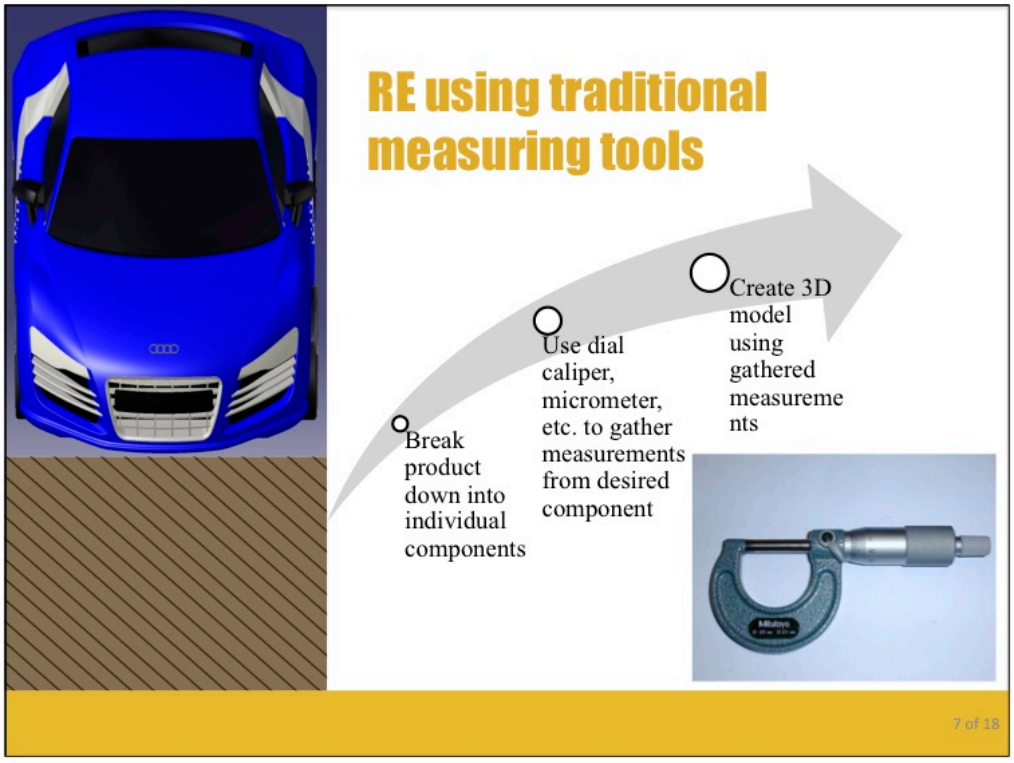
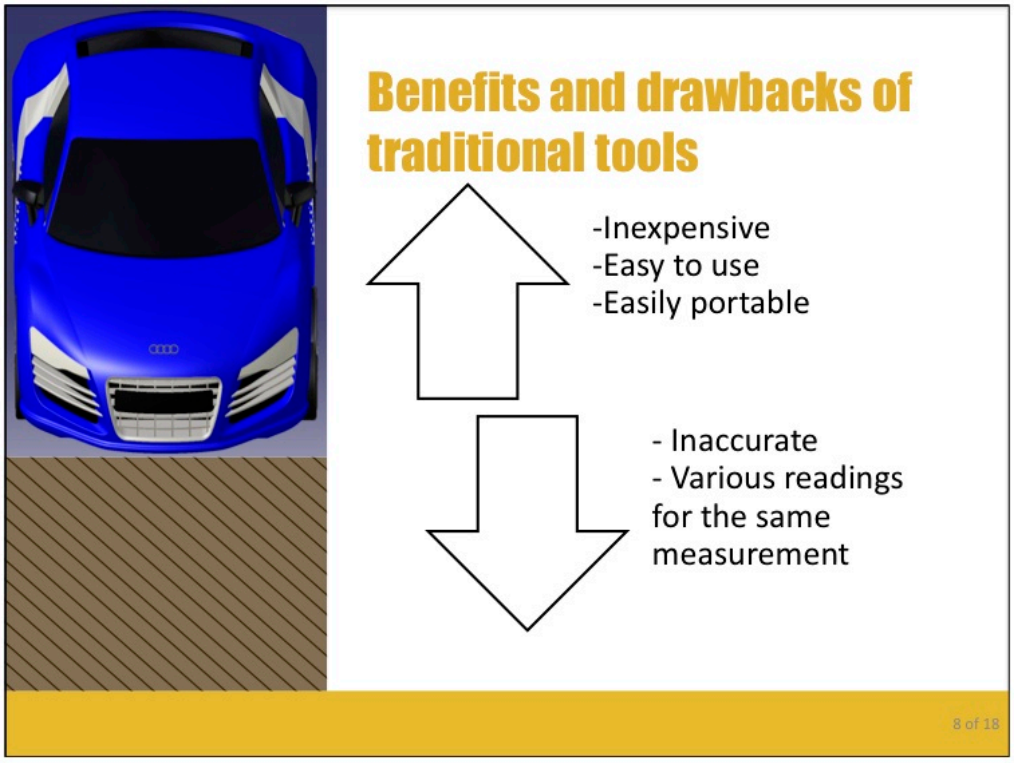
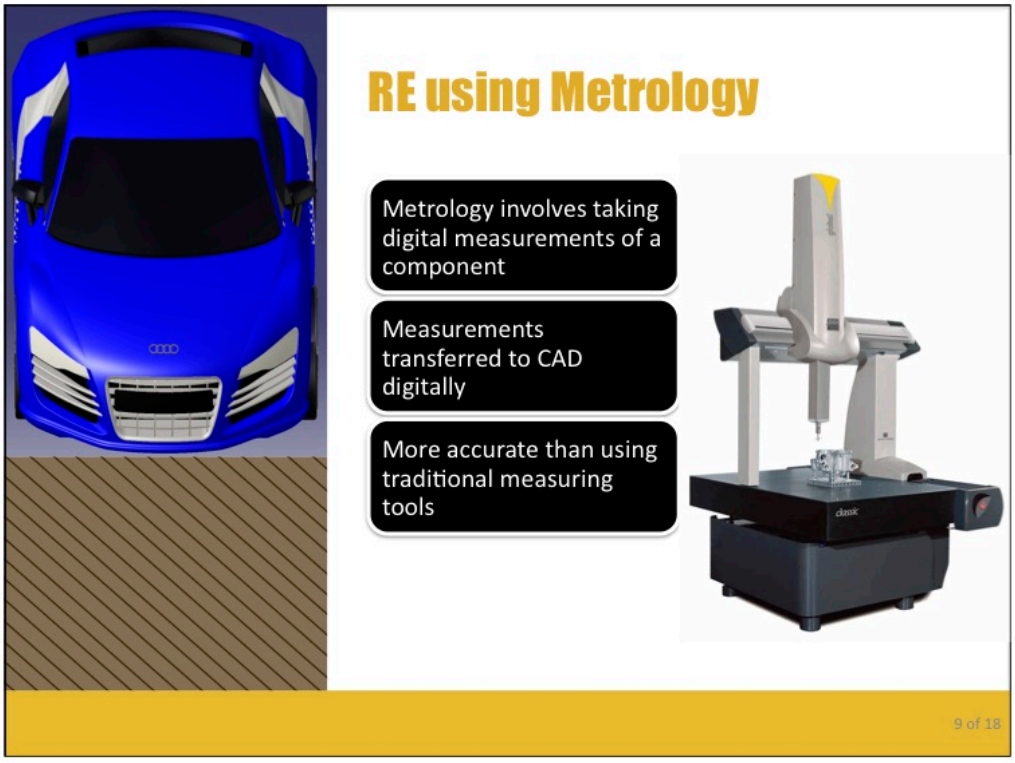
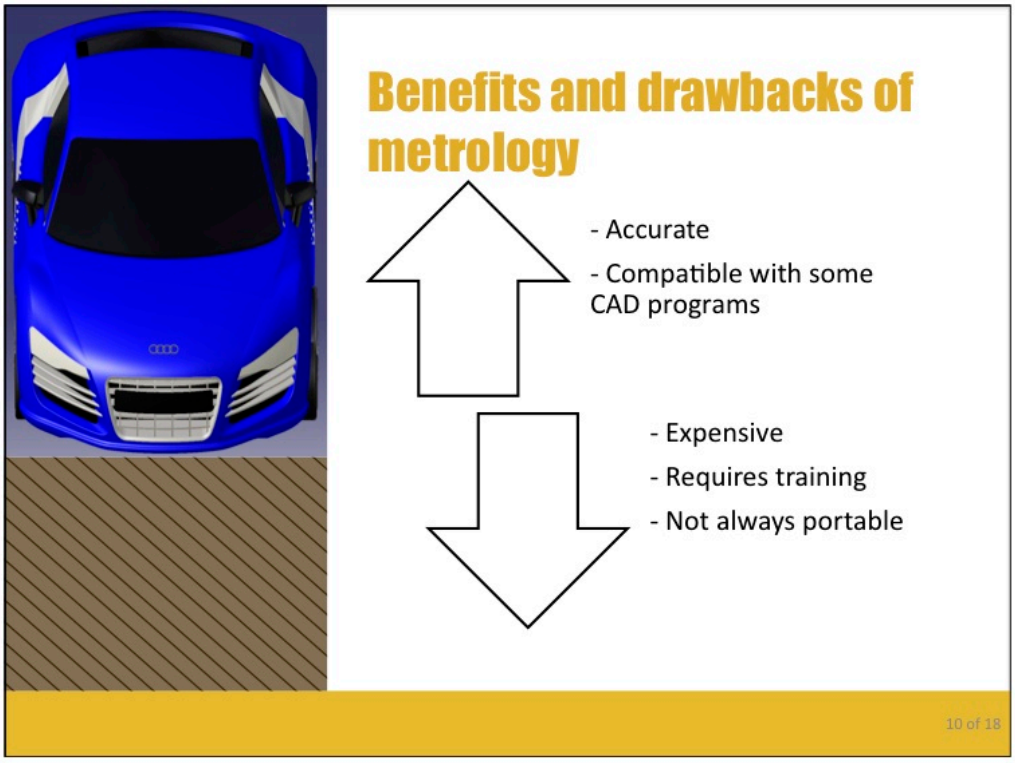


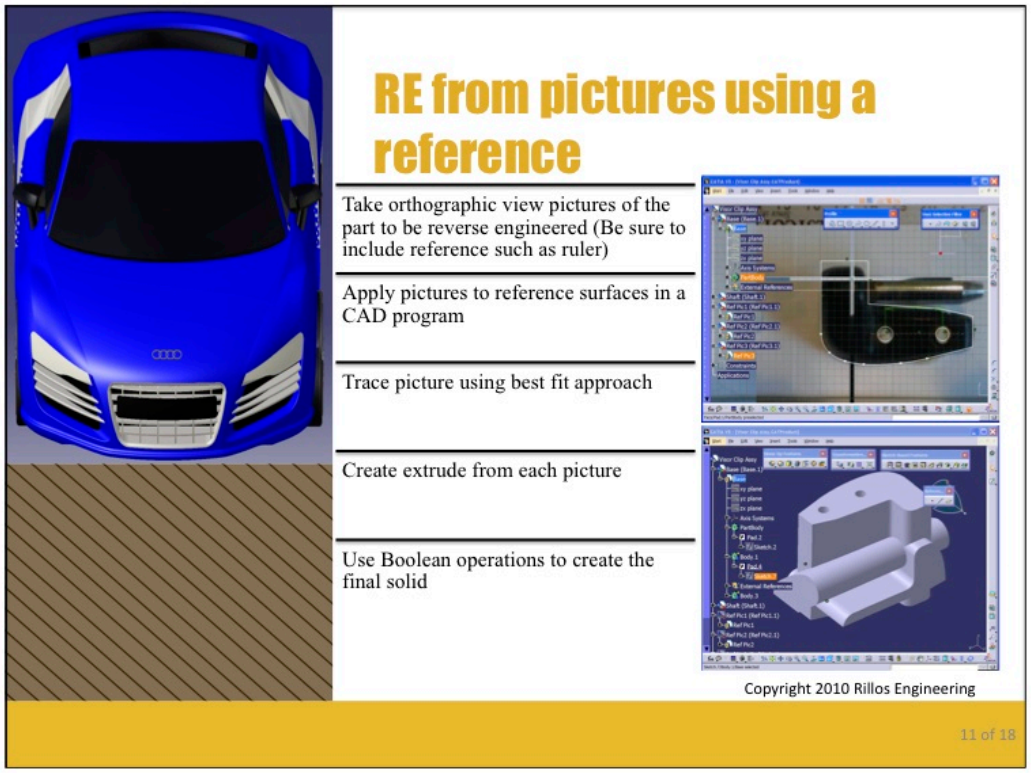


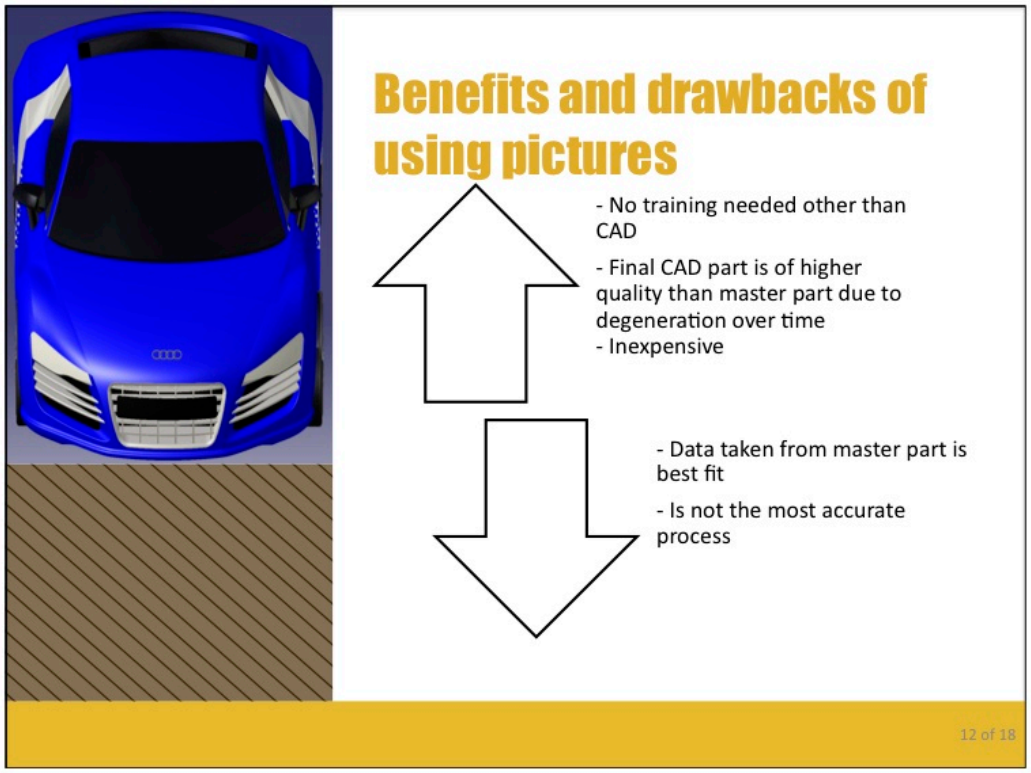


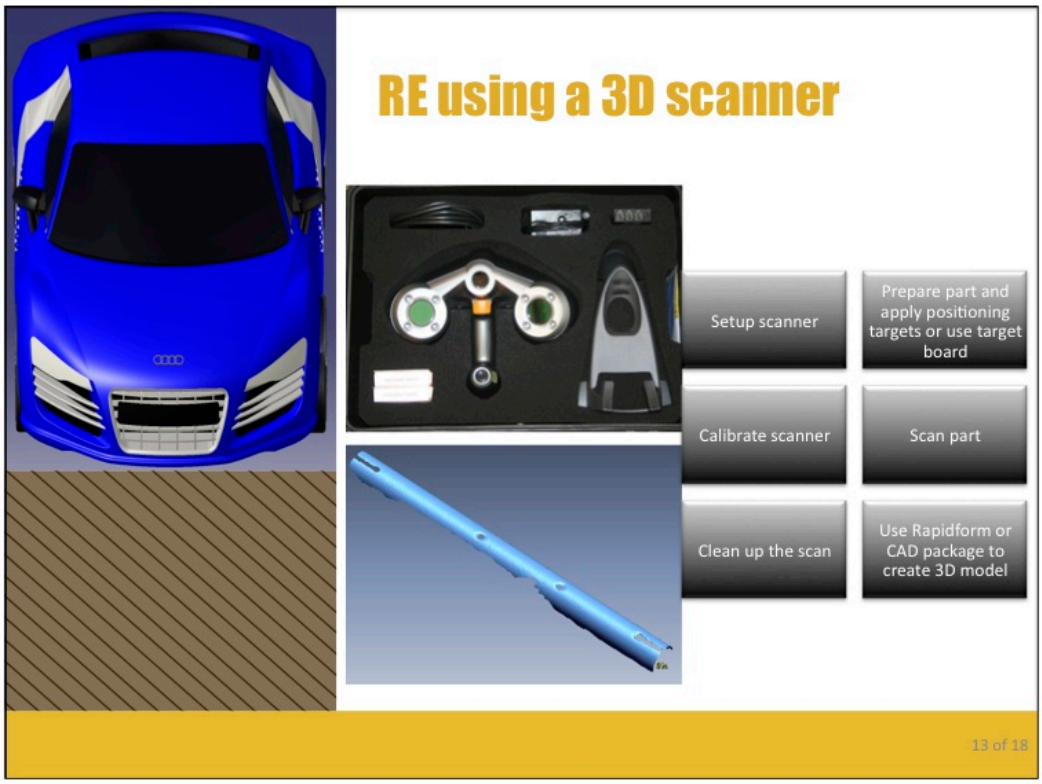


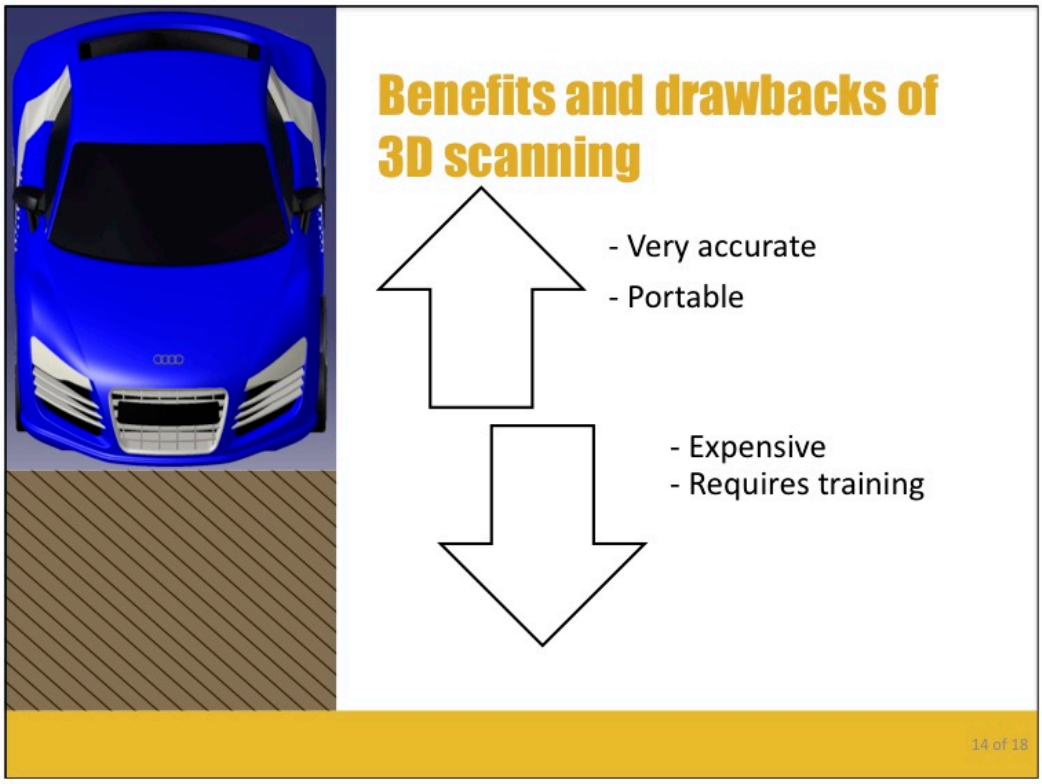


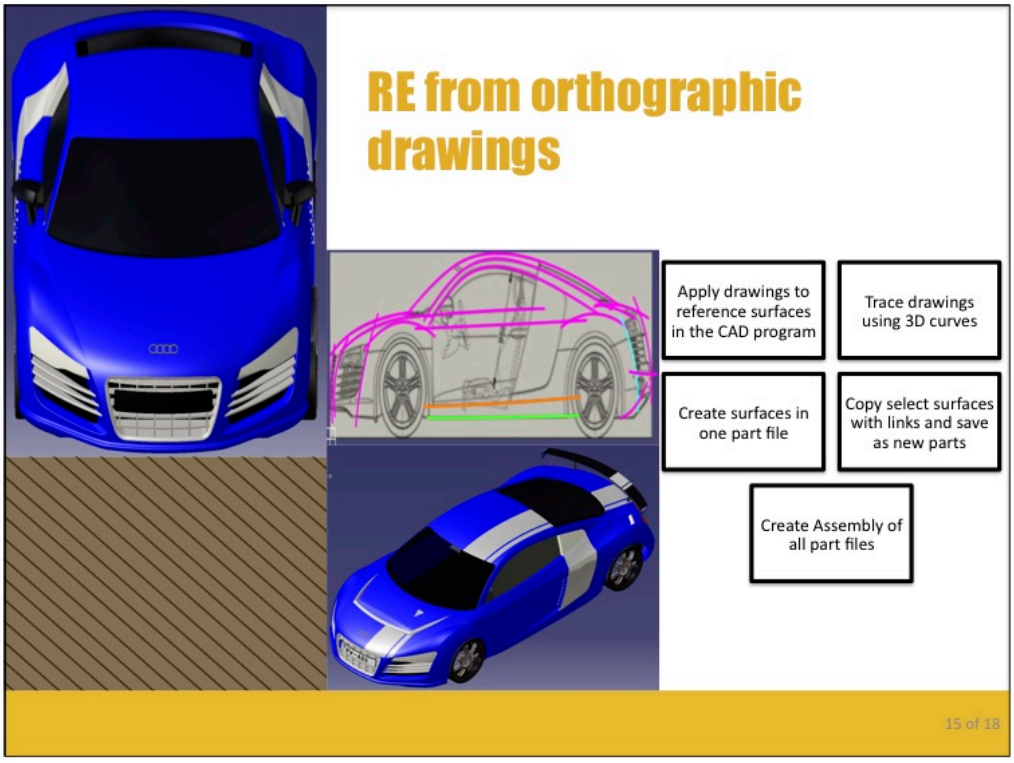


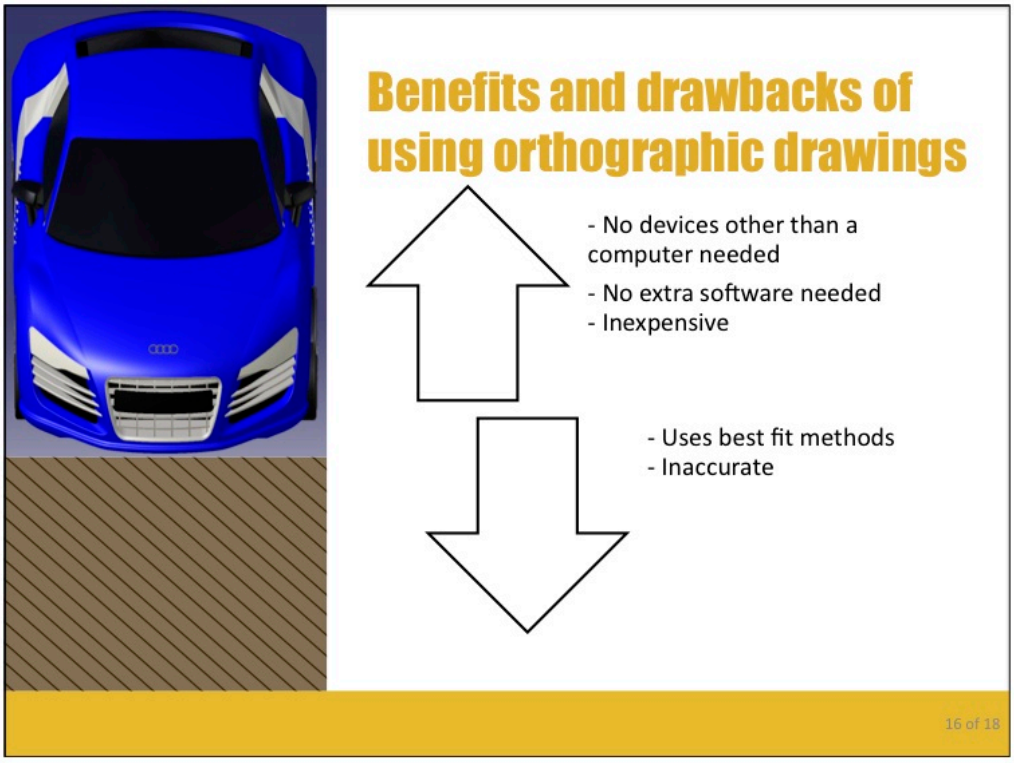


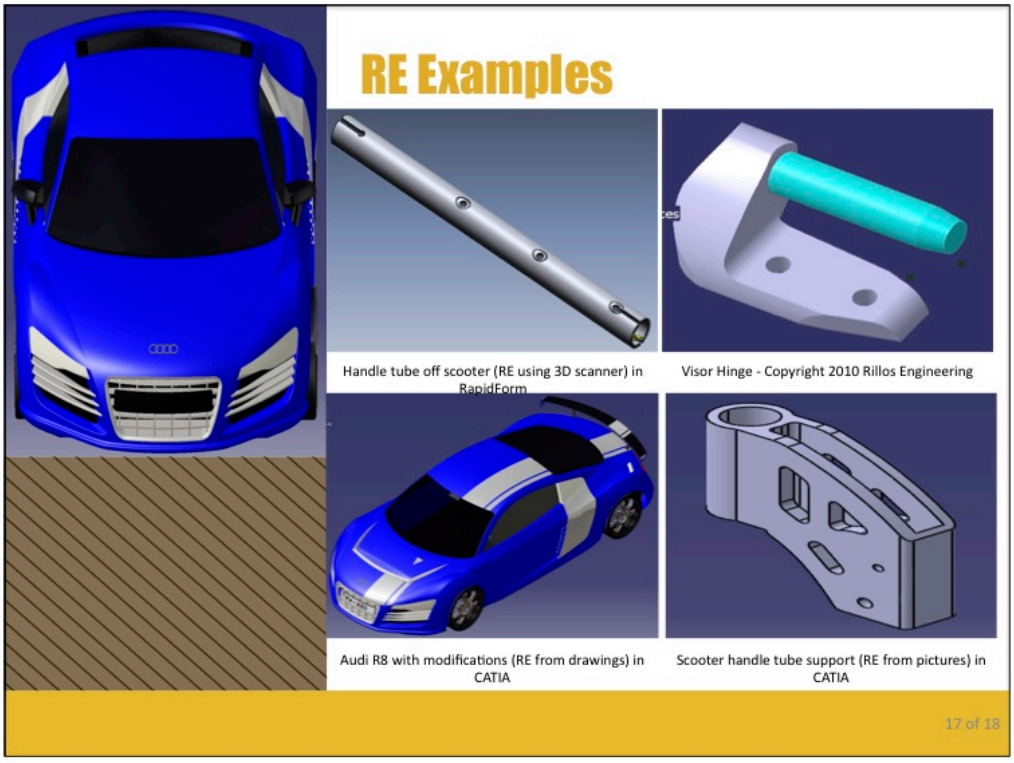


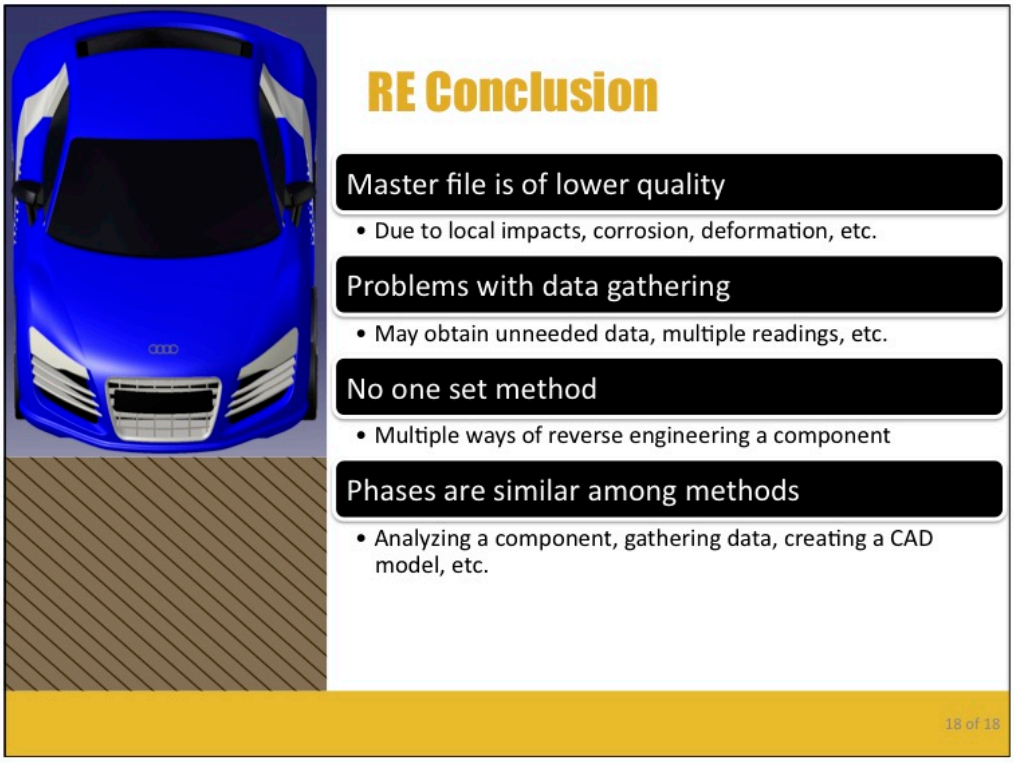




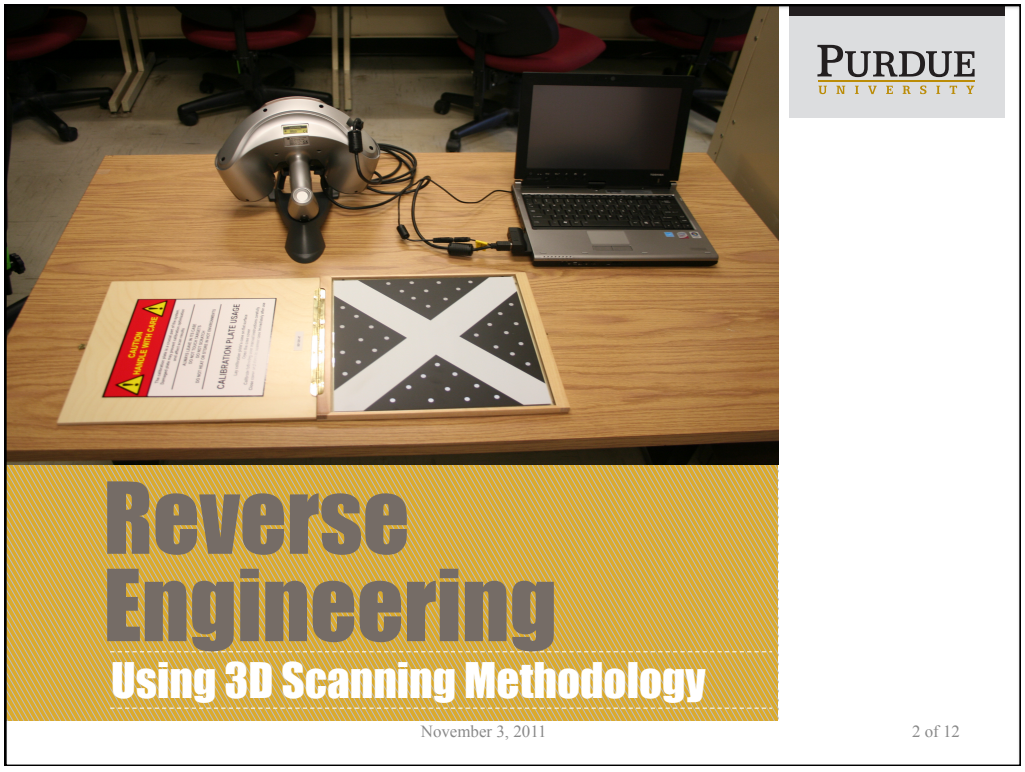








Appendix B. 3D Scanning Lecture



Scanner Preparation

Setup

Setup scanner hardware

Position equipment correctly

Start ZScan software

Scanner contents:

- 3D Scanner
- Scanner stand
- Power cables
- Firewire cable and Adapter
- Positioning targets
- Cleaning cloth
- Target board
- Calibration plate (GLASS BE CAREFUL)

Preparing the Part

Positioning targets

Prepping the part

- The part must be as clean as possible
  - The scanner will pick up any dirt, scratches, etc. as data
- Apply positioning targets

Types of Positioning Targets

- Black contour (stickers that are non-reusable)
- Magnetic black contour (reusable)
- Target board (reusable)

Preparing the Part (Cont.)

Common Issues

Cleanliness
- The scanner will pick-up everything
- Do not lay objects near scanning area

Curved Objects
- The scanner has issues recognizing positioning features on curved surfaces
- The best option for these parts is to use the target board

Positioning Targets
- More targets does not equal better scan
- The scanner must see 4 targets at all times
- Do not place on important features because the scanner does not pick up data behind the targets

Reflectivity
- The more reflective the part the harder it is to collect data

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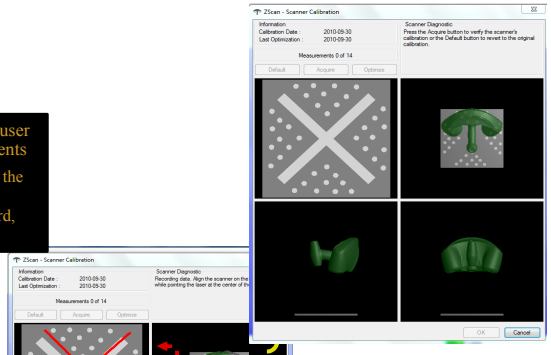
Calibration

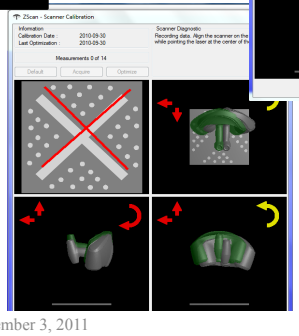
Using the calibration plate

Use calibration plate to calibrate the scanner
- This must be done every day or when conditions change (temperature, lighting, etc.)

Calibration requires the user to acquire 14 measurements
- 10 measurements are on the same plane
- The last 4 require forward, backward, and sideways rotations

You may take breaks during scanning





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Configuration

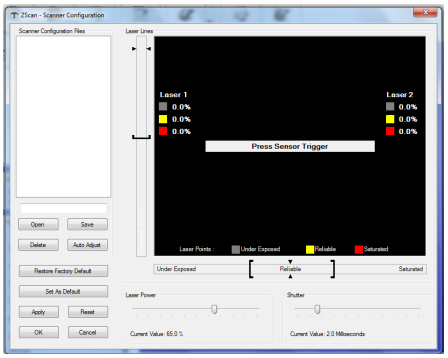
Scanner configuration

This option allows for the user to adapt scanning properties to the type of part they are scanning

- The more yellow the better
- Red means there is too much saturation
- Gray means it is underexposed

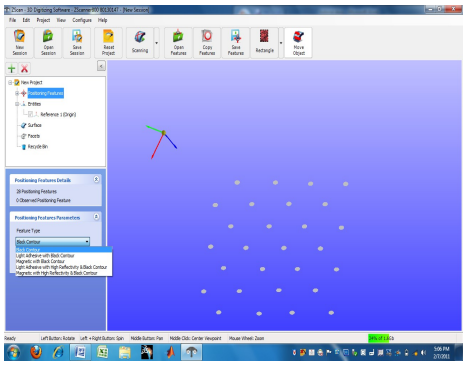
Use this process to adjust the laser power and shutter to achieve optimal scan

When using reflective parts, colored parts, etc. then use this process



Scanning

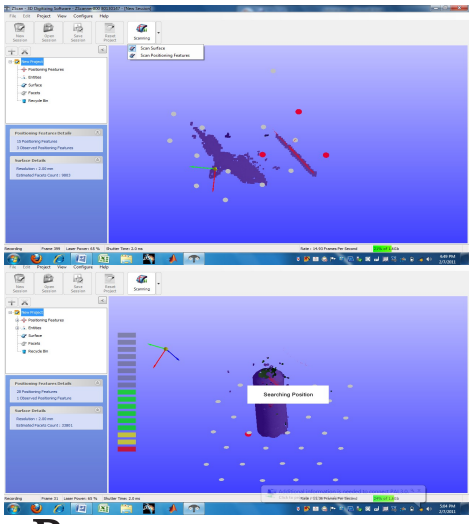
Scanner Settings



Set resolution for the scan	Set type of positioning targets used	Select to fill holes caused by positioning targets
• The smaller the resolution value the more accurate the scan (1mm is better than 2mm) • The smaller the resolution the more RAM the computer uses which may crash the program	• Black contour • Black contour with adhesive • Magnetic	• Anything behind the targets does not get scanned

Scanning (Cont.)

Scanning Process



When scanning move the scanner in a circular pattern slowly

Taking breaks

- If you take a break from scanning restart on a section you have already scanned

Must have 4 targets recognized at all times

The scanner does not scan the center of the X created by the lasers

Pay attention to the bar on the left

- Green is the best
- Red on the bottom means you are too far away
- Red on top means you are too close

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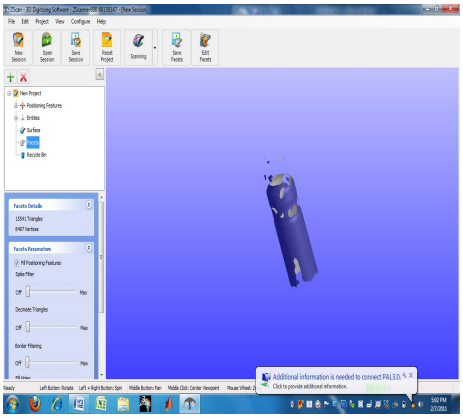
Cleaning up the scan

Clean up

Make sure to fill in the holes left by the positioning targets

Eliminate patches of non needed data

A third party software called RapidForm is needed to create the 3D model



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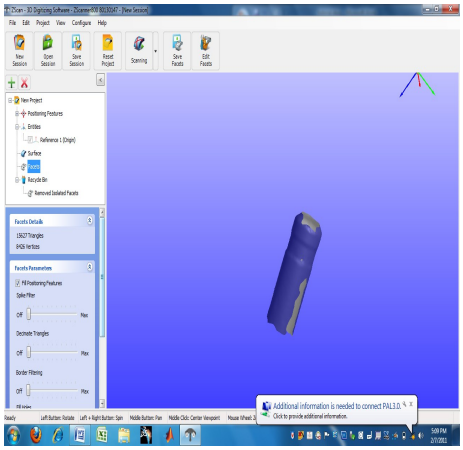
Exporting

Sending to other programs



Save the data as:

- Session of the scan
- The point cloud
- The positioning targets
- The facets

Point clouds can be imported into CAD programs

Facets can be sent to RapidForm

Positioning features can be saved and used for future scans of the part

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November 3, 2011

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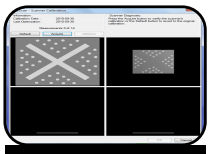
Conclusion

3D scanning reviewed

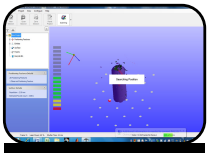
The equipment is expensive

It is very accurate but the more accurate the more RAM the program will use

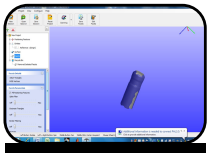


The equipment is portable

There are issues with reflective materials and curved features



Requires extensive training to become proficient



Requires training in third party software (RapidForm)

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Appendix C. Example Email Survey Invitation

CGT 163 students,

Please read this ENTIRE email.

Remember this survey is strictly voluntarily, and you must be 18 years old or older to participate. If you choose to participate by taking this survey you agree to complete questions of the survey honestly and entirely regarding the information you learned in the two class lectures involving reverse engineering methodology. If you come across a question that you do not feel comfortable answering you may skip that question and move on to the next one. No identifiable information will be asked for in this survey and you have the right to withdraw at any time without penalty. Participation in this survey will not affect your standing in the class or with the department. I ask that you complete the survey in its entirety and to the best of your ability in order to accurately assess your answers.

Once you have completed the survey you WILL NOT be able to return to it, so make sure that you answer all questions completely before submitting your survey or the information will not be valid. Remember that this survey is completely voluntary and your choice to participate will not affect your grade or standing in the course or with the department.

Click on the following link which will direct you to the survey:

https://purdue.qualtrics.com/SE/?SID=SV_cGAWTg2HZvaOM4Y

If you have any questions please email me at twanamak@purdue.edu

Thank you,

Trevor Wanamaker

Appendix D. Survey Consent Form

RESEARCH PARTICIPANT CONSENT FORM
Reverse Engineering Hands-on Learning Experience
Dr. Patrick E. Connolly
Purdue University
Computer Graphics Technology

Purpose of Research
This study is being conducted to discover what factors students feel need to be considered when incorporating reverse engineering methodology into their engineering curricula.

Specific Procedures
Prior to completing this survey you must give consent so that the researcher (Trevor Wanamaker) may access your answers to the following survey.

Duration of Participation
The completion of this survey should take no longer than one hour to complete.

Risks
You will not be exposed to any risk that is greater than what you would encounter in normal every day life. All answers you provide are anonymous and you are not asked to provide any identifiable information in the survey.

Benefits
You may learn reverse engineering methodology that could help you in your professional growth.

Compensation
If asked to participate in a hands-on learning experience you can receive up to 3% extra credit towards your final course grade. If you are not asked to participate you will have the opportunity to complete an alternative problem to receive the extra credit points.

Confidentiality
The project's research records may be reviewed by departments at Purdue University responsible for regulatory and research oversight. The data that is obtained from this study will be stored in the office of the Principal Investigator (Dr. Patrick Connolly) in a filing cabinet.

The data will only be accessible by the Principal Investigator and the Co-Investigators (Dr. James Mohler and Trevor Wanamaker). The data will be stored for a minimum of five years and will be used for other purposes in the future. This survey is completely anonymous and no identifiable information will be collected.

Voluntary Nature of Participation
You do not have to participate in this research project. If you agree to participate you can withdraw your participation at any time knowing you will not receive extra credit. Your decision to participate in or withdraw from the study will not affect your grade or standing with your department.

Contact Information:
If you have any questions about this research project, you can contact Dr. Patrick E. Connolly (765) 496-3943 and Trevor Wanamaker (513) 309-6704. Trevor Wanamaker is the first point of contact. If you have concerns about the treatment of research participants, you can contact the Institutional Review Board at Purdue University, Ernest C. Young Hall, Room 1032, 155 S. Grant St., West Lafayette, IN 47907-2114. The phone number for the Board is (765) 494-5942. The email address is irb@purdue.edu.

Documentation of Informed Consent
I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research project and my questions have been answered. By choosing YES below I consent that I am prepared to participate in the research project described above.

- Yes
- No

Appendix E. Reverse Engineering Survey

What is your major?

How much did you like the RE lectures?

Did you have any knowledge of RE prior to the lectures?

What was most interesting about the RE methodology lectures?

What part of the RE methodology lectures was not interesting and what would you suggest to improve it?

In your opinion do you feel that hands on or theory based textual/visual materials would be more valuable to your learning when incorporating RE into a course?

Is there an aspect of RE that you feel would be beneficial to your professional development? If so, why?

Is there an aspect of RE that you feel is overwhelming or too complex? If so, why?

Would you like RE methodology incorporated into your engineering curriculum? Why or why not?

Do you feel that the ability to visualize is important for the use and implementation of RE technology into engineering courses?

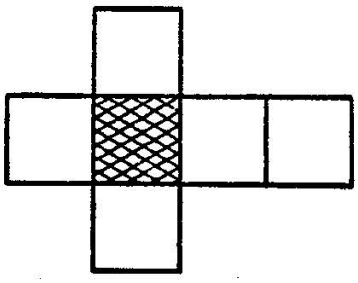
Appendix F. Purdue Spatial Visualization Test of Rotations

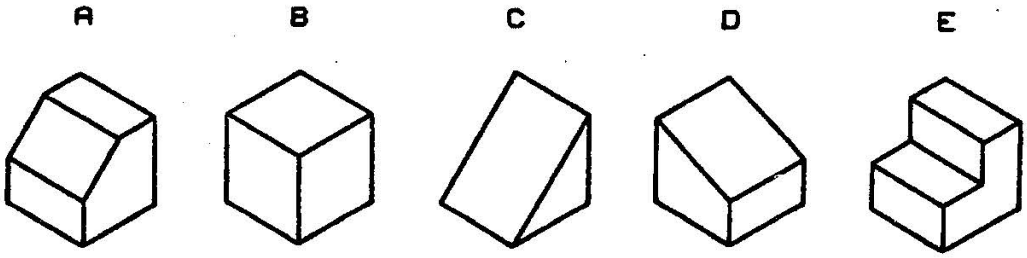
Do NOT make any marks in this booklet.
Mark your answers on the separate answer card.

SECTION 1: DEVELOPMENTS

Directions

The first section of this test consists of 12 questions designed to see how well you can visualize the folding of developments into three-dimensional objects. Shown below is an example of the type of question included in the first section of this test.





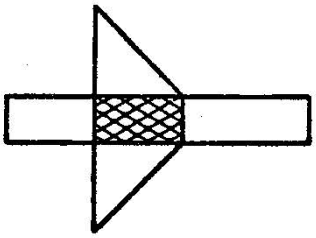
Presented is a development and five three-dimensional objects. The development shows the inside surfaces of a three-dimensional object. The shaded portion of the development indicates the bottom surface of the three-dimensional object. You are to:

1. picture in your mind what the development looks like when folded into a three-dimensional object;
2. select from among the five objects (A, B, C, D, or E) the one that looks like the folded development.

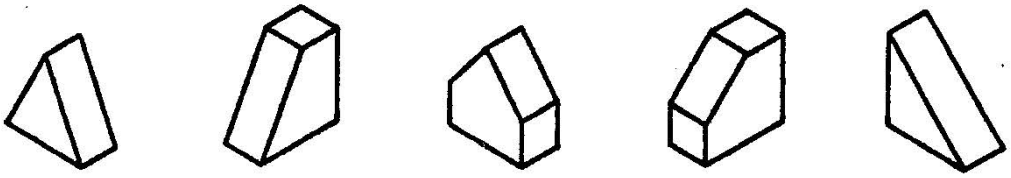
What is the correct answer to the example shown above?

Answers A, C, D, and E are wrong. Only object B can be made by folding the given development. In all three sections of this test, each question has only one correct answer.

Now look at the next example shown below and try to select the one three-dimensional object that can be made when the given development is folded. Remember that the development shows the inside of the object and the development's shaded portion indicates the bottom of the object.



A B C D E



The correct answer for this example is E.

During the test you are to show your choices on the answer card by making a heavy black mark in the space with the same letter as the answer you choose.

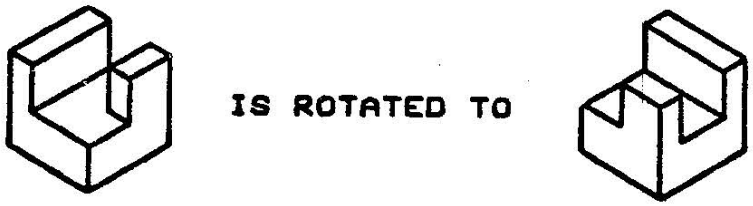
Do NOT make any marks in this booklet.
Mark your answers on the separate answer card.
You will be told when to begin.

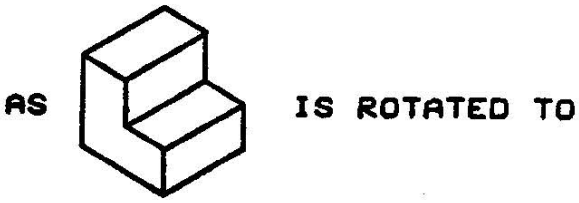
Do NOT make any marks in this booklet.
Mark your answers on the separate answer card.

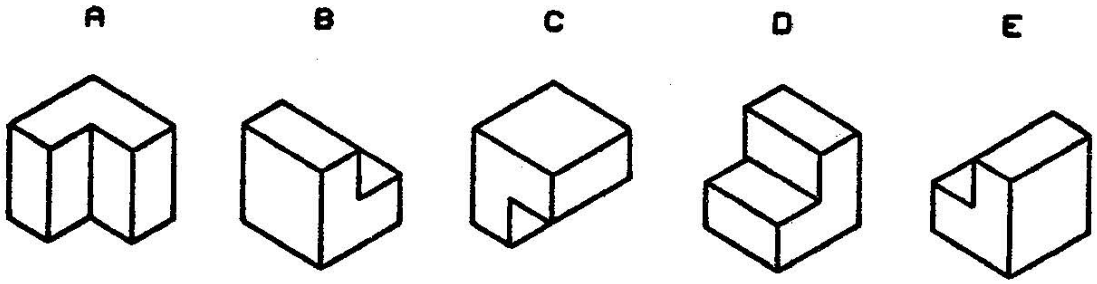
SECTION 2: ROTATIONS

Directions

The second section consists of 12 questions designed to see how well you can visualize the rotation of three-dimension objects. Shown below is an example of the type of question included in the second section.







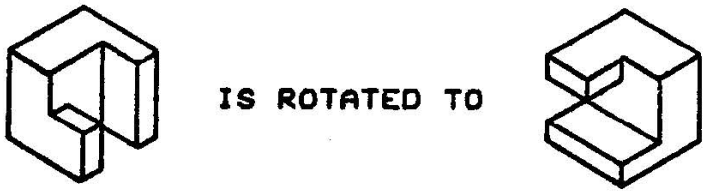
You are to:

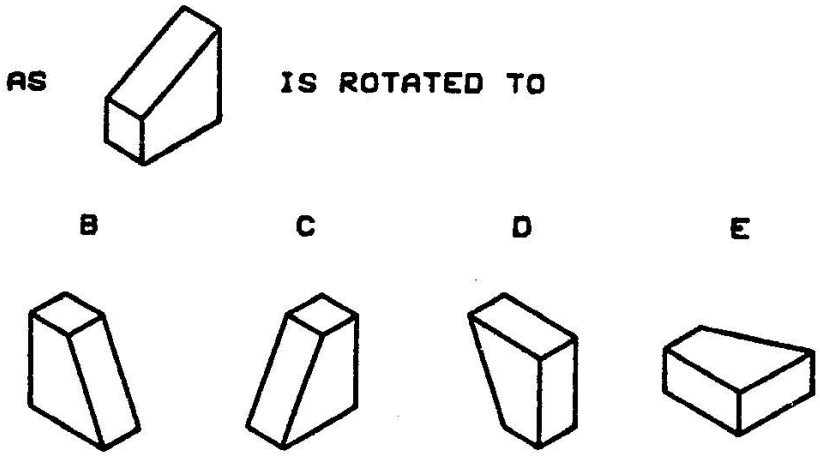
1. study how the object in the top line of the question is rotated;
2. picture in your mind what the object shown in the middle line of the question looks like when rotated in exactly the same manner;
3. select from among the five drawings (A, B, C, D, or E) given in the bottom line of the question the one that looks like the object rotated in the correct position.

What is the correct answer to the example shown above?

Answers A, B, C, and E are wrong. Only drawing D looks like the object rotated according to the given rotation. Remember that each question has only one correct answer.

Now look at the next example shown below and try to select the drawing that looks like the object in the correct position when the given rotation is applied.





Notice that the given rotation in this example is more complex. The correct answer for this example is B.

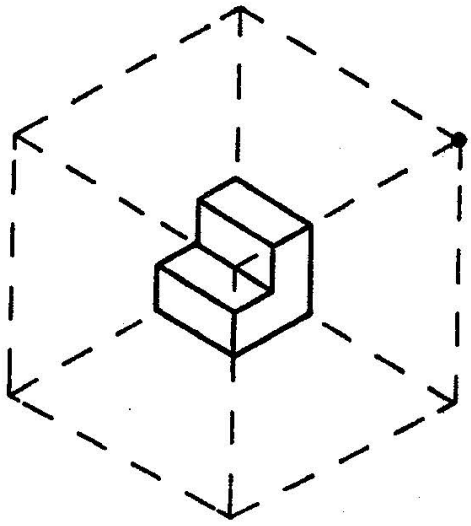
Do NOT make any marks in this booklet.
Mark your answers on the separate answer card.
You will be told when to begin.

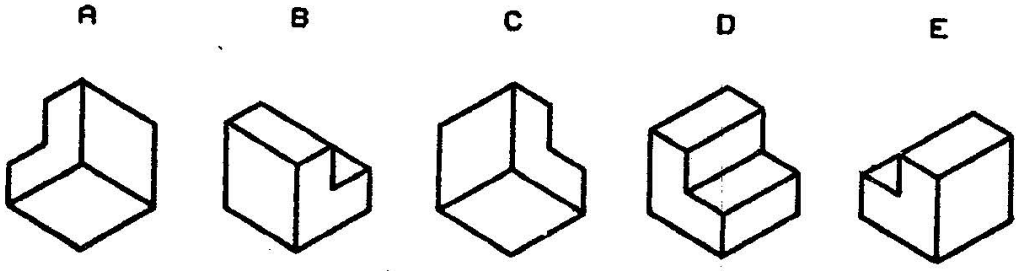
Do NOT make any marks in this booklet.
Mark your answers on the separate answer card.

SECTION 3: VIEWS

Directions

The third section consists of 12 questions designed to see how well you can visualize what three-dimensional objects look like from various viewing positions. Shown below is an example of the type of question included in the third section.





The example shows an object positioned in the middle of a "glass box" and five drawings representing what the same object looks like when seen from different viewing positions. The black dot in the top right corner of the "glass box" identifies the desired viewing position. You are to:

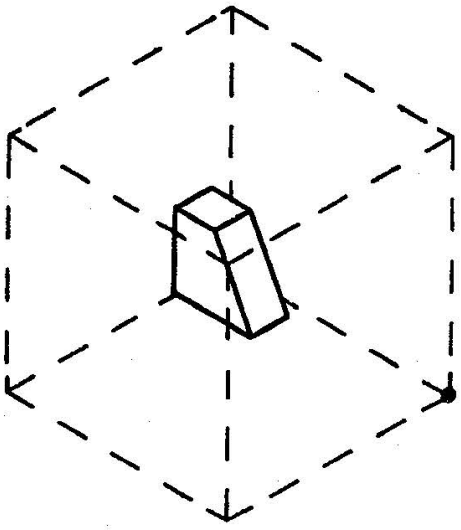
1. imagine yourself moving around the "glass box" until the black dot is located directly between you and the object;

2. from this viewing position picture in your mind what the object in the "glass box" looks like;
3. select from among the five drawings (A, B, C, D, or E) the one that looks like the object as seen from the viewing position.

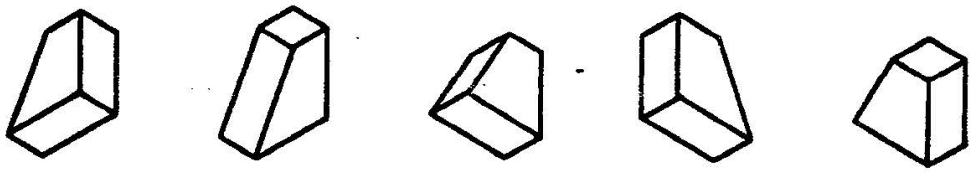
What is the correct answer to the example shown on the page just before this one?

Answers A, B, C, and D are wrong. Only drawing E looks like the object as seen from the given viewing position. Remember that each question has only one correct answer.

Now look at the next example shown below and try to select the one drawing that represents what the object looks like from the given viewing position. Remember that the object is located in the middle of the "glass box" and you are imagining yourself looking at the object with the black dot between you and the object.



A B C D E



The correct answer for this example is C.

You will be told when to begin.

Appendix G. Human Subjects Approval

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HUMAN RESEARCH PROTECTION PROGRAM
INSTITUTIONAL REVIEW BOARDS

To:	PATRICK CONNOLLY KNOY 323
From:	JEANNIE DICLEMENTI, Chair Social Science IRB
Date:	10/25/2011
Committee Action:	Approval
IRB Action Date	10/25/2011
IRB Protocol #	1109011199
Study Title	Reverse Engineering Hands-on Learning Experience
Expiration Date	10/24/2012

Following review by the Institutional Review Board (IRB), the above-referenced protocol has been approved. This approval permits you to recruit subjects up to the number indicated on the application form and to conduct the research as it is approved. The IRB-stamped and dated consent, assent, and/or information form(s) approved for this protocol are enclosed. Please make copies from these document(s) both for subjects to sign should they choose to enroll in your study and for subjects to keep for their records. Information forms should not be signed. Researchers should keep all consent/assent forms for a period no less than three (3) years following closure of the protocol.

Revisions/Amendments: If you wish to change any aspect of this study, please submit the requested changes to the IRB using the appropriate form. IRB approval must be obtained before implementing any changes unless the change is to remove an immediate hazard to subjects in which case the IRB should be immediately informed following the change.

Continuing Review: It is the Principal Investigator's responsibility to obtain continuing review and approval for this protocol prior to the expiration date noted above. Please allow sufficient time for continued review and approval. No research activity of any sort may continue beyond the expiration date. Failure to receive approval for continuation before the expiration date will result in the approval's expiration on the expiration date. Data collected following the expiration date is unapproved research and cannot be used for research purposes including reporting or publishing as research data.

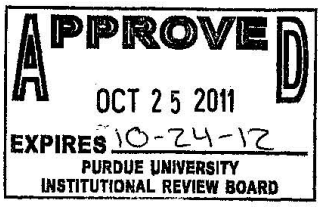
Unanticipated Problems/Adverse Events: Researchers must report unanticipated problems and/or adverse events to the IRB. If the problem/adverse event is serious, or is expected but occurs with unexpected severity or frequency, or the problem/even is unanticipated, it must be reported to the IRB within 48 hours of learning of the event and a written report submitted within five (5) business days. All other problems/events should be reported at the time of Continuing Review.

We wish you good luck with your work. Please retain copy of this letter for your records.

Ernest C. Young Hall, 10th Floor - 155 S. Grant St. - West Lafayette, IN 47907-2114 - (765) 494-5942 - Fax: (765) 494-9911

Appendix H. Consent Form

For IRB Office Use Only



Research Project Number 1109011199

RESEARCH PARTICIPANT CONSENT FORM
Reverse Engineering Hands-on Learning Experience
Dr. Patrick E. Connolly
Purdue University
Computer Graphics Technology

Purpose of Research

This study is being conducted to discover what factors students feel need to be considered when incorporating reverse engineering methodology into their engineering curricula.

Specific Procedures

Prior to participating in the study you must give consent so that the researcher (Trevor Wanamaker) may access your course grade. Your course grade will be averaged with your score on the Purdue Spatial Visualization Test to determine if you will be asked to participate in the hands-on learning experience. If your scores lie in the range that is needed you will be asked to participate in a hands-on learning experience involving 3D scanning technology. Following the hands-on process you will undergo an interview immediately following the process as well as an additional interview a week following the experience. If you do not wish to give consent to access your course grade you will not be asked to participate. However, you will have the opportunity to complete an alternative problem to receive the extra credit.

Duration of Participation

You will be participating over the course of two weeks. The hands-on learning experience will take between two to four hours and each interview can take up to one and a half hours.

Risks

You will be exposed to minimal risk. Breach of confidentiality is a risk that is related to the research and safeguards are in place as listed below in the confidentiality section to minimize this risk. Anonymity is a risk of this study but classifying you by your lab division and seat number will eliminate your name from the study. Remember, there is a risk to confidentiality which will be minimized by keeping any data from the study in a secure area as explained in the confidentiality section below.

Benefits

You may learn reverse engineering methodology that could help you in your professional growth.

Compensation

You will receive up to 3% extra credit towards your final course grade. If you wish to withdraw or do not complete the study for any reason, you will not receive extra credit but you may complete the alternative problem to receive extra credit.

Confidentiality

The project's research records may be reviewed by departments at Purdue University responsible for regulatory and research oversight. The data that is obtained from this study will be stored in the office of the Principal Investigator (Dr. Patrick Connolly) in a filing cabinet.

Initials _____ Date _____

Research Project Number _____

The data will only be accessible by the Principal Investigator and the Co-Investigators (Dr. James Mohler and Trevor Wanamaker). This data includes survey answers, scores on the Purdue Spatial Visualization Test, course scores and interview data. The interview data will be transcribed and classified according to their lab section and all names will be omitted so that all data is anonymous. All audio recordings will be stored with the transcripts and will remain anonymous. The data will be stored for a minimum of five years and will be used for other purposes in the future. Your course scores as well as your scores for the Purdue Spatial Visualization Test will remain confidential and will have no identifying information associated with them.

Voluntary Nature of Participation

You do not have to participate in this research project. If you agree to participate you can withdraw your participation at any time knowing you will not receive extra credit. Your decision to participate in or withdraw from the study will not affect your grade or standing with your department.

Contact Information:

If you have any questions about this research project, you can contact Dr. Patrick E. Connolly (765) 496-3943 and Trevor Wanamaker (513) 309-6704. Trevor Wanamaker is the first point of contact. If you have concerns about the treatment of research participants, you can contact the Institutional Review Board at Purdue University, Ernest C. Young Hall, Room 1032, 155 S. Grant St., West Lafayette, IN 47907-2114. The phone number for the Board is (765) 494-5942. The email address is irb@purdue.edu.

Documentation of Informed Consent

I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research project and my questions have been answered. I am prepared to participate in the research project described above. I will receive a copy of this consent form after I sign it.

_____ _____

Participant's Signature Date

_____

Participant's Name

_____ _____

Researcher's Signature Date

Appendix I. Purdue Spatial Visualization Test of Rotations Approval

PURDUE
RESEARCH FOUNDATION

OFFICE OF TECHNOLOGY COMMERCIALIZATION

PERMISSION TO USE

8/29/2011

Requesting Party:
Trevor Wanamaker
2976 Snowdrop Drive
West Lafayette, IN 47906

Material: Purdue Spatial Visualization Tests; PRF Ref. No. 79891

Work Incorporating the Material (the "Publication"): Purdue Research Foundation ("PRF") hereby grants the Requester permission to use the Material for research as described in the Permission Request Form dated 8/23/2011 and attached hereto.

This Material is provided by Purdue Research Foundation on behalf of Purdue University as consistent with Purdue University's instructional objective, and its overall mission as a non-profit educational institution.

PRF makes no warranty that the Material provided hereunder will not infringe any third party patent or copyright and PRF makes no covenant either to defend any infringement charge by a third party. THE MATERIAL IS PROVIDED "AS IS", and PRF MAKES NO REPRESENTATIONS OR WARRANTIES, EXPRESS OR IMPLIED, AS TO ANY MATTER RELATING THERETO, INCLUDING BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE.

The Requesting Party will include an acknowledgement of the source of the Material. All inquiries regarding use of the Material must be directed to the Purdue Research Foundation.

The authorization provided is valid only to the extent that all of the activities undertaken are consistent with the understanding and conditions as stated herein, and can be revoked at the sole discretion of PRF.

Should you have any questions please feel free to contact our office.

Sincerely,

Elizabeth Hart-Wells, Ph.D
Assistant VP and Director
Office of Technology Commercialization

1281 Win Hentschel Blvd. ■ West Lafayette, IN 47906-4182 ■ 765-588-3475 ■ Fax 765-463-3486

Permission Request Form

Requester:

Name Trevor Wanamaker

Title

Address 2976 Snowdrop Drive, West Lafayette, IN 47906

Phone (513) 309-6704

Fax

Email address twanamak@purdue.edu

Complete Description of Work requested: **(Author, Exact Title, Source, Type of Work)**
Purdue Spatial Visualization Test

How will the Work be used: **(Purpose, detailed complete description)**

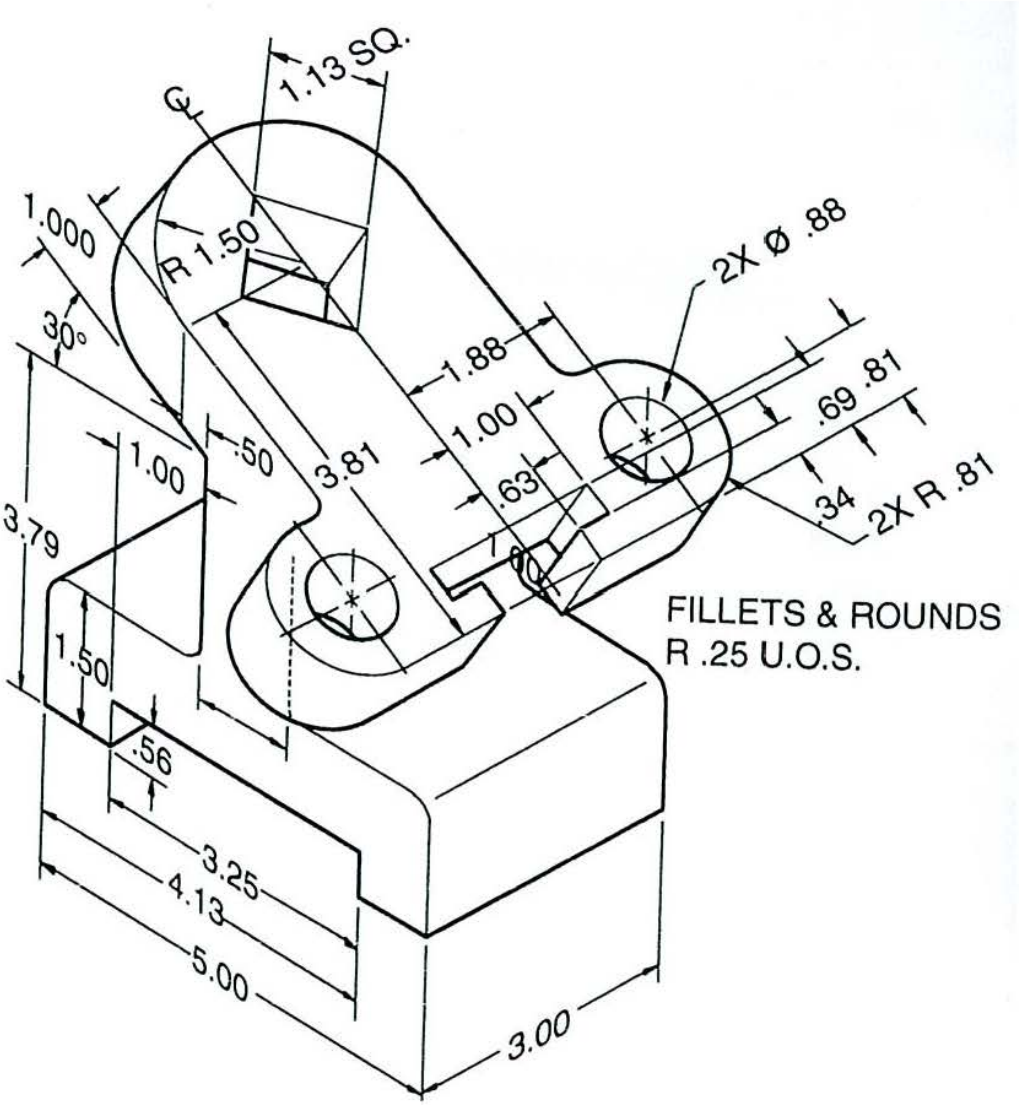
This work will be used in order to choose students to be involved in a research study. The students will take this test and from the results select students will be given an opportunity to complete activities in the classroom that will pertain to graduate research in the computer graphics technology department.

Trevor Wanamaker
Signature

8/23/2011
Date

RETURN COMPLETED FORM TO:
Office of Technology Commercialization
1281 Win Hentschel Blvd.
West Lafayette, IN 47906
Phone: (765) 588 -3474
Fax: (765) 463-3486
bkomalavally@prf.org

Appendix J. Extra Credit Problem



Support Vise

REQUIREMENTS:

Sketch

-Multiview sketch

*Front (inclined planes appears as an edge)

*Partial right side view (Use a convention break line to remove all inclined 3D geometry.)

*Partial Auxiliary view of the inclined plane

-SCALE: proportional

CAD

-3D solid model

*SCALE: full

-Multiview Drawing

*Front (inclined planes appears as an edge)

*Partial right side view (Use a convention break line to remove all inclined 3D geometry.)

*Partial Auxiliary view of the inclined plane

*Dimensioned

*Use an appropriate ANSI drawing sheet.

-Fill out the title bock

Points - 3% course grade but EVERY requirement has to be completed.

Appendix K. 3D Scanning Tutorial

ZSCANNER 800

Tutorial for ZScan Software

Written by:
Trevor Wanamaker

STEP 1: **Hardware setup**

Scanner container

Firewire cable (connects to scanner)

Scanner power supply (connects to outlet)

Adapter card (uses Firewire with scanner)

ZScanner 800 (3D

Scanner stand

Positioning Targets

Bottom of the case after removing the foam mold containing the scanner components

Cleaning cloth

Calibration plate (be very careful with this as it is glass)

Positioning target board (used to set objects on when you do not want to place dots)

Figure1: *Scanner components*

- to correctly position the scanner on the stand, place the scanner face down making sure to rest the middle camera between the two supporting arms as shown in **Figure 1.** This also shows the components that are needed. (Scanner, stand, adapter card, power supply, and power cord)

Figure2: *Power outlet on scanner*

- **Figure 2** shows the power outlet placement on the scanner from the front and top view. Make sure to attach the cord in the middle of **Figure 1** to the scanner using the ***L*** shaped connector.

Figure3: *Layout order*

- **Figure 3** shows the layout of the scanner and computer in the correct order. The scanner should be to the left of the computer due to computer port layout.

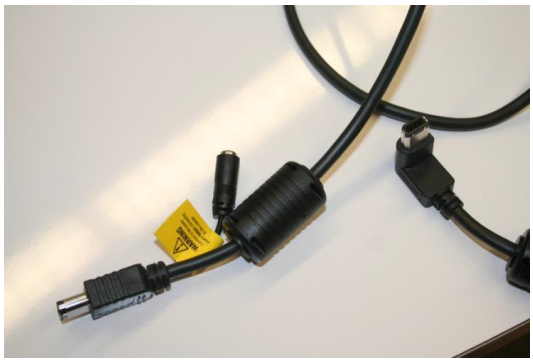


Figure4: *Power cord*

- In **Figure 4**, the power plug on the right is plugged into the scanner**.** The power plug on the left is plugged into the adapter card via the Firewire hookup.

Figure5: *Scanner components*

- **Figure 5** shows the power cord attached to the scanner.

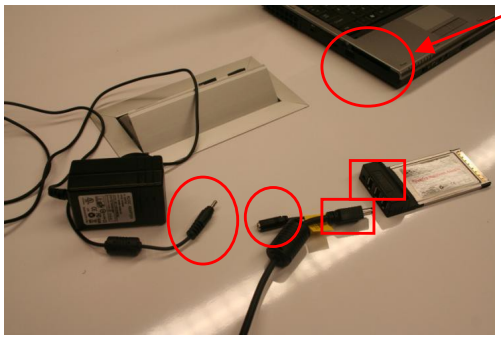


Figure6: *Connecting the power cords*

- **Figure 6** shows how to connect the power. Connect the power plug from the left power supply to the small adapter attached to the power cord. Then insert the Firewire cable into the adapter card (it doesn't matter which of the 3 ports on the card that you use). You can choose any of the 3 ports. **DO NOT** use the power supply port on the adapter card. Then insert the adapter card in to the computer. This will power the scanner on.

STEP 2: **Accessing the ZScan software and setting up calibration plate**

- There are two ways to access the ZScan software:
  1) Select the ***Launch ZScan*** from the desktop as shown in the **Figure 7** below
  2) Select ***Start*** ⇨ ***All Programs*** ⇨ ***ZScan*** ⇨ ***Launch ZScan***

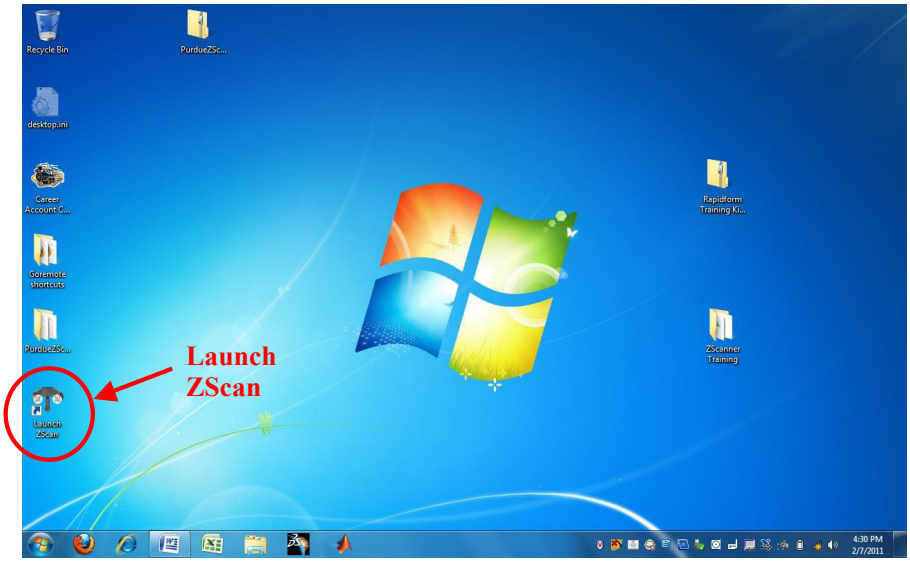


Figure7: *Computer Desktop*

- While software is loading, set up the calibration plate (this can be found in the bottom of the scanner case) that is in the wooden case
- Place the wooden case in front of the scanner and computer
- Unlatch the clasp and open the case to show the glass calibration plate (**DO NOT** take the plate out of the case, it is secured in place)

Figure8: *Software view upon opening*

STEP 3: **Calibrating the scanner**

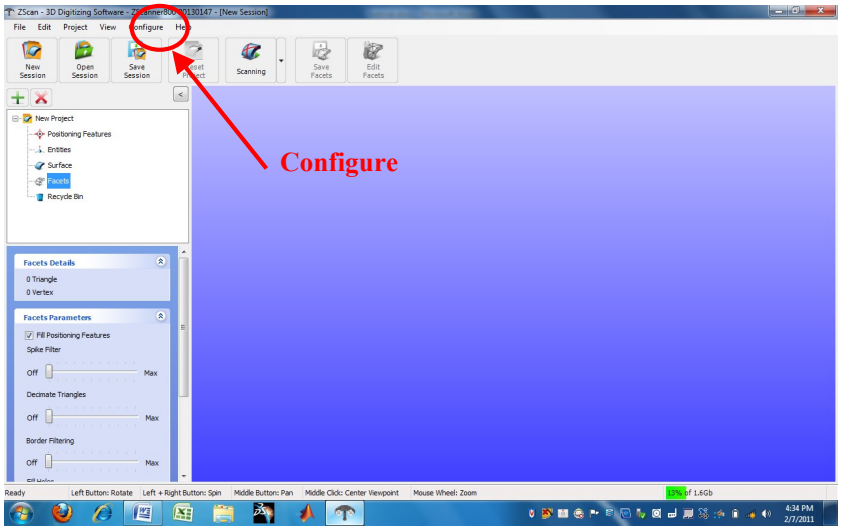


Figure9: *Software view upon opening*

- To enter calibration mode select ***Configure*** ⇨ ***Scanner*** ⇨ ***Calibration*** (Shown in **Figure 9**)

- After selecting, the screen will display a dialog box as shown below in **Figure 10**
- You will notice in the top left hand corner text that says ***Measurements 0 of 14***
  - You will perform 14 measurements that the screen walks you through
- When you are ready to begin select ***Acquire*** as shown in **Figure 10**

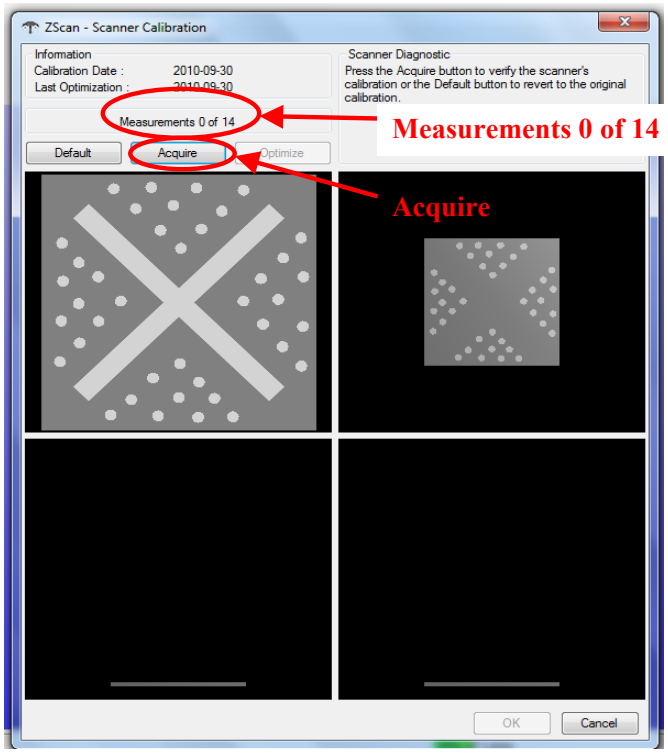


Figure10: *Calibration dialog box*

- After selecting ***Acquire*** the dialog will change to reflect that you are ready to begin as shown in **Figure 11**. The images of the scanner are green and show the position you need to match with the scanner. There is a left to right, front to back, as well as top to bottom.

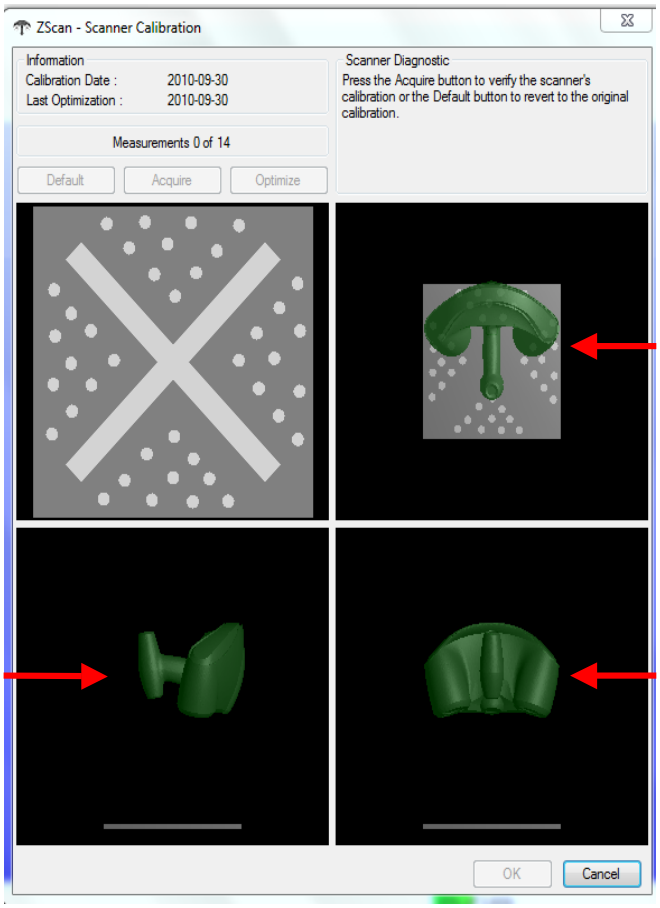


Figure11: *Calibration after selecting Acquire*

- There are four views shown in the calibration window. One of the calibration plate located in the top left hand corner and three of the scanner. The views of the scanner show the front (position left to right and top to bottom), the left view (position front to back and up and down), and the top view (position front to back and left to right).

- Pull the orange trigger on the scanner to begin calibration. Move the scanner to the position indicated by the green icons. In **Figure 12** the gray icons are your current position. In this case you would need to move the scanner upwards as well as to the left with a slight tilt to match the green icons. Once you match it you will see the measurements go from 0 of 14 to 1 of 14. You must obtain all 14 measurements. The best way to do this is to align the gray images with the green and then move the X to the proper position.

NOTE:

If you take breaks during the calibration process please place the scanner back on the stand. You can pick up where you left off when you pick the scanner back up.

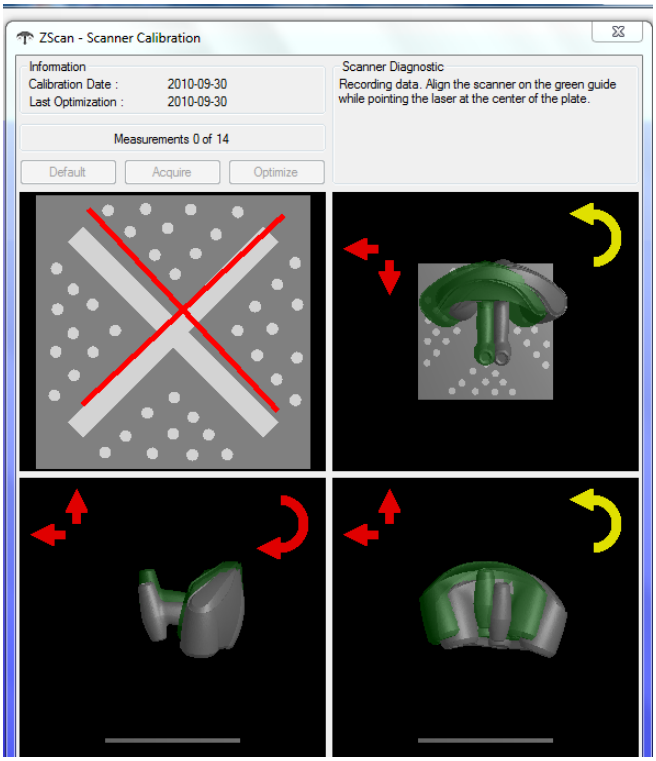


Figure12: *Calibration in progress*

- **Tips for Scanning**
  - Focus on one picture at a time and match the two icons in that view before moving to the next view
  - After matching each view one at a time, move the red X to the X pattern on the calibration plate itself

- The first 10 are based off of the same X and Y position and only changes in the Z direction. Once you acquire the first measurement just move the scanner vertically making sure to keep the X and Y positions from the first measurement

- The last 4 measurements require tilting the scanner to the front, the back , the left, and the right
- The easiest way to do this is to place the scanner in the middle of the plate to start and move from there
- Again, the simplest way is to line the scanner views up one at a time
- Once all 14 measurements have been acquired, the scanner icons on the screen will turn gray

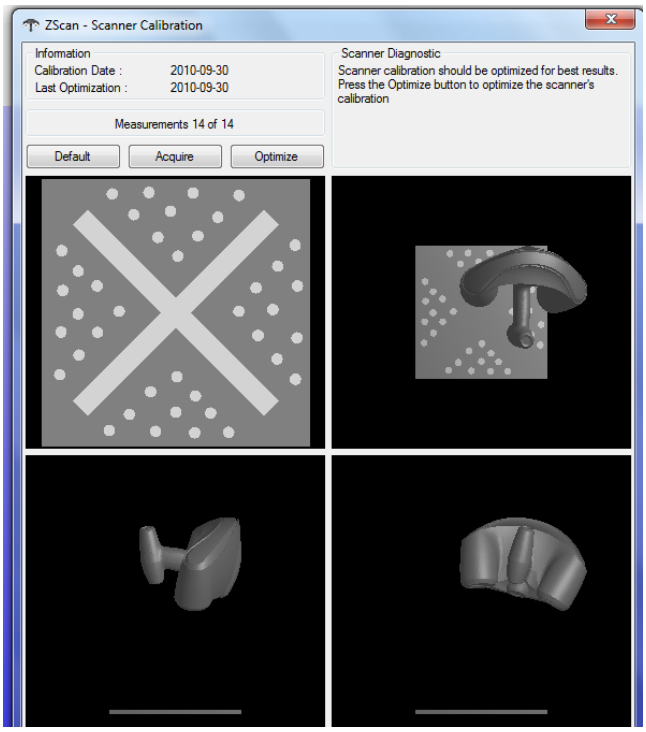


Figure13: *Calibration finished*

- **Figure 13** shows the calibration finished.
- Click ***Optimize*** ⇨ ***Ok***

NOTE: Once calibration is complete please close the calibration plate container and place back in the scanner case.

Advanced User Option

If you would like to change settings for the scan you can do so through the configuration menu.

- ***Configure*** ⇨ ***Scanner*** ⇨ ***Configuration***
- In most cases the default settings will be fine so there is no need to do this. **Figure 14** shows the configuration dialog box. You ideally want the bar on the left to be in line with the two arrows and the bar on the bottom to be in line with the two arrows within the reliable section.
- You can select Auto Adjust or manually adjust them yourself. Then pull the trigger on the scanner and face it at your part.

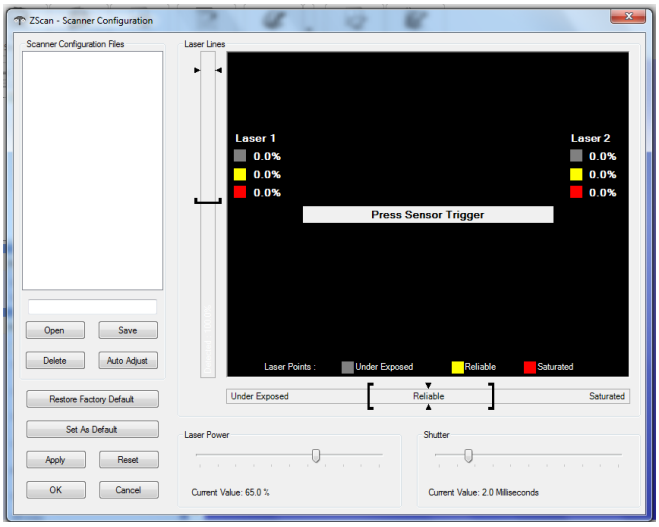


Figure14: *Configuration dialog box*

STEP 4: Preparing part for scan

Setting up positioning targets:

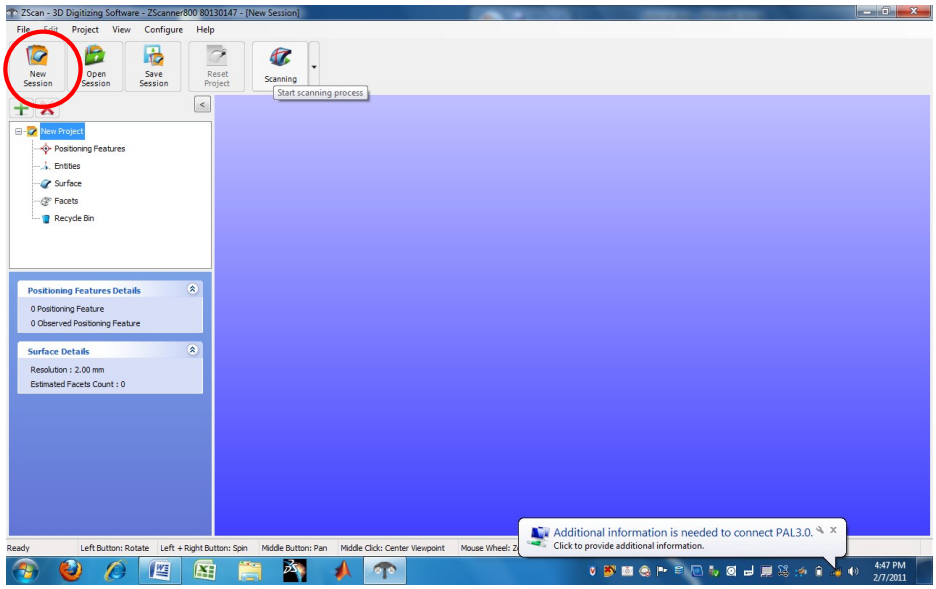


Figure15: Starting a new session

- To start a new scan click on the **New Session** button as shown in **Figure 15.**
  - You can also open a saved session or save the current session.

PROJECT TREE

- Under the **New Project** tree select the ***Positioning Features*** and choose the type of positioning targets you are using as shown in **Figure 16.**
    - There are 2 main types that we possess
        - The first type is the normal **Black Contour** which is essentially a sticker that is a black circle with a white circle inside of it (use this kind when you're part is not magnetic) **NOT REUSABLE**
        - The second type is the **Magnetic with Black Contour** which is a magnetic target that is a black circle with a white circle inside of it (use this kind when your parts are magnetic). **REUSABLE**
        - Select ***Apply***
- Now that you have chosen what type you will be using, you need to place these positioning targets on the part itself
    - Targets should be 20-35mm apart but can be placed up to 100mm apart.
    - The scanner must be able to see at least 4 targets at a time in order to work correctly
    - The scanner can only see targets within a 30 degree angle of the scanner, therefore if the part is curved then the targets will need to be closer than if the part is flat.
    - **DO NOT** place positioning targets over a feature that you would like to obtain with the scan as it will eliminate this feature
    - The more positioning targets you have the easier it will be to scan, however there are a limited number of **Black Contour** targets because these are not reusable so only place the minimum amount required to obtain all data

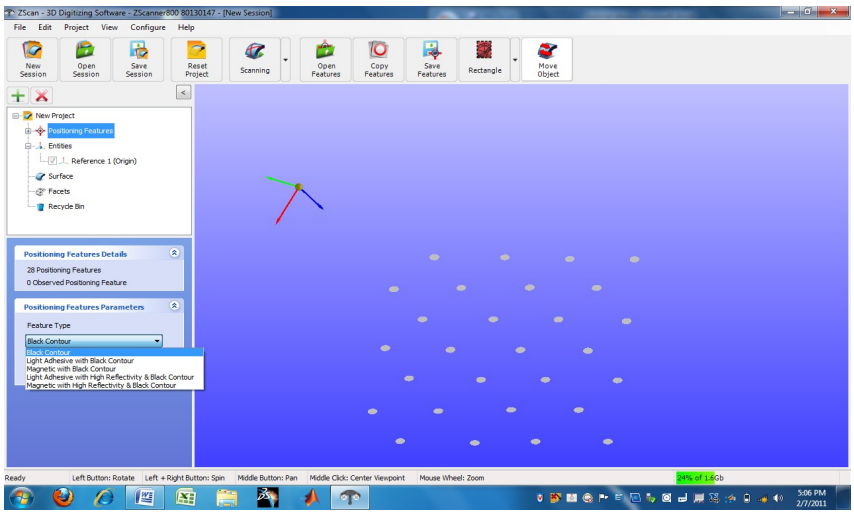


Figure16: *Selecting positioning targets*

PROJECT TREE Cont.

Setting up the resolution:

- Under the ***Surface*** tab under the new project tree you can change the resolution.
  - The lower the resolution value, the better the scan. However, keep in mind that a finer resolution requires a slower movement of the scanner when moving over the part's surface. This causes longer computing time and uses more RAM which can cause the program to crash if your RAM availability is not sufficient.
  - Ideally, you should set the resolution to the density that produces the best representation of what you are wanting to collect.
    - A resolution of 0.5mm is better than 1mm because there are positions are recorded every .5mm whereas the other would be every 1mm.
- Under ***Facets*** you will find sliding bars that you can use to fill holes, remove isolated patches you do not want, as well as other things. These are to be used after you complete your scan.
- When scanning, the area beneath the **New Project** tree will display the following:
  - Positioning feature details
    - How many positioning features the scanner has acquired
    - The number of observed positioning features (how many targets it is recognizing at that moment)
  - Surface details
    - The resolution in millimeters
    - The estimated facets count (the number of facets it creates from the positioning targets it has scanned)

STEP 5: Starting a new scan

- To begin a new scan click on the arrow next to the ***Scanning*** icon and select either ***Scan Surface*** or ***Scan Positioning Features*** as shown in **Figure 17.**
    - ***Scan surface*** means that you will scan the positioning targets and your part at the same time.
    - ***Scan Positioning Features*** means you will only scan the positioning feature.
        - You can save the positioning features to be able to recall them later. This can be very useful if your part is too large for just one scan.

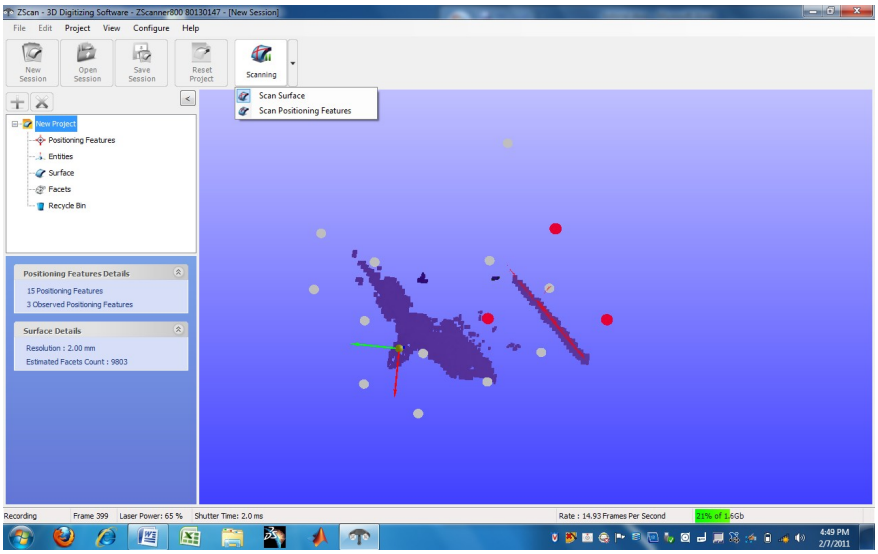


Figure17: *Scanning options*

- After selecting one of these two options, you must select the **Scanning** button to begin the scan
- Pull and hold down the trigger of the scanner and move over the part slowly and in a circular pattern.
    - Make sure to always overlap a few of your dots while you move because if you do not you will receive an error saying **Searching Position** as pictured in **Figure 18.** If the bar is red on the bottom you are too far away from your part. If it is red on the top you are too close to your part. If the scanner cannot see at least 4 dots at a time you will also receive this error.
    - **TIPS:** When scanning, it is useful to scan in a circular motion being sure to rotate your wrist in a clockwise or counter clockwise motion. It is also useful to scan in a zigzag pattern starting in one spot move the scanner up and down around the object. Doing this will help to obtain in a more efficient manner

- You may let off the trigger during scanning at any time. Just make sure when you pull the trigger again that you are positioned over a section of the part that you have already scanned so that the scanner can recognize the target positioning.

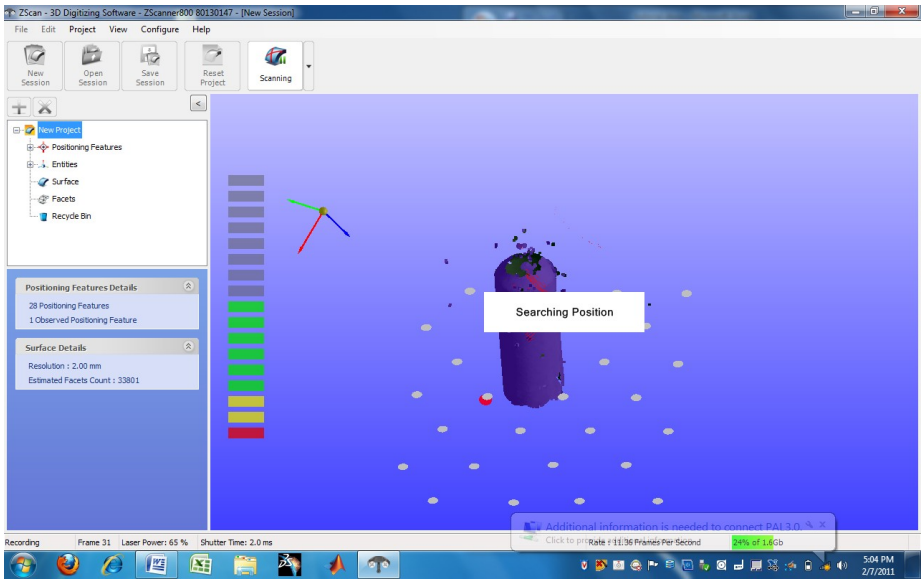


Figure18: Searching Position

- When you are finished scanning let off the trigger and select the **Scanning** button again to stop the scan.

STEP 6: **Cleaning up the scan**

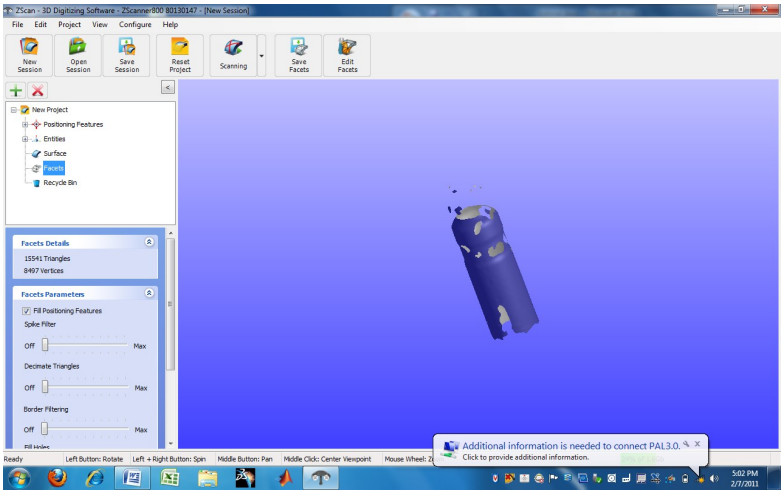


Figure19: Partial scan of water bottle

- **Figure 19** shows a partial scan of a water bottle
  - As you can see there are many small holes where the scanner did not obtain data. These are a result of moving too fast over the area or not capturing that area well enough.
- The first thing you should do is to make sure the box next to **Fill Positioning Features** is checked.
  - This will fill in the spots where the positioning targets were placed
- If you click on **Facets** in the tree, you can slide the bar to the right under the filling holes option to fill areas that are closed. The further you slide the bar to the right the larger the hole you can fill. I recommend you do not slide more than one or two dashes. If you need to you can always select the **Scanning** button and scan that are some more.
- Also under **Facets** you can see the number of triangles it created as well as the number of vertices. You do not see these things in the image but they are the framework upon which that image is built.
- **Figure 20** shows the same water bottle after eliminating isolated patches and minor holes.

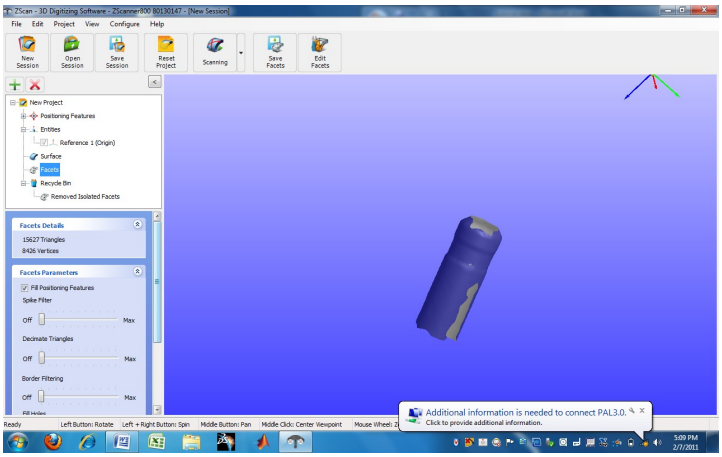


***Figure20:** Partial scan of water bottle after clean-up*

- As you can see in **Figure 20**, you cannot eliminate holes that are not closed within a boundary
- To save the session select **Save Session** and name your file and save

ZScanner 800 Recap

- You can start the ZScan software from the desktop or start menu
- It is recommended that you calibrate the scanning system each day before you commence scanning or after a significant change in ambient temperature.
- After calibrating the scanner you can configure the settings to match the part you are working with
- You can change the resolution of the scan under the **Surface** option in the tree
- You can change the type of positioning targets under the **Positioning Features** in the tree
- You can choose to either scan just the positioning features or the surface and features together
- If you scan just the positioning features you can save them and recall them later which is useful with larger scans
- If you are too far away, too close, or do not see at least 4 positioning features on your part the scanning will stop and say **Searching Position**. Let off the trigger move to a spot you have already scanned and try again.
- You can eliminate isolated patches and fill small holes under the **Facets** option in the tree

►**NOTE**: You can choose the **Reset Project** button to restart your scanning. This will eliminate everything you have scanned thus far and restore the session to the beginning. This will not eliminate your calibration or configuration settings.

Appendix L. Interview 1 Guide

Interview #1 Guide

(Phone on silent; non-essential programs shut down; sign on door)

The purpose of this interview is to see how you feel about the hands-on learning experience you completed using the 3D scanner.

3D Scanner tutorial

1. Did the tutorial help you in completing the 3D scanning portion of the hands-on learning experience?

2. Is there anything you would change about the tutorial in order to make it more user friendly?

Calibration Process

1. How do you feel you did on the calibration process? Was there anything that you found particularly easy or difficult about the calibration process?

2. Do you feel your level of spatial ability was advanced to a sufficient level to complete the scanning calibration or did it need to be more advanced to successfully complete this task?

3. What was the easiest or most difficult aspect in the calibration process?

Scanning Process

1. Did you like or dislike the 3D scanning process?

2. What was easy or difficult about the scanning process (i.e. weight of scanner)?

3. Is there anything besides the tutorial that helped you to complete the scanning process (i.e. spatial ability, other hands on activities)?
4. Did you understand what the scooter parts were and where they belonged on it?

5. How would you explain the scanning process to someone who has not completed this process (i.e. in a job interview)?

Course

1. Did any assignments, lectures, or other course activities in CGT 163 help you to complete the task of creating a 3D model from the 3D scanned data?

2. If this technology was implemented into your engineering curricula, what do you feel would need to be considered before the implementation could be successful?

Study

1. Did you have any knowledge about Reverse Engineering (RE) prior to completing this study?

2. What is your general opinion of this study?

3. Do you tend to leave an interview or meeting wishing there was additional information you had given?

4. Did you find the scanning exercises to be enjoyable?

5. Do you learn better from hands-on exercises or from textual material?

6. Is there anything you would change about this study as far as the hands-on learning experience is concerned?

7. What are your thoughts on incorporating RE methodology such as 3D scanning into your engineering curricula?

8. Do you feel the scanning equipment would be beneficial as a first-year engineering student or would it be more beneficial to learn it in a junior or senior level course?

9. What factors to you feel must be taken into account if RE (scanning) technology is incorporated into engineering curricula?

10. What did you like or dislike about this experience?

11. Do you feel spatial ability helped?

12. Do you play video games?

Appendix M. Interview 2 Guide

Interview #2 Guide

(Phone on silent; non-essential programs shut down; sign on door)

The purpose of this interview is to allow you to address any information you wish to add about your experience with the hands-on learning process.

3D Scanner tutorial

1. What is your opinion on the 3D scanning tutorial? Was it helpful?

2. Is there anything you would add or change about the tutorial?

3. Do you feel this tutorial is effective in learning the technology?

Calibration Process

1. Do you think spatial ability contributed to the calibration process of the scanner? Why or why not?

2. What were the easiest and most difficult parts of the calibration process?

Scanning Process

1. Did you like using the 3D scanning technology?

2. What did you like/dislike about the scanning process?

3. Is there anything you feel would help with the scanning process that was not covered during the process?

4. In the future, what products would you like to see used in this process besides the scooter?

5. Would you recommend other students participate in a hands-on learning experience such as this?

Model Creation

1. What is your opinion of the RapidForm software used in this study?

2. Do you feel this process was relevant to CGT 163?

3. What did you think of RapidForm compared to the software used in CGT 163 (Inventor, CATIA, Pro Engineer)?

4. Would you take a course involving RE methodology and RapidForm software?

Course

1. What factors do you feel would need to be considered when incorporating RE methodology into engineering curricula (i.e. time, cost, student experience)?

2. Were there any parts of the hands-on learning experience where your knowledge obtained through CGT 163 was helpful?

Study

1. What did you think about the study involving RE?

2. Do you feel having a secondary interview was beneficial to you by allowing you a secondary opportunity to provide information?

3. Was this hands-on learning experience enjoyable?

4. What is the best way in which you learn material (i.e. hands-on learning or textual learning)?

5. Is there anything you would change about this study or the materials involved?

6. Do you feel RE methodology will help with your professional growth?

7. Provided the opportunity, would you enroll in a course that is based solely on RE methodology and the different methods that are used?

8. Do you feel you would take more away from this experience if it was given in a junior or senior level course as opposed to a first year engineering course?

9. What type of project involving RE do you feel would be enjoyable?

10. What aspects do you feel would be necessary to consider prior to incorporating RE methodology into the engineering curricula?

11. Do you have any additional questions or comments about RE?

Appendix N. Instructor Interview Guide

Instructor Interview Guide

(Phone on silent; non-essential programs shut down; sign on door)

The purpose of this interview is to gather your view on incorporating reverse engineering methodology into engineering curricula within universities.

1. What is your name? What department are you a professor for? What courses do you teach?

2. When and how did you first learn about reverse engineering?

3. What interest do you have in reverse engineering? What do you not like about it?

4. Do you feel engineering students should learn reverse engineering skills as part of their engineering curricula? Why or why not?

5. What majors do you feel would benefit most from learning reverse engineering methodology?

6. What methods of reverse engineering do you feel would be beneficial to learn from an academic standpoint (i.e. 3D scanning, from pictures, from drawings, etc.)?

7. What factors need to be considered before implementing reverse engineering methodology into engineering curricula (i.e. cost time, etc.)?

8. What steps would need to be taken to create a course based on reverse engineering methodology?

9. If a course was created around reverse engineering or reverse engineering was implemented into a current course, what do you think it should cover and why?

10. What types of materials should be included in a reverse engineering course (i.e. texts, readings, PowerPoint, interactive examples, etc.)?

11. Should it be a project based course, text and theory based, or based on some other method of learning? Why?

12. Would you like to see reverse engineering incorporated into the engineering curricula? Why or why not?

13. What would students and professors need to do to prepare for a course involving reverse engineering?

14. What type of equipment would you like to see students use in a reverse engineering course?

15. If you were proposing the creation of a reverse engineering course to an engineering department at Purdue University what would you tell them was important? What would you tell them needed to happen before the implementation could be successful?

16. What are your feelings on using 3D scanning technology? Would you like to see students use this technology in their engineering curricula?

17. Do you feel incorporating reverse engineering methodology into engineering curricula would improve retention rates? Why?

18. Do you feel incorporating reverse engineering methodology into engineering curricula would improve students' design skills? Why?

19. Do you feel incorporating reverse engineering methodology into engineering curricula would help in students' professional growth? Why?

20. If you were the professor in charge of teaching a reverse engineering course, what types of products would you have the students use for reverse engineering?

21. If you were the professor in charge of teaching a reverse engineering course, what types of projects would you have students complete during the duration of the course?

22. Do you have any additional comments that you would like to add?

Appendix O. Industry Interview Guide

Industry Interview Guide

(Phone on silent; non-essential programs shut down; sign on door)

The purpose of this interview is to gather your view on incorporating reverse engineering methodology into engineering curricula within universities.

1. What is your name? What company do you work for? What is your job title?

2. What programs or computer software do you use most often in your work?

3. How often do you use reverse engineering methodology?

4. Which methods of reverse engineering do you use most often (i.e. 3D scanning, best fit to pictures)? Why?

5. Do you feel engineering students should learn reverse engineering skills as part of their engineering curricula? Why or why not?

6. What factors need to be considered before implementing reverse engineering methodology into engineering curricula (i.e. cost, time, etc.)?

7. What skills are needed for performing reverse engineering methods?

8. If a class was created based around reverse engineering, what do you think it should cover and why?

9. What type of material should be included in a reverse engineering course (i.e. texts, PowerPoint, etc.)?

10. Should it be a project based course, text and theory based, or based on some other method of learning? Why?

11. What do you think students would need to do to prepare for a reverse engineering class?

12. What do you think professors would need to do to prepare for a reverse engineering class?

13. If you were proposing the creation of a reverse engineering course to an engineering department at a university what would you tell them was important? What would you tell them needed to happen before the implementation would be successful?

14. What type of equipment do you feel professors and students should be familiar with to do reverse engineering projects?

15. What are your feelings on using 3D scanning technology? Would you like to see students use this technology in their engineering curricula?

16. Do you have any additional comments that you would like to add?