

A STUDY IN DIGITAL PROTOTYPING AND MULTIDISCIPLINARY  
DESIGN TEAM COLLABORATION

BY

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THESIS

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## ABSTRACT

This thesis presents results of work that: (1) examined collaboration between engineering and industrial design students in solving biomedical design tasks, as well as gathering information on student perceptions of the relative usefulness of digital prototyping tools employed in the development of the design projects, and (2) reviewed the design literature while focusing on areas related to a computer-aided product realization course curriculum, namely: reflective practice in design, design thinking, computer-aided design (CAD) and creativity, prototyping, 3D printing, and next generation CAD.

In the fall of 2015 twenty-three students were enrolled in a testbed computer-aided product design course. In the first half of the semester these students were familiarized with a common set of 3D CAD and digital prototyping (i.e., 3D printing, 3D scanning) tools. The second half of the semester was devoted to biomedical device design project tasks, where course participants were assigned to six teams in order to solve a specific design problem. Each team included members from bioengineering, industrial design, and either systems or mechanical engineering, or both. There were two main course instructors, one from engineering and one from industrial design. The course also included a teaching professor from bioengineering, a graduate research assistant, as well as a graduate teaching assistant.

We hypothesized that *ready access to 3D printing aids in successful design outcomes* and addressed the following research questions: (1) what activities do multidisciplinary student teams pursue in the early stages of design?, (2) what benefits and challenges with regard to multidisciplinary design collaboration do students frequently note?, (3) what are the students' perceived understandings of the effectiveness of cloud-based 3D CAD tools on both team collaboration and design concept development?, and (4) what are the students' perceptions of the use of 3D printing for developing design solutions? A combination of methods, including audio recordings, reflection journals and surveys were employed to answer these research questions. The results of this work showed that course participants had positive views of the multidisciplinary composition of the design teams. Another finding was that the use of the digital

prototyping tools, in particular the use of the cloud-based 3D CAD tool and 3D printing was helpful in supporting collaboration as well as in improving the likelihood of successful design outcomes. Another key finding from reviewing design literature was the role and importance of reflection in design education and practice. The results of this study have implications for promoting design team collaboration across disciplines, in particular among engineering and design students, and for contributing to effective teaching, learning and exploitation of new 3D CAD digital prototyping tools in engineering design education. Finally, based on the overall results of this thesis, recommendations aimed at improving the course curriculum are discussed.

**Keywords:** multidisciplinary design collaboration, engineering design, design thinking, reflective practice, 3D CAD, 3D printing, 3D scanning, physical prototyping

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<sup>1</sup> 3D design, engineering, and entertainment software company

## TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION.....	1
CHAPTER 2: BACKGROUND.....	5
2.1 Computer-Aided Product Realization Course.....	5
2.2 Digital Prototyping Tools.....	7
2.2.1 3D CAD.....	7
2.2.2 3D Printing.....	11
2.2.3 3D Scanning.....	12
2.3 Reflective Practice in Design.....	15
2.4 Protocol Analysis Using Linkography.....	19
CHAPTER 3: RESEARCH APPROACH.....	22
3.1 Research Procedure.....	22
3.2 Literature Review.....	24
3.3 Data Gathering Tools.....	24
3.3.1 Design Protocol.....	24
3.3.2 Reflection Journals.....	26
3.3.3 Survey.....	27
CHAPTER 4: RESULTS.....	28
4.1 Results from the Linkography Analysis.....	28
4.2. Survey Results.....	37
4.3 Findings of Reflection Journals.....	41
4.4 Design Outcomes.....	45
4.5 Literature Review Results.....	55
CHAPTER 5: CONCLUSIONS AND DISCUSSION.....	66
5.1 Conclusions.....	66
5.2 Discussion.....	68
5.2.1 Improvements of Fusion 360 Platform.....	70
REFERENCES.....	73
APPENDIX A: THE MEETING TRANSCRIPTS OF DESIGN TEAMS.....	76
APPENDIX B: REFLECTION JOURNAL WRITING GUIDELINE.....	97
APPENDIX C: SURVEY QUESTIONNAIRE.....	98
APPENDIX D: DESIGN PROJECT BRIEF.....	100

APPENDIX E: DESIGN PROJECT POSTERS .....	103
APPENDIX F: GE 402 COURSE SYLLABUS, FALL 2015 .....	105
APPENDIX G: GE 402 COURSE SYLLABUS, FALL 2016.....	107
APPENDIX H: READING LIST FOR COMPUTER-AIDED PRODUCT REALIZATION COURSE, FALL 2016 .....	109
APPENDIX I: DESIGN QUALITY RUBRIC.....	110

## CHAPTER 1: INTRODUCTION

Organizations rely on innovation in order to stay competitive and thrive in a today's fast moving global market (Schlecht and Yang 2014; Chang 2014). In the field of design, innovation is predicted to accelerate at unprecedented levels as a result of the rapidly advancing and growing availability of powerful modern CAD tools (Hatch 2013; Anderson 2012). These design tools are being incorporated into engineering design classrooms for the purpose of teaching design, and to develop the creative abilities of students (Guidera and MacPherson 2008). Therefore, there is a greater need to understand the influence of modern CAD tools in order to facilitate successful design learning and to prepare engineers who have the skills and the abilities needed to develop innovative solutions to modern complex design problems.

Increasingly, multidisciplinary collaboration is credited with fostering creativity in both academia and industrial practice. For example, the world-renowned design firm IDEO is well known for relying on multidisciplinary team collaboration, brainstorming and prototyping when developing solutions to ill-defined design problems. However, multidisciplinary collaboration is not without challenges, as differing viewpoints and diverse expertise possessed by each individual must come together and be negotiated during the collaborative design process (Younglove-Webb et al. 1999; Dym et al. 2005). This highlights the importance of good communication and teamwork skills that one should possess in order to function effectively in a multidisciplinary work setting. Therefore, we believe that examining the interactions of multidisciplinary team communications will aid in the effective facilitation of design team collaboration, and that such data can be further used in providing for a quality team experience.

A computer-aided product realization course in the fall semester of 2015 served as a testbed for this research. The overarching goal of this study was to inform and enhance the computer-aided product design course curriculum. As such, we examined the collaboration of multidisciplinary student design teams as they carried out design projects using digital prototyping tools, and gathered their perceptions related to the effectiveness of these design tools. We also reviewed

the design literature, focusing on areas directly related to the course curriculum, for example reflective practice in design, design thinking, CAD and creativity, physical prototyping, 3D printing, and next generation CAD. By digital prototyping tools we are referring specifically to 3D CAD modeling, 3D printing and 3D scanning tools.

The hypothesis of this research project states that *ready access to 3D printing aids in successful design outcomes*. This hypothesis is based on the findings of previous design literature indicating that the use of physical models is beneficial in developing effective design solutions (Yang 2004; Yu 2015; Simondetti 2002; and Viswanathan & Linsey 2009). Many design researchers note that a physical model provides a look and feel in real-time that can help eliminate design flaws. Another benefit gained from construction of physical models is that it aids in the mitigation of design fixation (Viswanathan et al. 2015 and Youmans 2011). Design fixation is a phenomenon commonly experienced by both novice and expert designers, where the designer directly copies components or produces similar features from examples of existing designs during idea generation process. Many engineering classroom instructors make use of physical models as a design strategy to support effective design learning and to encourage creativity among students. Considering the two main characteristics of the computer-aided product realization course, (1) collaboration between engineering and industrial design, and (2) the use of digital prototyping tools for developing design solutions, the engineering course instructor was initially interested in exploring the following questions:

- How do digital tools (3D CAD, CAE, CAM) affect the design process?
- Can freeform modeling be used effectively early in the design process?
- How does the availability of 3D printing accelerate the design process?
- How do multidisciplinary teams affect the design process?
- How does instruction in design thinking affect the design process?
- How does cloud-based 3D CAD affect design collaboration?
- What are some good tips for coaching design teams?
- How does 3D scanning technology impact the design process?



- How does the physical space affect the success of the design project?
- What sorts of project characteristics increase the likelihood of a project's success?

Given the limited time for conducting this research, exploring all of the above questions is difficult. Instead, we chose to focus on the following;

1. What activities do multidisciplinary student teams pursue in the early stages of the design process?
2. What benefits and challenges with regard to the multidisciplinary design collaboration do students frequently note?
3. How do students view the effectiveness of 3D CAD software (i.e., Fusion 360) for team collaboration and for design concept development?
4. How do students view the role of 3D printing on design concept development?

To address the proposed research questions, we took a qualitative approach and used data obtained from a combination of sources, including protocol analysis, reflection journals and an online survey. The audio recordings of design team meetings in the conceptual stage were used for understanding the early stages of design team activities. These audio recordings were analyzed using *linkography*, a research method used for understanding designers' thinking process and cognitive activity involved in designing. Data obtained through reflection journals and an online survey administered at the end of the semester were used to understand student perceptions of 1) the multidisciplinary design team collaboration experience, and 2) the effectiveness of using digital prototyping tools on collaborative design tasks. Moreover, the feedback obtained through the reflection journals also helped to critically examine whether the course objectives and learning outcomes are being met.

Another component of the study was a literature review, conducted in order to inform the course curriculum and to broaden our understanding of engineering design education. Guided by the course instructor's questions, we searched design publications on topics concerned with

reflective practice, design thinking, prototyping, 3D printing, next generation CAD etc., using a wide variety of online databases, including ProQuest, Scopus, ScienceDirect, Google Scholar, etc. Most of these publications are the work of well-respected design scholars and published in peer-reviewed journals. The collected publications were organized into separate categories and are presented in the Results section.

Chapter 2 begins with an introduction to the computer-aided product realization course testbed, and then provides a background context on CAD tools and their development. In addition, an overview of reflective practice in design and the protocol analysis method used in the study are introduced in Chapter 2. The research procedure, data gathering methods from the multidisciplinary course projects, and the research approach taken in reviewing design literature are discussed in Chapter 3. The project findings are summarized and the results of the design literature review are reported in Chapter 4. We conclude our work by discussing implications and drawing conclusions, as well as making recommendations for the improvement of the computer-aided product realization course.

## CHAPTER 2: BACKGROUND

### 2.1 Computer-Aided Product Realization Course

The computer-aided product realization course was first offered as a 400-level CAD Technology course in the spring of 2003. The course was first created through a grant from the Academy for Excellence in Engineering Education (AE<sup>3</sup>), a unit within the College of Engineering at the University of Illinois at Urbana-Champaign. The initial aim of the course was to introduce engineering students to various 3D CAD tools such as Autodesk Inventor and Rhinoceros, as well as to engineering analysis software such as MSC's Dynamic Designer and ANSYS Workbench. In the spring of 2008 the course was added to UIUC's official course catalog, under the new name Computer-Aided Product Realization. In the following year, Autodesk provided a grant to the course to promote engineering and industrial engineering collaboration. Shortly thereafter students from industrial design enrolled in the course, and the collaboration between engineering and industrial design first started. Also around that time a faculty member from industrial design became involved with the course, and helped facilitate course activities.

The engineering and industrial design course instructors co-authored a paper entitled *Engineering and Industrial Design Education Collaboration* on the design collaboration of engineering and industrial design students. The paper was presented at the American Society for Engineering Education (ASEE) annual conference in 2011. Since then the computer-aided product realization course curriculum has continuously evolved and today the course covers topics such as geometric modeling, 3D printing, 3D scanning, upfront analysis, collaborative design and design thinking.

A total of twenty-three students, in roughly equal numbers from bioengineering, systems engineering, mechanical engineering, and industrial design, both 4<sup>th</sup> year undergraduate and graduate level were enrolled in the testbed course. In the first six weeks the students were familiarized with a common set of digital prototyping (i.e., 3D CAD modeling, 3D printing, 3D scanning) tools, design thinking and brainstorming techniques for developing creative design solutions. The second half of the semester was fully devoted to design project activities. During

the design project period each team was assigned a workstation in the Product Design Laboratory (PDL) where they sat as a group during class times to work on their design projects. The layout of the PDL is shown in Figure 2.1. The design teams presented their design project progress on four separate occasions, as three intermediate and one final presentation.



**Figure 2.1 Product Design Laboratory showing design teams workstations**

The available software tools in the laboratory include but are not limited to Autodesk Fusion 360, Geomagic Design X, SketchBook Pro, Inventor, and SolidWorks. Hardware tools include a Creafom handheld laser scanner and a David structured light scanner, a Dimension 3D printer, and an Ember 3D printer.

As was mentioned earlier, the course had two instructors, one from engineering and one from industrial design. In addition, a teaching professor from bioengineering, a graduate research assistant, and a graduate teaching assistant were involved with the course. The engineering instructor was responsible for delivering main course concepts like CAD technology

and the use of next generation CAD tools, whereas the industrial design instructor was responsible for introducing the students to aspects of collaborative design such as design thinking, brainstorming etc. The bioengineering professor provided support to the design teams regarding the requirements and specifications of the biomedical projects as the biomedical design tasks were proposed by the bioengineering professor through her professional connections in the healthcare industry.

Digital prototyping tools used by the student design teams for their design projects included the cloud-based product innovation platform Fusion 360, a Creaform handheld laser scanner, and a Dimension 3D printer. The Fusion 360 design software was selected for the course in part because of its cloud feature for supporting team collaboration and also because it incorporates the freeform surface modeling technology, T-Spline, making it suitable for concept design. In regard to the 3D printing, the design teams were encouraged to make use of the 3D printers in testing the design ideas as much as possible.

## **2.2 Digital Prototyping Tools**

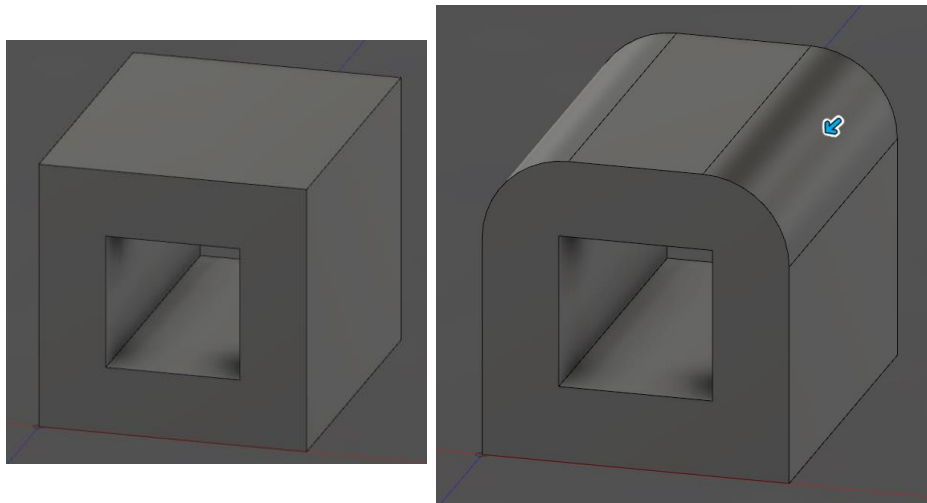
*Digital prototyping* refers to the digital simulation of a product in order to test its form, fit, and function. A complete digital prototype provides a true digital representation of the entire end product and can be used to visualize and simulate the product in order to reduce the necessity of building expensive physical prototypes. The term virtual prototyping is also used to describe this concept of building a product digitally before physically building it. The digital prototyping tools used by the student design teams in their design projects are discussed in the following sections.

### **2.2.1 3D CAD**

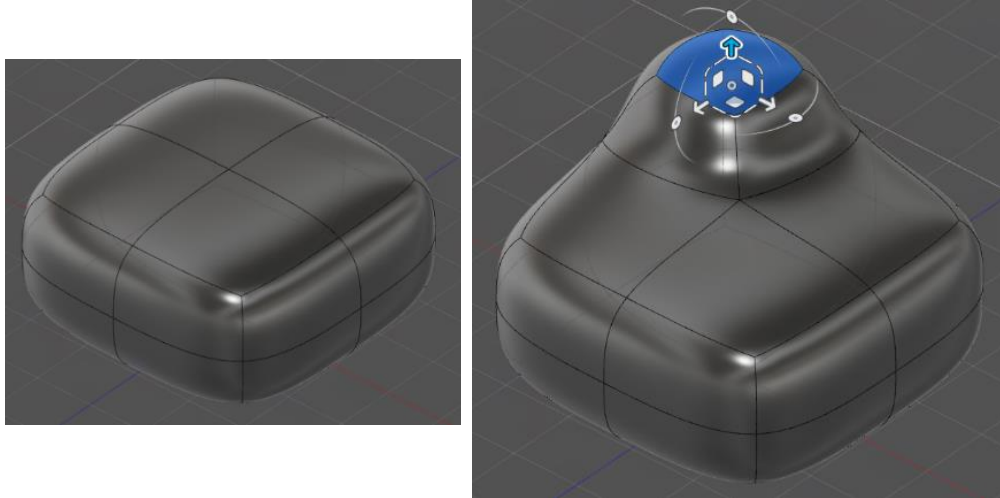
The 3D CAD tool that the students used for the team design projects is a cloud-based product innovation platform, Fusion 360 by Autodesk. Fusion 360 incorporates both history-based parametric and history-free direct modeling approaches. These two approaches both have their

strengths and weaknesses. In parametric modeling the size and the shape of a model's geometry is determined by dimensions, constraints, and parametric relationships between model features. The term history-based means that the steps performed to construct a model are automatically recorded, and can be played back to reveal how the model was built. The underlying structure of a parametric model is like a computer program. If a feature is modified, deleted, etc., the entire model may fail because of dependencies between features.

Direct modeling, on the other hand, does not keep a record of the design history, but instead allows the user to directly interact with the model geometry as it is being built by pushing, pulling and twisting on model faces, edges and vertices. Tools typically associated with direct modeling include *Push/Pull* (See Figure 2.2) and *Transform* (See Figure 2.3). Because of its ability to directly manipulate a model, direct modeling provides a faster and more intuitive way to create model geometry than parametric modeling. This is not to say that the direct modeling approach is better than parametric modeling, but rather that they both have important roles to play.

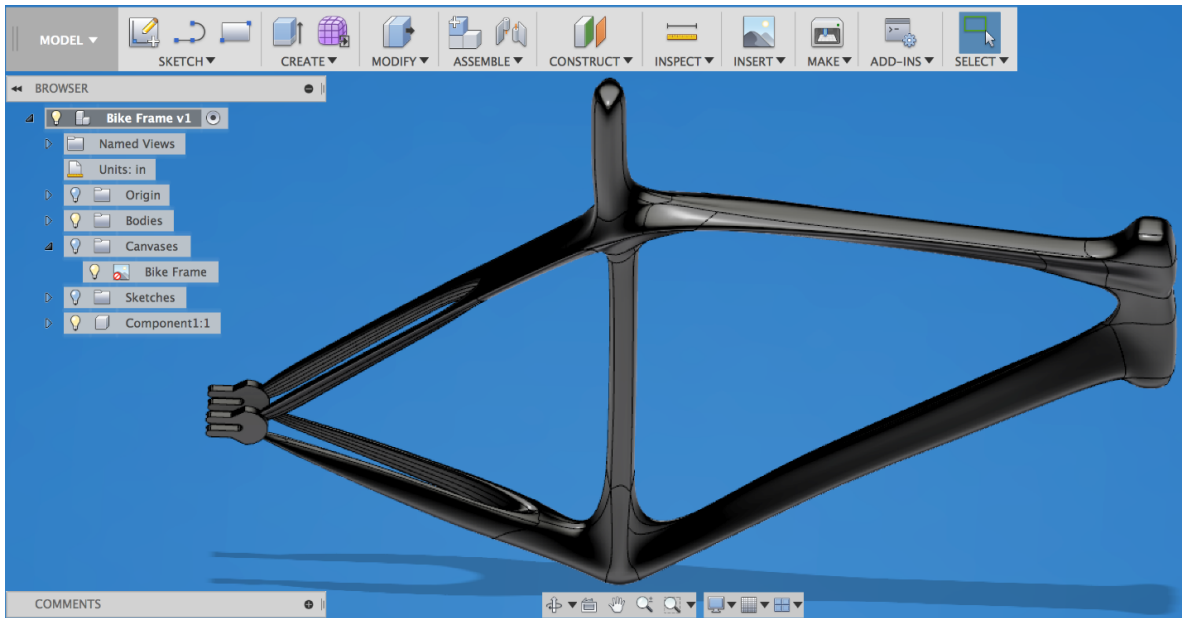


**Figure 2.2 Direct modeling push/pull tool performing Fillet operation, Fusion 360**



**Figure 2.3 Direct modeling transform tool, Fusion 360**

Fusion was first introduced in 2009 as a “fusion” of both the parametric and direct modeling approaches. In 2011 Autodesk acquired *T-Splines*, a revolutionary freeform surface modeling technology originally developed by Sederberg et al. (2003). In 2013 Autodesk first released Fusion 360, a cloud-based CAD platform. The T-Splines technology was incorporated into Fusion 360. Fusion 360 includes both a traditional parametric and direct modeling environment, as well as a sculpt modeling environment, based on T-Splines. Users can switch between these environments depending on what is required for the modeling task. The modeling capabilities of T-Splines allows for creation of complex and organic geometry, such as a bike frame model shown in Figure 2.4.



**Figure 2.4 A T-Spline bike frame model**

Because T-Splines uses non-rectangular topology, creating a smooth surface with unique features can be done with ease. The standard surface modeling technique NURBS, however, uses only rectangular topology, so a model with intricate features would require a time consuming process of building of multiple individual surfaces and patching them together. T-Splines is also compatible with NURBS, meaning T-Spline models can be converted into NURBS and NURBS model can be represented as T-Spline body. Also, Fusion 360 is cloud-based, and thus provides an ideal platform for design collaboration.

Over the past few years Fusion 360 has continuously evolved and its capabilities have significantly expanded. This is due to Autodesk's innovative and customer-oriented business model. The company works closely with its customers in anticipating and identifying unmet user needs, by receiving input on new features and making future product development plans available to customers. The company broadly utilizes online discussion forums, blogs and various digital platforms like Fusion 360 Roadmap and IdeaStation. Autodesk is also well known for its cooperative relationships and strong ties with the leading universities across the globe. In



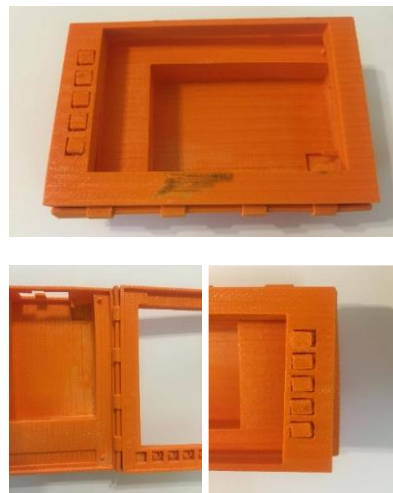
addition, through various educational programs and activities, Autodesk recruits and trains industrial design and engineering students to become Fusion 360 student experts.

### 2.2.2 3D Printing

3D printing refers to the building of a physical model layer by layer from CAD data. The design teams used Dimension 1200 (see Figure 2.5) and Dimension Elite 3D printers by Stratasys in their design projects. The Dimension 3D printers are based on *fused deposition modeling* (FDM) technology and uses an ABS thermoplastic model material and a water soluble support material to build parts. Support material is needed whenever model layers overhang previously fabricated lower layers. It is water-soluble and dissolves in a chemical solution in an ultrasonic tank. The Dimension 1200 and the Dimension Elite build a model at layer thickness of 0.254 mm and 0.178 mm respectively. The maximum build of each machine is 10" x 10" x 12" and 8" x 8" x 12". Like all 3D printers, the Dimension is capable of building assembly models with moving parts, as seen in Figure 2.6.



**Figure 2.5 Dimension 1200 3D printer by Stratasys**



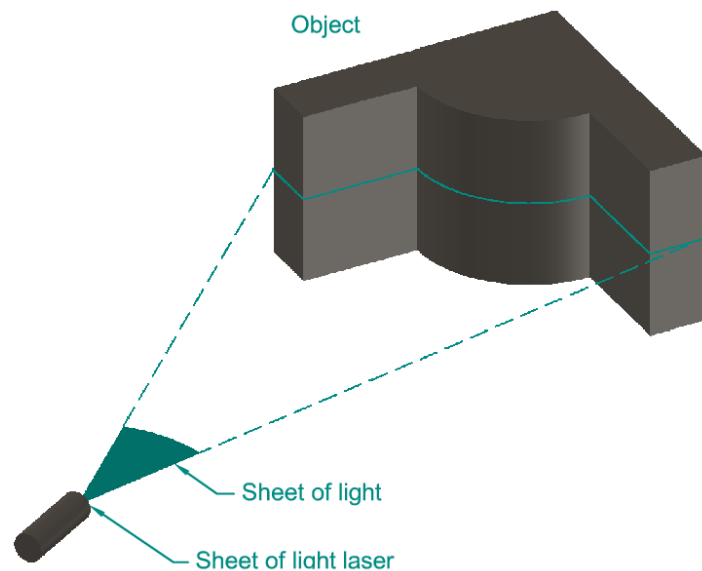
**Figure 2.6 A Raspberry Pi case 3D printed model consisting of moving parts, created by Dimension 1200**

### 2.2.3 3D Scanning

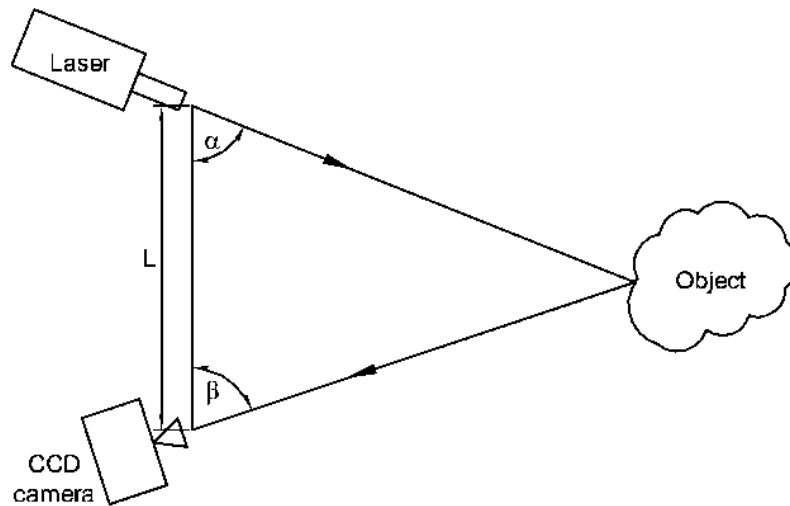
A Creaform handheld laser scanner and Geomagic Design X scan data processing software were used by the computer-aided product realization course design teams. The Creaform laser scanner (see Figure 2.7) is a high accuracy, portable, and short-range scanner. The Creaform is a sheet-of-light laser (see Figure 2.8) and uses triangulation (see Figure 2.9) to capture data points.



**Figure 2.7 The Creaform laser scanner**



**Figure 2.8 Sheet-of-Light illumination method**

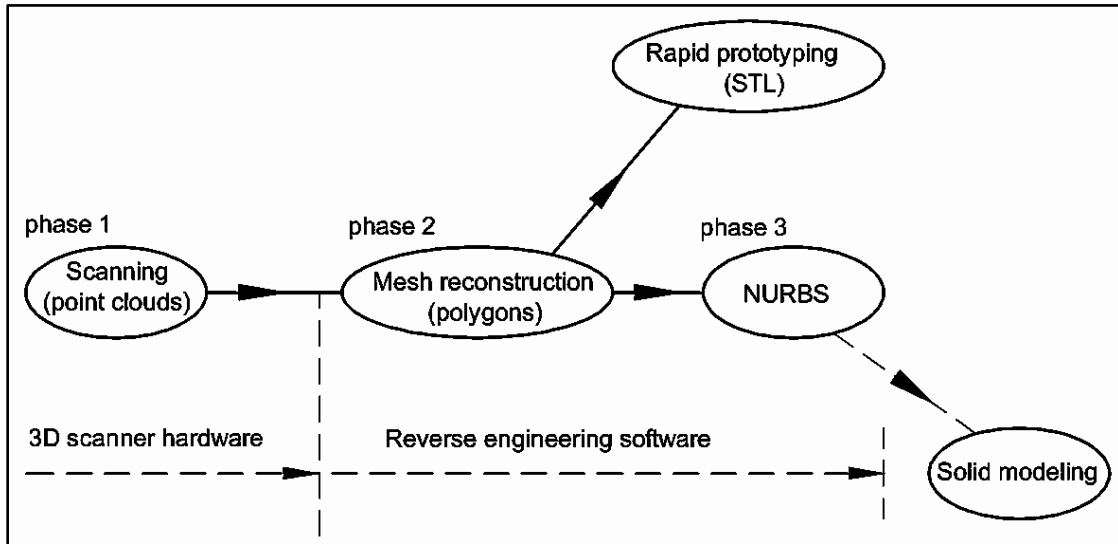


**Figure 2.9 Triangulation method**

Triangulation based laser scanners use a laser emitter and a camera to collect 3D data of a physical object. The laser emitter projects a laser line to a surface and the laser dots on the surface are located by the camera. In this process, the scanner triangulates between the camera, the laser emitter and the object being scanned. Based on three pieces of information, distance between the camera and the laser emitter, the angle of the camera, and the angle of the laser, the location of laser dots on the surface are determined. The external surface of the object is then represented with data points in the Creafom software that runs with the laser scanner. The software automatically converts the data points into a triangular mesh. The scan data is then imported into Geomagic Design X for further processing.

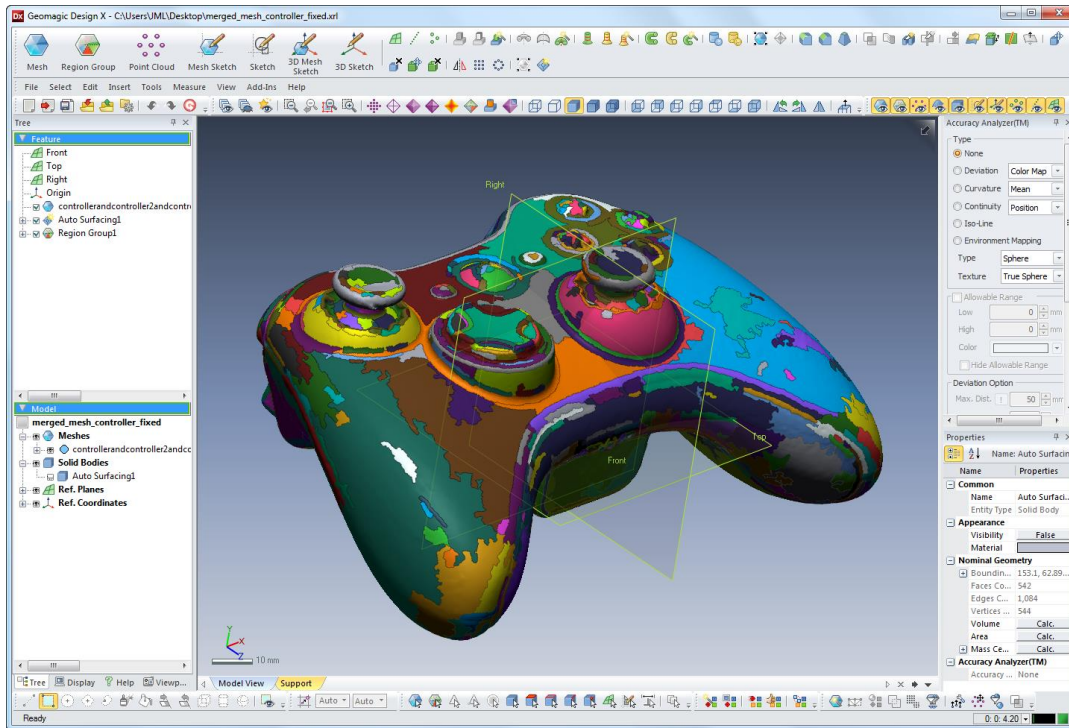
The processing of scan data in Geomagic Design X includes several steps. If scan data was imported as a point cloud then a triangular mesh is first created from the scan data by connecting neighboring points. Next multiple scan shots are aligned and the common areas are merged to create a single mesh. The merged mesh can be further modified by filling holes and removing undesired triangles from it. The result is a clean mesh. If it is watertight then it can be directly exported as a STL file for 3D printing. Alternatively the mesh can be converted into NURBS surface

and then exported as a neutral CAD file, for example STEP. The model can then be opened in any CAD application. The entire process is illustrated in Figure 2.10.



**Figure 2.10 Processing pipeline from 3D scanning of an object to its final outputs**

Geomagic Design X originated as Rapidform XOR, a 3D scan data processing software originally developed in South Korea. In 2012 3D Systems, a leading additive manufacturing company, acquired Rapiform. In 2013 3D Systems also acquired Geomagic, a scan data processing software company. 3D Systems later changed the name from Rapidform to Geomagic Design X. Today Geomagic Design X is 3D Systems' flagship reverse engineering product. Figure 2.11 illustrates the Geomagic Design X.



**Figure 2.11** The user interface of Geomagic Design X

## 2.3 Reflective Practice in Design

Design can be seen as scientific problem solving or as reflective practice. Before we discuss these two views, or perspectives, on design, it is helpful to provide some background on the origin of modern approaches to teaching and learning how to design. The early attempts to understand and to describe design started with the *Design Methods* movement in the early 1960s (Goldschmidt, 2015; Huppatz, 2015; Cross, 2001). The first conference to focus on design methods was held at London's Imperial College of Science and Technology in 1963, which was followed by a series of other design conferences. The early design researchers of this time believed that design should be based upon scientific principles and should be teachable and learnable (Goldschmidt, 2014). Therefore, design was principally seen as scientific problem solving. Design researchers started to consider new ways in which computer and computational techniques could be utilized in the conceptual stage of design, ultimately leading to the development of CAD. In order to use computer aids in design, it became crucial to understand how designers think and go about creating new ideas. Unfortunately, not much was known about

designers' thinking in the 1960's. Therefore, researchers turned to cognitive science and employed the *Protocol Analysis* method in order to gain insights into a designers' thought process. A more detailed explanation of protocol analysis method is given later in this section.

Growing out of the design methods movement, in the late 1960's a new perspective that described design as scientific problem solving was proposed by Nobel Prize winner<sup>2</sup>, Herbert A. Simon. His approach to design focused on the application of scientific theory and techniques to design problems, and is known in design literature as the *Science of Design*. Simon's view of design as a science was first presented in his lecture "The Science of Design: Creating the Artificial" in 1968, and was later published as a chapter in his 1969 book *The Sciences of the Artificial*. In the book, Simon describes a designer as anyone who, "...devises a course of action aimed at changing existing situations into preferred ones" (Simon, 1996). For Simon, design is a rational problem solving technique that is based on scientific principles. He also used the term *Bounded Rationality* to characterize a human's limited cognitive capacity to process a large amount of information and to produce optimum results. For Simon, a problem solver operates only in a part of the design space due to a limited cognitive capacity. Hence, the resulting solution to the problem is "satisficing", and not optimal.

It is believed that Simon's theory of design as rational problem solving is largely derived from his broad research expertise in various domains such as artificial intelligence, information processing and decision theory, as well as his experience teaching engineering and architecture in the 1940's at the Illinois Institute of Technology (Huppatz, 2015). Based on his teaching experience, he came to conclude that "engineering education needed less vocationalism and more science." He also called for a reform in design curriculum, stating that "The professional schools can reassume their professional responsibilities just to the degree that they discover and teach a science of design, a body of intellectually tough, analytic, partly formalizable, partly empirical, teachable doctrine about the design process." (Simon, 1996).

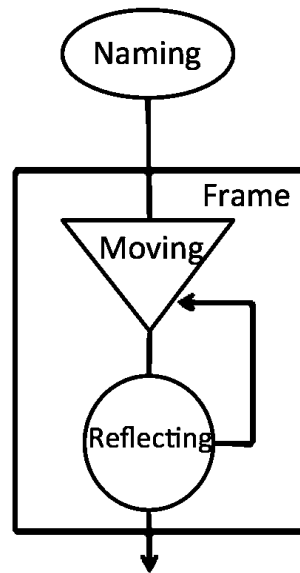
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<sup>2</sup> Herbet A. Simon was awarded Nobel Prize in Economic Sciences in 1978

Although Simon's positivist view of design was appealing, it was criticized for not being suitable for solving the "wicked" problems of real-world practice. The notion of "wicked problem" was proposed by Rittel and Webber (1973) in describing the complex and indeterminate problems of modern society. They used the term "wicked" due to the lack of clarifying traits needed to understand and solve the problem. For Rittel and Webber, in-real life design practice, information at the start of the problem is often incomplete and the requirements are contradictory. As problem solvers go about solving a design problem, design information changes, and also strong interdependencies among design considerations make it impossible to employ the rules of science and engineering. Simon's Technical Rationality continued to be challenged by many other design researchers. For example, in summarizing the general theme of the Design Research Society's conference held in 1980, Cross (2001), a leading design researcher, concludes that "The general feeling from that conference was, perhaps, that it was time to move on from making simplistic comparisons and distinctions between science and design; that perhaps there was not so much for design to learn from science after all, and that perhaps science rather had something to learn from design." Despite these criticisms, Simon's design theory still remains pervasive in engineering design education and in design practice.

In the 1980's a new view of design based on constructivist theory was proposed by Donald A. Schön. He rejected Simon's design as rational problem solving and believed that complex and ambiguous real-life design problems cannot be solved by application of scientific principles. Instead, he developed a new theory that described design as a *reflective practice* that is outlined in his 1983 book *The Reflective Practitioner: How Professionals Think in Action*. Schön claims that working professionals (like engineers, architects, urban planners, physicians, etc.) deal with the complex and unstable situations of practice through reflection; he used the term *reflection-in-action* to describe how designers deal with design problems. In his own words, "it is this entire process of reflection-in-action which is central to the "art" by which practitioners sometimes deal with situations of uncertainty, instability, uniqueness, and value conflict." He further explained that professional themselves cannot describe what they know, but their knowing is exhibited through their intelligent actions.

Reflection-in-action was further developed by Valkenburg (2000), and she distinguished four activities within the reflection-in-action model. They are naming, framing, moving, and reflecting, as shown in Figure 2.12. In this iterative process, designers start by naming the materials of the situation and framing the problem. Based on previous actions, designers generate moves toward a solution and then reflect upon the effect of these moves. This then leads the problem solver either to reframe the problem or to make new moves.



**Figure 2.12** The schematic representation of four design activities based on reflection-in-action model (Valkenburg and Dorst, 1998)

Schön also characterized three types of reflections: reflection-in-action, reflection-on-action, and reflection-on-practice. Of these, his focus was more on reflection-in-action, which he described as being caused by a surprise when the unpredictability of the design situation interrupts the workflow of a practitioner, and when he or she thinks back on his or her actions. The response to this surprise Schön called “back talk”. As described by Schön, “back talk” is a reflective conversation with the situation through which a deeper understanding of the problem forms. So the notion of surprise and reflection-in-action are important components of the theory of reflective practice.



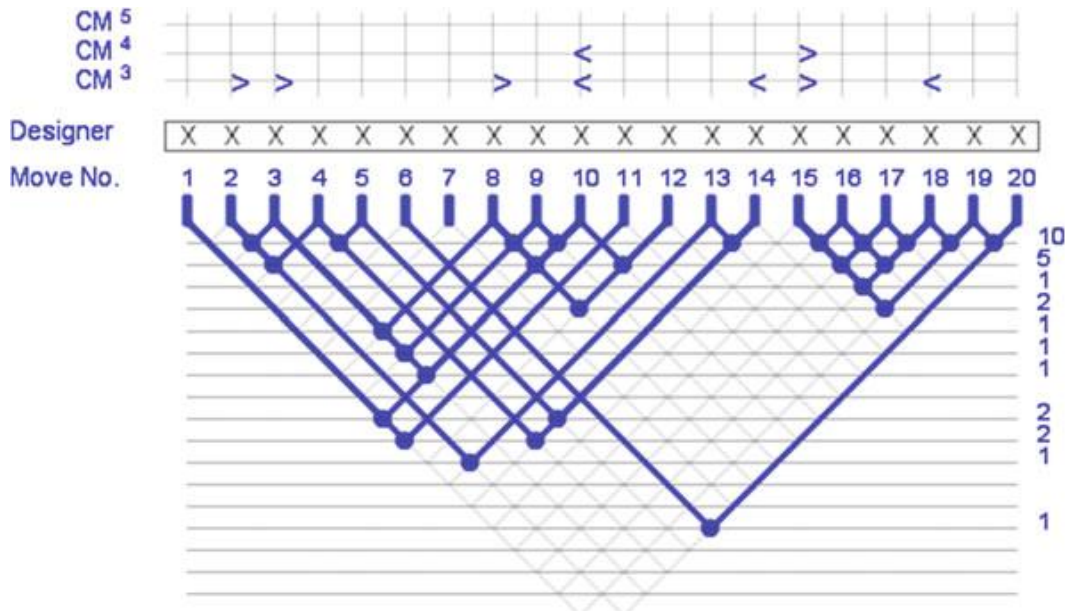
A few researchers have tested the model of reflective practice while investigating the team design process. Some have even introduced various forms of reflective journal activities as a way to encourage student reflection. Using the four activity categories (naming, framing, moving, reflecting), Valkenburg and Dorst (1998) analyzed design protocols of two multidisciplinary design teams. The study found that the distribution of time and effort put forward by the two teams on each activity class varied considerably. Adams et al. (2003) studied the design process of freshmen and seniors through the reflective practice theory as well. The aim of the study was to identify to what extent the student teams exhibit reflective behavior during design and what process factors contribute to successful design outcomes. The study found that effective problem setting and the students' ability to engage in a reflective conversation with the design situation are important characteristics of a good design process. In this study, seniors exhibited more effective problem setting and problem solving behaviors in comparison with freshman. In another study by Hey et al. (2006), a "lessons learned" exercise was used as a tool to encourage reflective practice in students enrolled in a multidisciplinary product development course. The students were asked to take a note of what they think they learned at the end of each class. In studying the ideation process of designers, Currano et al. (2011) found evidence that designers come up with new ideas while engaging in non-design related activities. They call this "reflection-out-of-action".

## **2.4 Protocol Analysis Using Linkography**

Protocol analysis is a research method broadly used for analyzing design activities of both individual designers and design teams. Two forms of data used in protocol analysis are verbal and visual-graphic data. Verbal data can be defined as the recorded spoken words of designers during a design activity, collected either using audio or video recordings. Visual-graphic data refers to sketches produced by designers during the design session. These two types of data are used for studying the cognitive activities and thinking patterns of designers.

A significant contribution to the protocol analysis method was made by Goldschmidt. She introduced and developed an analytical tool called *linkography*, a research method for notation

and analysis of a design process session. She used the term *linkography* and defined it as a graphical representation of protocol data constructed on a small unit of the design activity. An example linkography is given in Figure 2.13.



**Figure 2.13 A linkograph indicating critical moves with different thresholds (Goldschmidt, 2013)**

The main purpose of linkography is to capture the cognitive activities of an individual designer or design team. Its construction is based on the *moves* generated by the designer(s). According to Goldschmidt, a move is “a step, an act, an operation, which transforms the design situation relative to the state in which it was prior to that move.” Another important component of linkography is a *link*, which is established between two independent design moves by asking, “Is move “n” connected to move “n-1”?” If a move has a relationship with the preceding move, then a link is created between the two moves and is represented by a dot in a linkograph. The count of the links associated with a move is used as an indicator of a designer’s contribution to the design activity. The term *critical move* is therefore used in linkography analysis to identify the productivity of a designer and of the design session as a whole. However, there are no strict criteria for how many links qualify a move as a critical move. It is determined by the goal and the

granularity of the study. Links created with the preceding moves are called *backlinks* whereas the links with foregoing moves are defined as *forelinks*.

The purpose of examining the direction of the links is to help identify the idea generation process of the design activity. For Goldschmidt, moves with forelinks indicate divergent thinking of designers, and moves with backlinks represent convergent thinking (Goldschmidt, 2013). The ratio between the moves and the links is called the *link index*. The value of a link index can be used to determine the productivity of a design session.

The original intention of linkography was to measure the productivity of an individual designer. Now the technique has been extended to be flexibly applied in many areas of engineering design study, such as the social and design information behaviors of individual designers and design teams. One of the major extensions to the linkography method was by Kan and Gero (2004). They proposed a new approach to investigate team design process by characterizing the links into distinct activity categories. This approach is adopted in this study in order to understand what activities the student teams engage in.

In order to conduct an activity analysis of the design teams, distinct activity categories must be first established. Hence, we looked into the design literature that focused on engineering design team activities. It was found that an early framework for distinguishing team design activity was developed by Baya and Leifer (2000). Leifer and Milne (2000) have further extended this work and devised a rather comprehensive design team activity categories. In their work, design team activities are divided into two major categories, information-handling activity and social activity. This activity classification framework was adapted in this study.

## CHAPTER 3: RESEARCH APPROACH

### 3.1 Research Procedure

In the first six weeks of class, students were familiarized with course materials covering the basics of parametric, direct and freeform modeling, 3D printing and 3D scanning technology, as well as design thinking and collaborative design. It was intended that this knowledge would then be used to develop solutions to design problems involving biomedical devices. In the 7th week the design projects were introduced. After the introduction, the students ranked their top three preferences from the proposed design tasks. Based on their preferences, the students were organized into six teams consisting of three to four members in such a way that each team included at least one member from bioengineering, industrial design, and systems/mechanical engineering. Two of the teams were given the same design task, while the other teams were assigned different biomedical design projects. Through professional contacts of the bioengineering professor, each project had a sponsor. From the beginning of the design project, the student teams worked closely with their respective project sponsors in the healthcare industry. Table 3.1 shows the design task distribution by team. More details of the design projects can be found in Appendix D.

**Table 3.1 Design task distribution by teams**

<b>Teams</b>	<b>Biomedical design tasks</b>	<b>Main considerations</b>
1	Neonatal Pneumothorax	Improving the functionality and the ease of use, reducing the harm on the subject.
2	Nose Retractor	Eliminating the need of involvement of multiple people when operating
3	Eating Utensils	Developing customized utensils to allow the client to eat independently
4 & 5	Multispectral USB microscope	Increasing the comfort of the design for people of varying size
6	Slit Lamp	Improving the aesthetic and efficiency of the device

Throughout the design project period, there were three interim reviews and one final presentation. The design reviews were held in the 10th, 13th, and 16th week of the semester respectively. The final presentation took place during finals week. After the presentation the design project deliverables, including conceptual sketches and virtual and physical models developed by the teams were collected. The summary of the requirements for the project deliverables is given in Table 3.2.

**Table 3.2 Final design project deliverables**

<b>Design Project Deliverables</b>	<b>In Detail</b>
Power point presentation	<ul style="list-style-type: none"> <li>● Including result of the research</li> <li>● Including design outcome</li> <li>● 10 min in length</li> </ul>
A poster	<ul style="list-style-type: none"> <li>● Describing design project</li> <li>● 34 x 22 inches in size</li> </ul>
Free hand sketches	<ul style="list-style-type: none"> <li>● From concept and ideation activity in digital format</li> </ul>
3D prints	<ul style="list-style-type: none"> <li>● All 3D prints created for the project</li> </ul>
Scan data	<ul style="list-style-type: none"> <li>● Raw scan data from Creaform scanner in file format of “stl”</li> <li>● Geomagic output files in file format of “xrl”, “stl” and “stp”</li> </ul>
Assembly drawings	<ul style="list-style-type: none"> <li>● Including principal views, isometric views, sections views, details and exploded views</li> </ul>
Part drawings	<ul style="list-style-type: none"> <li>● Showing four views, centerlines, center marks and critical dimensions</li> </ul>
Stress analysis simulation study	<ul style="list-style-type: none"> <li>● Using Fusion 360</li> </ul>
Rendered images	<ul style="list-style-type: none"> <li>● Including perspective, cutaway sections views, detail views, etc.</li> </ul>
Animation	<ul style="list-style-type: none"> <li>● Showing how the final design works</li> <li>● Using Fusion 360</li> </ul>

## **3.2 Literature Review**

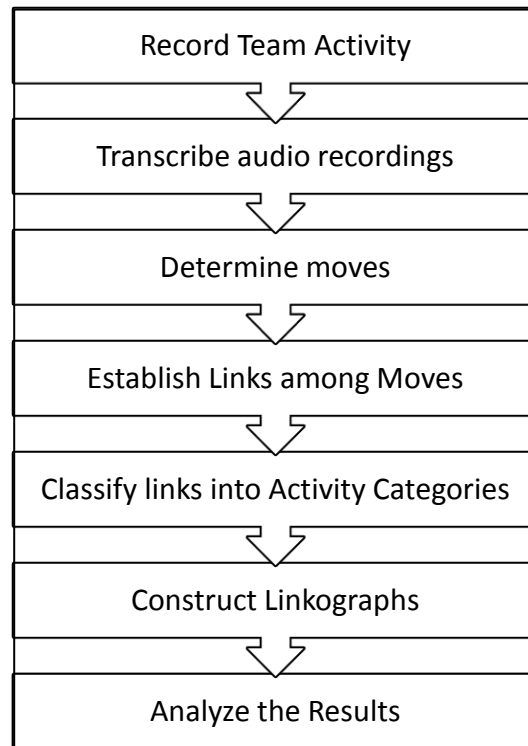
Guided by the research questions proposed by the course instructor, as described in the Introduction, a literature review was started in the summer of 2015. The primary goal was to identify the most important publications within research areas (e.g. design thinking, reflective practice, CAD and creativity, 3D CAD, 3D printing etc.) that are directly related to the computer-aided product realization course. In the search and selection of these publications, we mainly focused on recent research articles and conference papers, using a wide variety of online databases including ProQuest, Scopus, ScienceDirect and Google Scholar. Another consideration for selecting literature was the reputation of the publication and the number of times the work has been cited. Our literature review conducted using these measures resulted in twenty-four articles, organized into six categories, most of which were authored by leading researchers in their respective fields. These articles are presented in Results section.

## **3.3 Data Gathering Tools**

The data gathering tools used in this study include design protocols, reflection journals and an online survey. The design protocol method was used to investigate the team activities in the early stages of design. The reflection journals and online survey were used to gain insight into students' perception of multidisciplinary team collaboration as well as the impact of using digital prototyping tools on the design process. We will discuss each tool in the following sections.

### **3.3.1 Design Protocol**

The meetings of all six design teams, except for the first session, were audio recorded. The first design meeting was devoted to brainstorming activities and understanding the design problem, and therefore was excluded from the analysis. The design protocols obtained during the second team meetings of three design teams were transcribed and used in the team activity analysis. The transcriptions of these three team can be found in Appendix A. These teams are identified as Team 1, Team 2 and Team 3. Fictional names were used for each team member. Figure 3.1 demonstrates the process used for conducting the protocol analysis.



**Figure 3.1 Protocol study process**

First, meetings of the design teams were audio recorded, and the audio files were transcribed. Based on the transcriptions, along with careful listening to the audio recordings, moves were determined and noted with a student's fictional name. After the establishment of the moves, the next step was to examine whether a move was related to the previous one. Each statement, starting from statement 2 until the last statement, has undergone this procedure in order to generate links among the moves. Next each link was coded according to the activity categories described in Table 3.3. Finally, linkographies of the three design teams were constructed, and represent quantitative and qualitative analyses of the team activities.

**Table 3.3 Activity categories for coding the links**

<b>Design Content and Process Related Activities</b>	
<b><i>Analysis</i></b>	<ul style="list-style-type: none"> <li>• Evaluating and discussing new ideas or concepts, discussing design requirements</li> <li>• Asking questions, providing information, providing explanations upon one’s inquiry to clarify ideas or concepts</li> <li>• Organizing ideas or concepts in some fashion, assigning tasks, activities relating to team planning</li> <li>• Other design related communication acts</li> </ul>
<b><i>Clarification</i></b>	
<b><i>Planning</i></b>	
<b><i>Other</i></b>	
<b>Social Related Activities</b>	
<b><i>Social</i></b>	<ul style="list-style-type: none"> <li>• Communication acts not related to the design task at hand</li> </ul>

The two main categories used were 1) design content and process related activity and 2) social related activity. The former has the subcategories of analysis, clarification, planning and “other” activity. All discussions not relating to the design task at hand fell into the category of social related activity. The five activity categories were inspired by Leifer and Milne (2000).

### **3.3.2 Reflection Journals**

Reflection journals were submitted three times over the course of the design project period. The first reflective entries were collected during the 10th week, the second was in the 13th week, and the final reflective entries were submitted during the final exam week. The main purpose of the reflective writing assignment was to understand student’s perceptions of the influence of multidisciplinary design collaboration on design, as well as their experiences using digital prototyping tools. Therefore, in the reflection journal assignment, the students were asked to write about their experiences relevant to these two majors areas. The average grade of the three reflection journals counted as five percent towards the final grade. The full guideline for the reflection journals can be found in Appendix B.



### **3.3.3 Survey**

The online survey was conducted during the final exam period, after the final design presentations. Participation in the survey was optional. The survey consisted of eleven questions, seven of which were multiple choice, while the remaining four were descriptive. The questionnaire was developed by the engineering course instructor and the graduate research assistant. We asked the participants to rate the usefulness of the 3D CAD software, 3D printer and 3D scanner in the multiple-choice questions. The descriptive questions asked the students to describe their experiences in using the 3D CAD tools, as well as with multidisciplinary team collaboration. The survey questionnaire can be found in Appendix C.

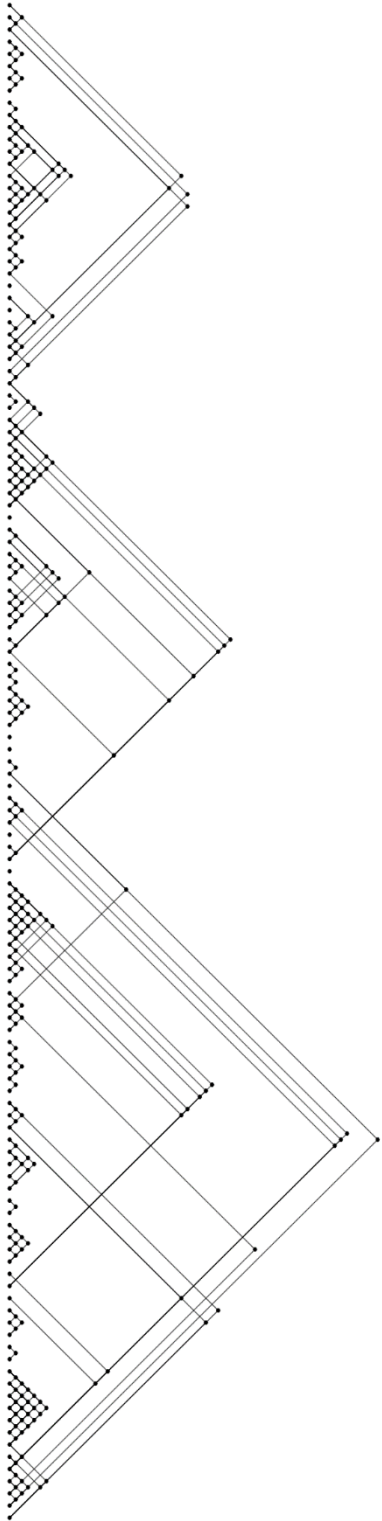
## CHAPTER 4: RESULTS

### 4.1 Results from the Linkography Analysis

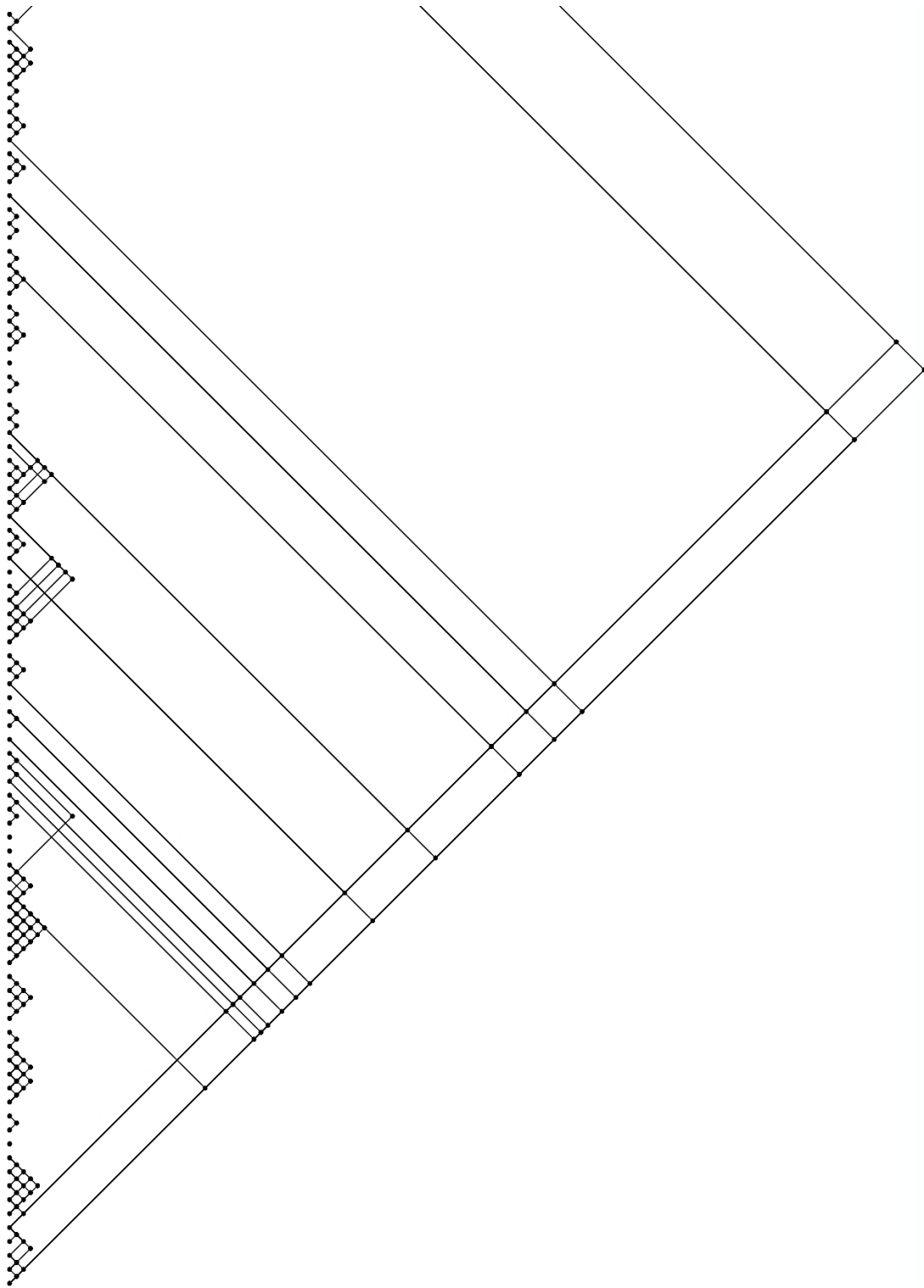
Design protocol of design teams can be studied from many aspects using the linkography tool. Considering the primary goal of understanding the early stage activities of the multidisciplinary design teams, our analysis was principally focused on these design activities and the participation of the individual student in the team discussions. As was previously mentioned, meeting recordings of three out of the six design teams were used for this analysis. The design session of team 1 lasted 22.83 minutes, team 2 lasted 17.83 minutes, and team 3 lasted 25.66 minutes. In the team 1 meeting, only two out of four team members were present. In the team 2 meeting, all four team members participated. In the design session of team 3, three out of four students were present. The quantitative results of the linkography analysis of the three teams is presented in Table 4.1. Linkographies constructed on these data is depicted in Figure 4.1, 4.2 and 4.3.

**Table 4.1** *Quantitative results of linkography analysis*

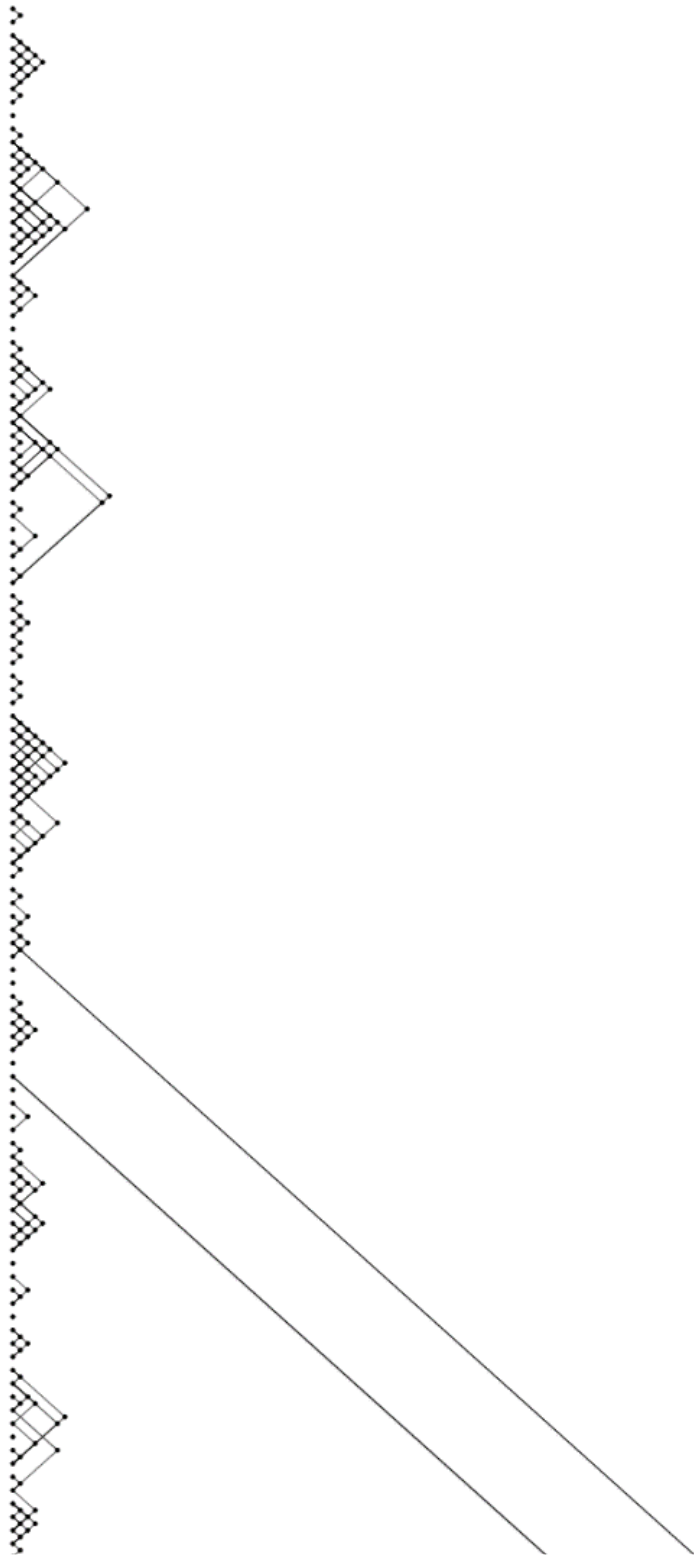
	<b>Team 1</b>	<b>Team 2</b>	<b>Team 3</b>
<b>Total moves</b>	61	125	202
<b>Total links</b>	122	209	295
<b>Link Index</b>	2.00	1.67	1.46



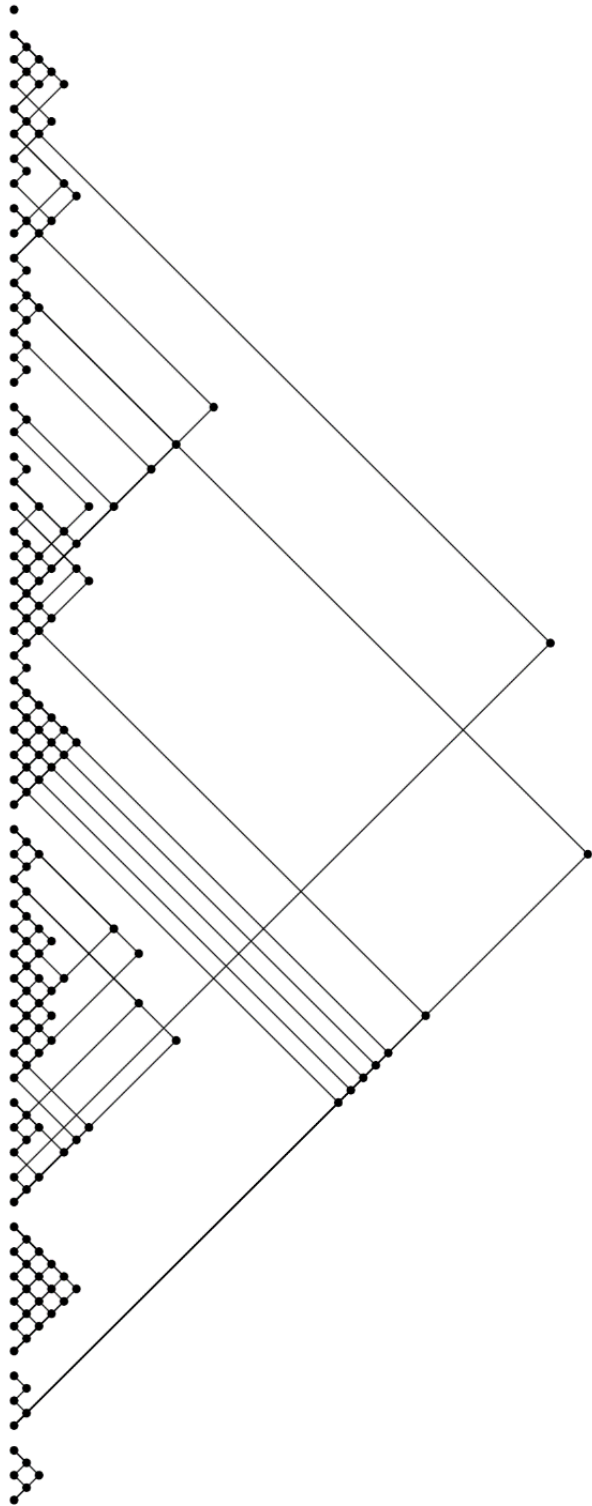
**Figure 4.1 Linkography of Team 1**



**Figure 4.2 Linkography of Team 2**

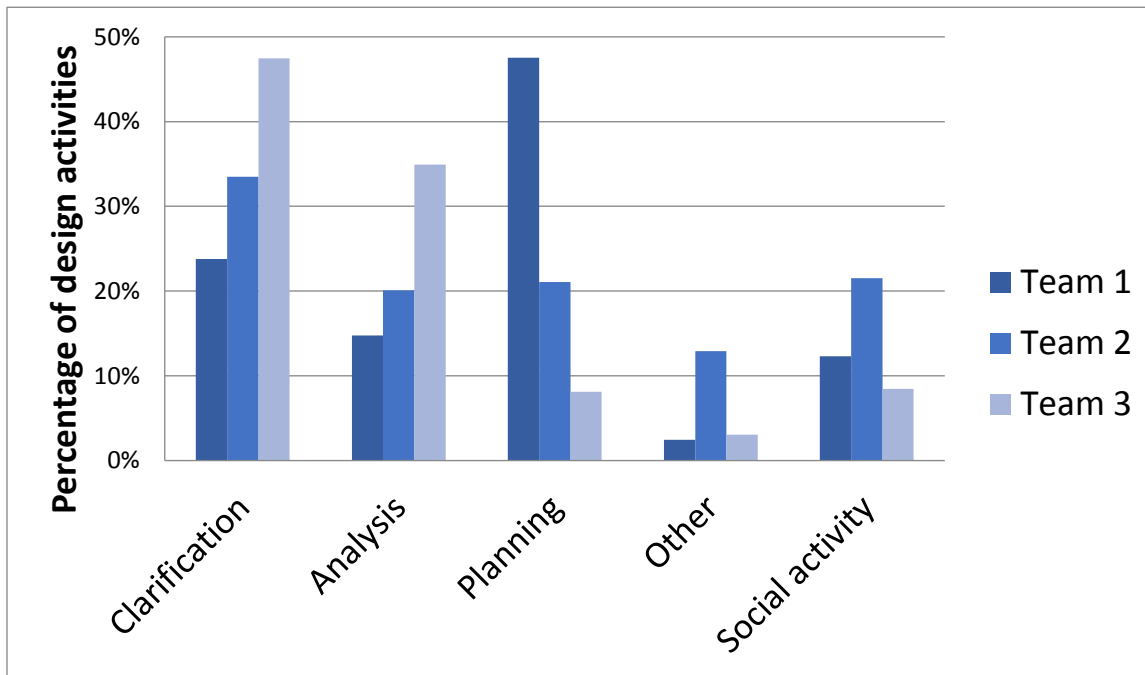


**Figure 4.2** (cont.)



**Figure 4.3 Linkography of team 3**

Because the design sessions for each team varied in length, there was a big gap between the number of moves made by each team. The link indexes of 2.00, 1.67, and 1.46 suggested that the team meetings were weak. However, some design researchers noted a link index lower than 2 is common among novice design teams as it is caused by lack of focus on one topic, which is a salient characteristic of student designers. Note that the link index of team 1 was higher than that of team 2 and 3. It might have something to do with the fact that the team 1 design session was carried out by only two students, and as a result there was less diversity of ideas and fewer topics brought out, compared to teams 2 and 3. Design activity distribution between the teams is shown in Figure 4.4.



**Figure 4.4 Percentage distribution of the design team activities**

In their meetings each design team exhibited similar activity patterns. Their discussions revolved around design and team coordination activity. In team 1, 47.54% of the links fell into the planning activity. This means that team 1 focused more on organizing and distributing the design tasks during their design session. As for teams 2 and 3, the majority of the links (33.49% & 47.45%) belonged to the clarification activity. This means that the main theme of their design sessions

was questioning, answering and clarifying questions about the design task. We assume that the fact that the clarification activity received high attention by both teams might be due to the multidisciplinary team composition, as each student differed in their ability to grasp the design problem and had differing focus towards the design task.

Next we looked at the participation and contribution of each student. The number of critical moves (i.e., has more than five links) generated by a student was used in assessing his or her contribution. Critical moves coded as a social activity were excluded as those communication acts are not related to the design task itself, but to social conversations.

**Team 1:** Table 4.2 shows the breakdown of the moves and the critical moves associated with each student. CM5> denotes the critical moves with forelinks and <CM5 indicates critical moves with backlinks.

**Table 4.2 Team 1 moves and critical moves** (Last two columns show the critical moves with backlinks and forelinks)

Student name	Number of moves	Critical moves	
		CM5>	<CM5
Kelly	31	57.14 %(5)	40%(2)
Java	30	42.86 %(3)	60%(4)

Java and Kelly made a roughly equivalent number of moves and critical moves. This suggests that they were equally active and made an equal contribution to the design session. Now let's look closely at the content of the design communication. The team meeting started with Kelly's inquiry to Java, "So you are in industrial design? You probably draw a lot of sketches". This is understood as Kelly's attempt to identify the expertise and resources within the team. From the beginning of the design session, Kelly took the initiative in the discussion and generated five critical moves with forelinks. This suggests that she was in more of a leading role, and brought many new topics/ideas to the discussion. This can be illustrated by her comment, "Let's start listing a bunch of things we want to achieve and then we can characterize them all". Also, she played a



coordinator role, an example being when she said “...Today do you want to decide dimensions and break it into the categories? Do you have any specific part of it you would like to work on?” Looking at the questions raised and statements made by Java, she appeared to be more interested in getting to know the general functionality of their assigned medical design task, a neonatal pneumothorax device. For example, in the first half of the meeting she made many inquiries related to the general working principles and functionality of the device. Upon looking at the image of the concept sketch of the device provided by the project sponsor, she asked “what does it exactly do”, “Both are one”, and “what is this one?” Kelly provided answers to Java’s inquiries. It can be assumed that Java needed more explanations in understanding how the device functions.

**Team 2:** Table 4.3 shows the breakdown of the moves and the critical moves per student.

**Table 4.3 Team 2 moves and critical moves (Last two columns show the critical moves with backlinks and forelinks)**

Student name	Number of moves	Critical moves	
		CM5>	<CM5
Sara	47	44.44% (4)	33.33% (2)
Rose	1	0 (0)	0 (0)
Mark	31	11.11 % (1)	33.33% (2)
John	47	44.44% (4)	33.33% (2)

Sara and John contributed 47 moves and Mark made a total of 31 moves, whereas Rose made only one move. The reason for her poor participation could be because, being from industrial design, she did not feel comfortable collaborating with engineering students in the beginning. Other contributing reasons could be her personality, previous experience, work environment and so on.

Sara and John were actively involved in the design session. Each made four critical moves with forelinks. This implied that they were leading the discussion and brought more new ideas and

topics to the discussion, compared with the other two members. For example, Sara started the design meeting by suggesting that they should ask the physician about the general functionality and the procedure for using the nose retractor device that they were assigned. John also asked whether there was a picture of the device that the team could see. John appeared to be very enthusiastic, and exhibited more of an implementer role as he raised many alternative design solutions. An example is when John said, "I think we can combine these two into one. Because I do not think these four can be combined into one." Sara seemed to be rather knowledgeable about the nose retractor device, providing detailed answers to the questions raised by other team members. She also appeared to be in a leadership role as she led the discussion, for example, she suggested "... I think like these are all from brainstorming without criticizing. What do you think? I like magnifying idea".

Mark did not enter the discussion until after the first 6 moves had been made and he seemed to be more analytical and was decisive when making design decisions; he listened to the discussion carefully and analyzed the design situation and then proposed his idea, an example is when he said "let's just make all these tools like maneuverable with two hands, I think".

**Team 3:** Three out of four members attended the design session. It was found that there was not much difference in the number of moves contributed by each student. However, the number of critical moves made by each student varied considerably. Tom made a total of seven critical moves. Of these, five were associated with forelinks and two with backlinks. This result suggests that Tom was more productive than Nathan and Ella. Nathan and Ella made four and two moves respectively. Note that Ella made the most moves with 78, but only two of these qualified as critical moves. The conclusion we can draw here is that the level of participation in the discussion does not necessarily reflect one's contribution to the design activity. Table 4.4 shows the percentage of moves and critical moves made by each student.

**Table 4.4 Team 3 moves and critical moves (Last two columns show the critical moves with backlinks and forelinks)**

Student	Number of Moves	Critical moves	
		CM5>	<CM5
Ella	78	14.28%(1)	16.6% (1)
Nathan	61	14.28% (1)	50 %(3)
Tom	62	71.42% (5)	33.3% (2)

Engineering student Tom posed many critical questions regarding not only the eating utensil device itself, but also about the medical condition of the user. One example is when he said, “What is the problem? What is the specific problem that inhibits their eating abilities?” Ella was more in a support and coordination role. She was very active in the discussion and provided her opinions to the questions posed by Nathan and Tom. For instance, Ella said, “... this is not something that we have to list off. It is good to reference during a phone call”. Additionally, she appeared to be in charge of organizing design information and coordinating team activity.

## 4.2. Survey Results

The participation in the survey was optional. Ten out of the 23 students took the survey. The results show that all of the students except one entered the class with prior CAD experience, as shown in Table 4.5.

**Table 4.5 3D CAD Proficiency of Students prior to taking the course**

Very proficient	Proficient	Moderately proficient	Minimally proficient	No experience
2	3	2	2	1

90% of the survey participants agreed that the Fusion 360 software was either “useful” or “extremely useful”, whereas 70% indicated that 3D scanning was either “useful” or “extremely

useful”. 90% of the students agreed with the statement that their teams were able to create the geometry needed for their designs using the Fusion 360 software. The finding that all students (100%) viewed their experiences in developing physical prototypes through 3D printing as either “useful” or “extremely useful” is significant (See Table 4.6).

**Table 4.6 Survey responses on the use of Digital Prototyping Tools in percentage**

Prompts	Not Useful	Somewhat Useful	Neutral	Useful	Extremely Useful
Rate the usefulness of Fusion 360 as a communication and collaboration tool	0	0	10%	70%	20%
Rate the usefulness of 3D scanning in improving design outcomes	10%	0%	20%	50%	20%
Rate the usefulness of 3D printing in improving design outcomes	0	0	0	20%	80%

Descriptive survey responses concerning the use of digital prototyping tools and the benefits of multidisciplinary team composition on design are organized below.

**On 3D CAD software:** Fusion 360 was extensively used by the teams both during the concept and the detailed stage of design. Two survey participants indicated that the use of Fusion 360 allowed them to express their design ideas creatively and make design changes easily. Their responses are:

*“Fusion 360 was very useful in terms of collaboration and working quickly on a team based design...”*

*“...Fusion 360 made a lot of the design process much easier”*

However, a few students noted that they encountered many technical difficulties:

*“Fusion 360 will crash when I make drawing files and updating the software does not help. I also cannot simply drag the material from the Fusion library to the component to apply different material. I can only change it by editing the default material and apply the changes. Also when doing the animation, once it crashes switching from model mode to the animation mode, it will always crash”*

*“The Fusion 360 software was not able to output high quality output rendering locally, however we were able to do this using the “cloud rendering” feature”*

*“Fusion 360 was very useful in terms of collaboration and working quickly on a team based design. However, we did face on technicality. We added features onto several designs that did not save correctly and we had to redo the designs the next day. We were able to model all the necessary components of our design in Fusion 360”*

**On 3D Printing:** Three students indicated that the use of 3D printing was very helpful in testing and developing design concepts. The following are example responses:

*“Can figure out whether our design is functional and practical immediately with 3D printing. Yes, 3D printing can aid our team’s ability to creatively develop our design ideas since it can help us have a physical concept of our design.”*

*“Our team’s design criteria was 3D printed utensil grip handles, so this was necessary for our project. It did allow us to try building different ideas into our grip and physically observing how they would work very quickly”*

*“We were able to notice significant differences in comfort from the 3D prints when making minor dimension changes. Without the prints we probably would not have made these changes”*

**On 3D Scanning:** Some of the design teams did not use the 3D scanning technology. Three students who used 3D scanning indicated it was useful, whereas two students were only partially satisfied with the performance of the 3D scanner. Their responses are presented below:

*“The 3D scanning in [the lab] is not very precise and ergonomic. We have to spend so much time fixing the model through Geomagic. I think 3D CAD scanning can aid our ability to creatively develop our design, because we cannot download a 3D model of nose retractor in some websites like GrabCAD and if we build it without any data and only looking at the real retractor, there will be a large deviation between the 3D model and the physical model”*

*“We use 3D scanning to scan the product we want to develop. Depending on the material of the product and different scanning tool, the outcome of the 3D scanning does not get to what we expected. However, it can still be use as a reference for analysis and redesign”*

**On Multidisciplinary Collaboration:** The majority of the survey participants highlighted the different skills and perspectives brought to the team owing to the multidisciplinary team make-up. No common theme emerged in terms of difficulties related to the multidisciplinary team composition. Each individual student’s assessment was unique in the way they evaluated their experience of working with individuals from other disciplines. The general feeling from their responses is that the students had positive experiences. They are reflected in the following responses:

*“I really enjoyed working with students in different disciplines. Everyone added a unique perspective to the project. The most challenging aspects were in terms of communication. The engineers had to explain technical details to the designers and the designers had to take on more responsibility with the aesthetic aspects of the project. “*

*“I had a great experience working with students from other disciplines. It was useful to have multiple perspectives on solutions to the same problem.”*

### **4.3 Findings of Reflection Journals**

The reflective journal entries of the students were collected on three separate occasions. The students and teams expressed differing experiences and varying viewpoints regarding the 3D CAD software, 3D printing and 3D scanning. The majority of the students stated that their teams extensively utilized the cloud feature of Fusion 360. They concluded that the cloud feature of the Fusion 360 tool reduced the need for face-to-face meetings and enabled effective team collaboration. It was also found that on a number of occasions team members worked simultaneously on different parts of one model and experienced increased productivity. The following quotes from reflection entries illustrate this point:

*“My team has recently faced challenges with collaborating on a single CAD model while having varied schedules and while being in different parts of the country over the Thanksgiving break. Fusion 360’s cloud system made this challenge relatively easy to overcome by allowing us to each contribute to the model and update it in real time”*

*“During our work meeting before the design review, it was helpful to have the collaborative cloud based CAD because I was working on one model of the retractor, while another group member was working on another idea at the same time”*

*“We are utilizing the Autodesk Cloud feature in Fusion 360 so we can all work on specific parts of the design at the same time. This is very useful and has saved us a lot of time because one person worked on the poles for the stand, another worked on the chin rest and headrest, and another worked on the base”*

Consistent with the survey results, a large number of students described a variety of difficulties and uncertainties encountered while using Fusion 360 software. The following is an example statement:

*“One thing I’ve noticed is the difficulty to simultaneously collaborate online through fusion. As nice as it is to see changes made by another person to a design, there is no good way to simultaneously edit a design. Two people can create two different versions, but they cannot edit one version, which I think would be much more useful”*

While a few students indicated that using 3D scanning was beneficial in design concept development, a number of students expressed feeling of frustrations with the performance of 3D scanning:

*“A technical challenge for us is that we are still not comfortable with Geomagic, Fusion 360 is great because it has a wealth of online resources, but it is harder to find support for Geomagic”*

*“While the Structure scanner gave us a complete object, it was not very high resolution and therefore resulted in a very uneven and “bumpy” mesh. While the Z-scanner gave a higher quality mesh, it did not pick up many part of the Slit Lamp due to material changes (shiny metallic parts and soft black rubber knobs are missing from our scan).”*

*“What challenge we the most now is whether we can remodel the retractor successfully based on the scan data. After several times attempts, the scan data are still incomplete and messy with pixels though we have sprayed the retractor evenly”*

The students frequently noted that it was their first experience being a part of multidisciplinary design team, and that this opportunity served as a beneficial learning experience. In addition, the students highlighted how a diversity of skills and knowledge brought from each member complemented one another and enriched their learning of design:



*“Working with a bioengineer, a mechanical engineer, and another fellow industrial designer has been incredibly pleasant, and possibly more enjoyable, productive, efficient, and valuable than any other group I have worked with in college”*

*“I would admit working in this set up has accelerated the entire process greatly comparing to my other projects who only work with students from my own department”*

*“I wish more courses on campus offered this type of experience, as it is much more realistic to what we will expect in the workforce”*

*“This experience has given me a lot of insights about what my own skills are and what I can learn from my peers. I had not had many opportunities in the past to work with students in other fields and I really appreciated seeing how other disciplines work through a problem and develop a design”*

Examination of the reflection journal entries revealed interesting findings about student perceptions on collaboration between engineering and industrial design students. Comments from industrial design students on his/her team members from engineering and vice versa were abundant in the reflection journals. It did not come as a surprise that for almost all students, taking the computer-aided product realization course was their first experience of collaborating with students from an engineering/industrial design background. Illustrative statements are given below:

*“Coming from an engineering background, the mentality is that if it works, then it is good enough. Working on a project with design students has helped me to see beyond just function but to also examine form from both a qualitative and quantitative standpoint. I now take a much broader look at design problems than I previously considered.”*

*“The collaborative aspect of this project has been great so far. Being able to work with a diverse group of students adds an extra dimension of perspectives that I have not*

*encountered in previous group projects (where the groups consisted mainly of engineers). As an engineer, it is great to have feedback from an industrial designer on how organic, aesthetic, and appealing a design might be. "*

*"I have to note that having a designer or artist in the team is very useful to bring our idea into physical reality. It is uncommon experience due to most of my old teammates are engineer who do not draw well in the most case."*

*"The industrial design student was very focused on the look of our device at all times, and was more concerned about things like choosing the best color for the renderings and the final poster, while those details would have been quickly glanced over by an engineering student like myself"*

*"My knowledge of engineering is much lower ...I focus more on aesthetic and ergonomic aspects. Our diverse skillsets and personalities work very well together"*

Besides the advantages and benefits of multidisciplinary team collaboration, two students noted the downside of multidisciplinary collaboration. They are as follows:

*"I think this helps the team to avoid wasting time, but it also has its disadvantage that people only do what they are familiar with and not learning new things. However, for the best quality of the team project I think this is a good strategy."*

*"We ended up splitting the tasks based on our strengths, and while this would be the optimal way to do it in the real world, I think that in a classroom environment, this approach doesn't allow students to learn or practice tasks that they aren't strong at."*

Another finding was that many students wished that they had more time to spend on the design project itself. A few students went on to suggest spending less time on familiarizing with the course concepts and more time on the design project. Other frequently cited challenges faced by

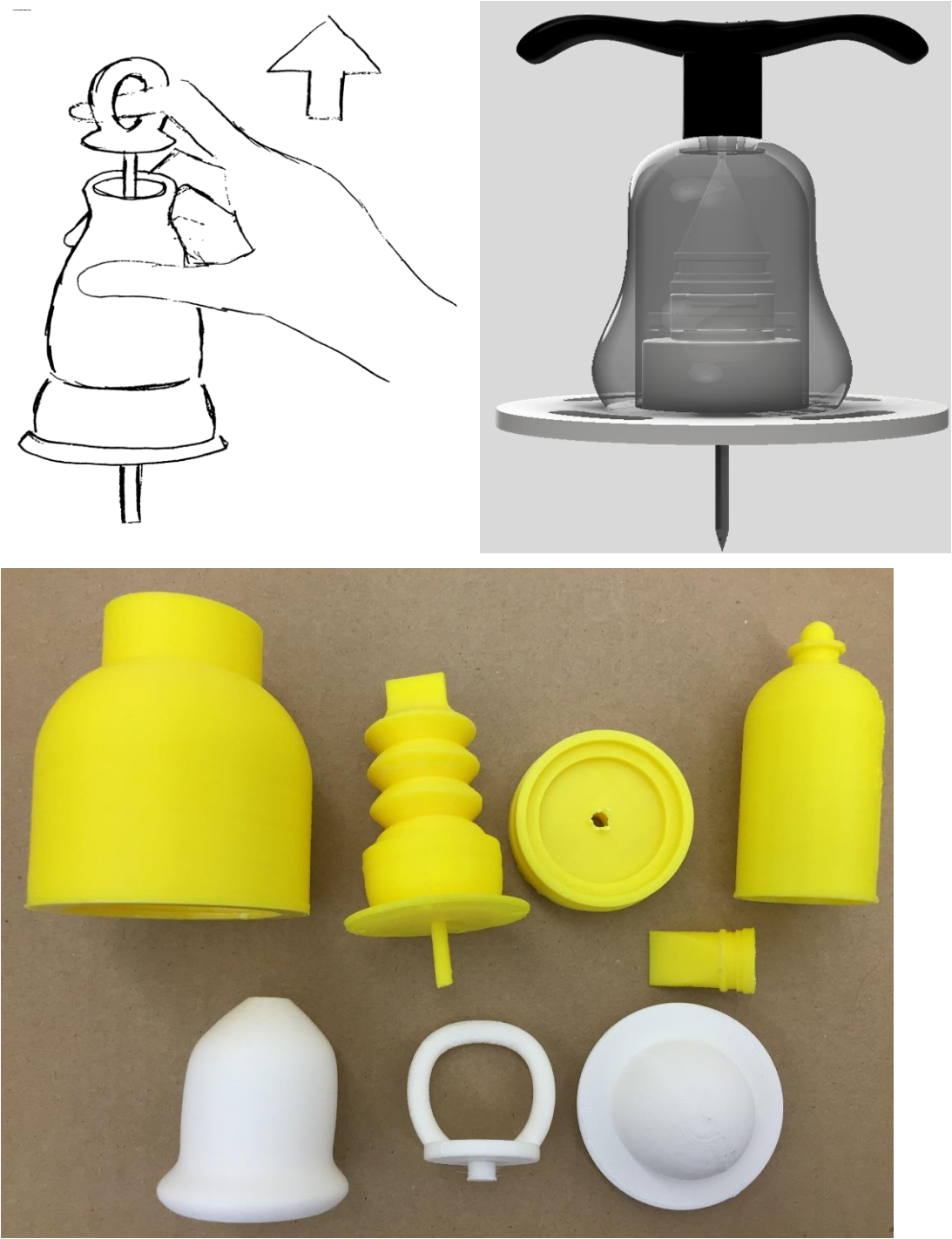
students include scheduling conflicts and uneven task contribution within a team. Overall, the reflection journal analysis complemented our survey findings and helped to better understand the students' experiences in using the digital prototyping tools, and their opinion on multidisciplinary design collaboration. More importantly, reflection journal data offered windows into individual student viewpoints, perceptions, and experiences that otherwise would not have been possible.

#### **4.4 Design Outcomes**

Owing to the professional contacts of the teaching professor in bioengineering, each design project had a sponsor from the medical industry. Throughout the project period, the student teams worked closely with their respective industry sponsors in gaining a better understanding of the design task, its objectives and requirements, as well as frequently receiving feedback on their progress. During the design process, the student teams produced a great number of free-hand sketches, virtual and physical prototypes, all of which were collected at the end of the semester. In the following paragraphs we provide an overview of design outcomes of the six design teams. Further details can be found in the final project posters of the design teams (see Appendix E)

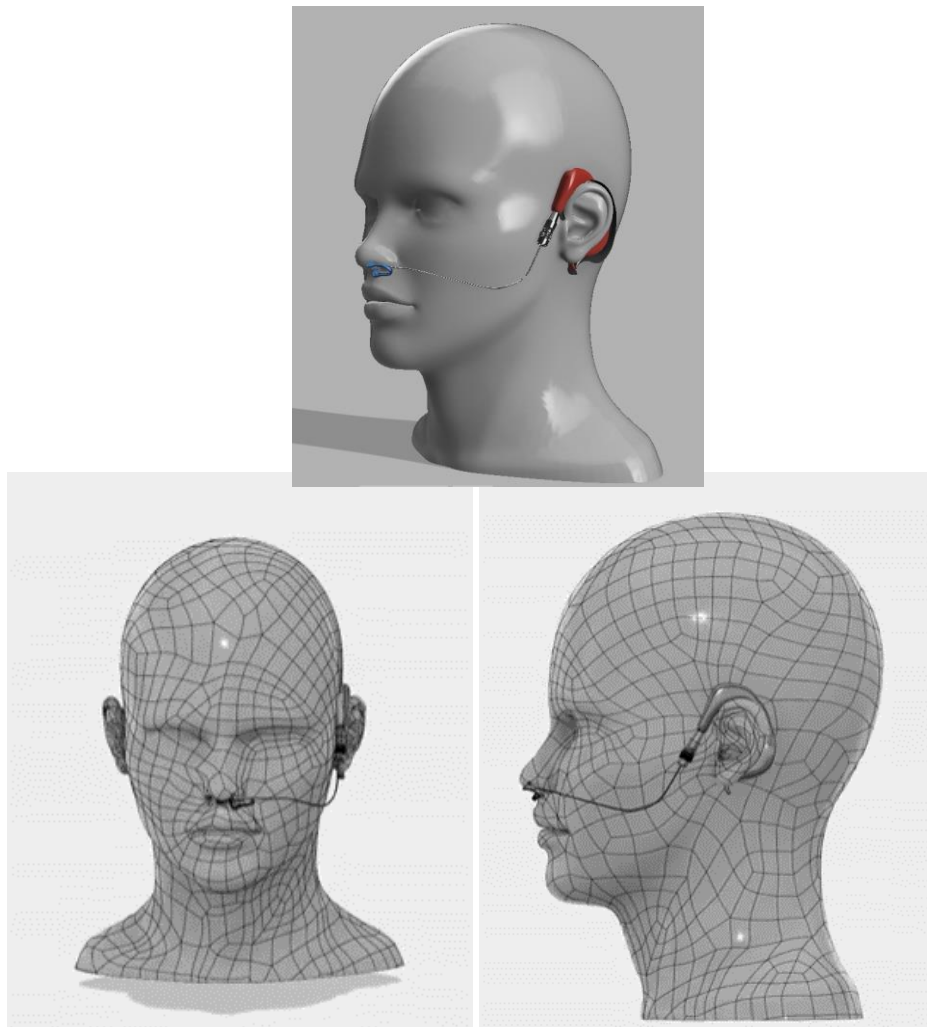
Team 1 was asked to design a neonatal pneumorax device. They used Fusion 360 and the Dimension 3D printer extensively. The team also worked closely with the project's sponsor, a physician, mostly through written communication. A design sketch of neonatal pneumorax device, as developed by the sponsor, was given to team 1 at the start of the project. The team then developed the virtual and physical prototypes based on the provided concept design. Throughout the design project period, the team generated a number of prototypes and consistently received feedback from the sponsor on their progress. One of the team members mentioned that the Fusion 360 software was extremely useful in making fine refinements and small feature modifications to the device. Two of the team members continued to work on the neonatal pneumorax device after the project closeout. This work was mainly aimed at perfecting

the fit of the components in order to ensure that the device functions reliably. The resulting design obtained at the project closeout is shown in Figure 4.5

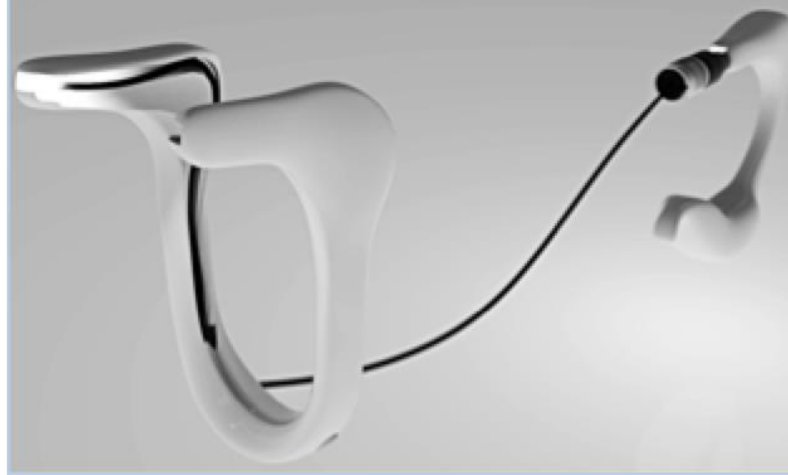
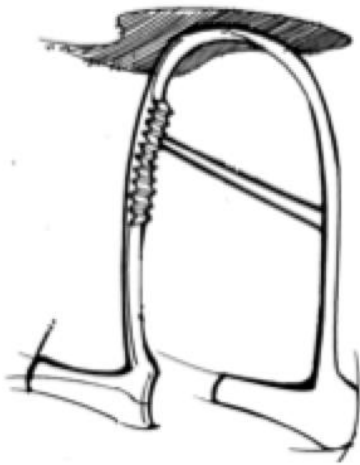


**Figure 4.5 Example concept sketches, rendered 3D CAD images and 3D printed models produced for the multispectral USB microscope design project, by team 1**

Team 2 designed a nose retractor, and their design solutions are shown in Figure 4.6 and Figure 4.7. Their final solution was a retractor with an integrated fiber optic wire and an ear battery pack. The fiber optic wire has an LED used to illuminate the patient's nostrils, and the earpiece part contains the battery and circuitry components. Due to the retractor's ability to self retract, along with the light attached to it, the need for a nurse during the process was eliminated. In the project, Fusion 360 software and the Dimension 3D printer was extensively utilized by the team.

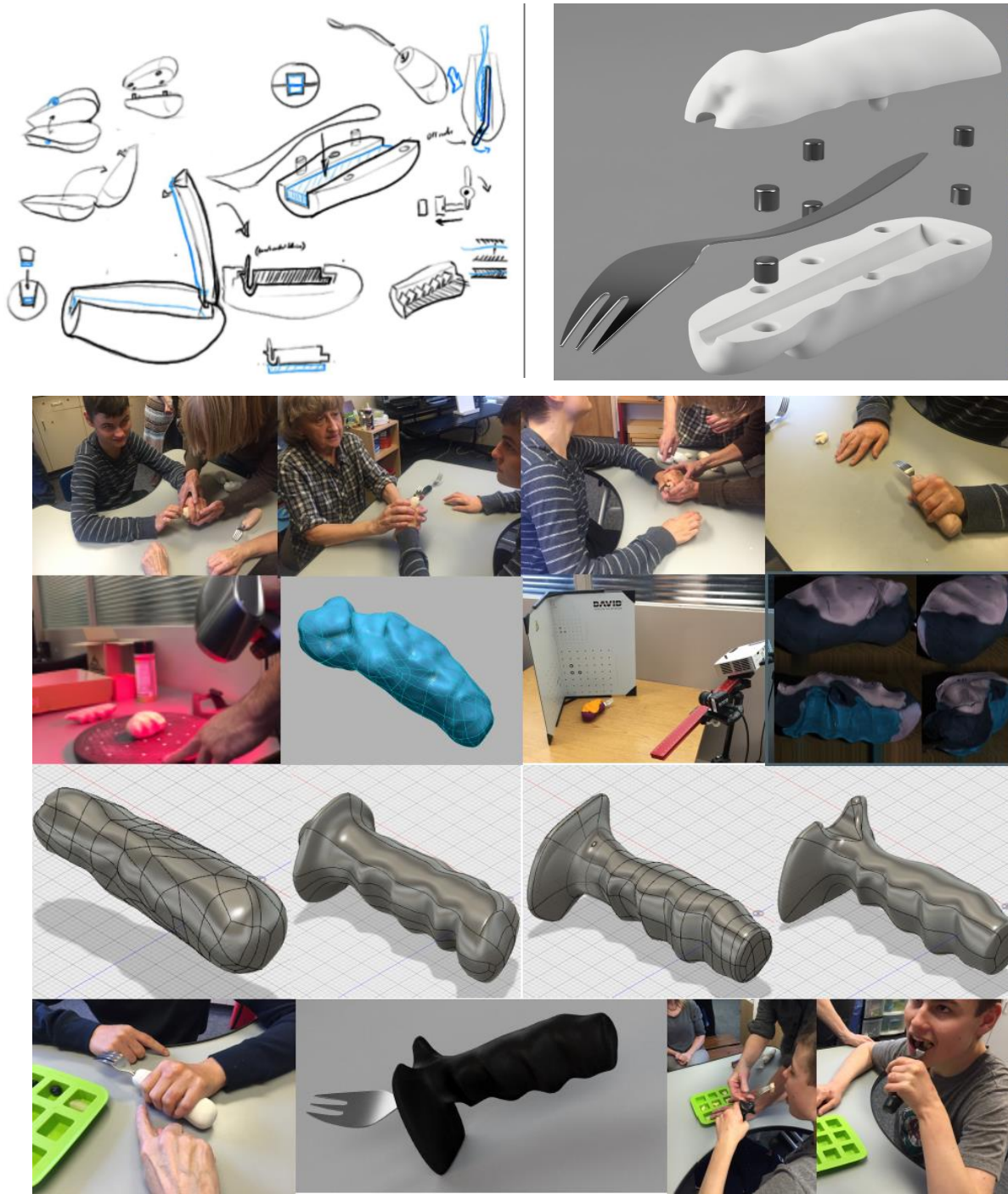


**Figure 4.6 Full design demonstration of nose retractor device design**



**Figure 4.7** Example concept sketches, rendered 3D CAD images and 3D printed models produced for the nose retractor design project, by team 2

Figure 4.8 shows the resulting design solution of the eating utensils project as carried out by team 3. The eating utensils project was specifically developed for an individual with a birth defect, agenesis of the corpus callosum. It imposes a limitation on hand mobility and prevents the individual from eating independently, so that he requires assistance during meal times. From the beginning, team 1 interacted closely with the project end user, his speech pathologist, occupational therapist as well as his mother in gaining a better understanding of his condition and eating habits. The team made multiple trips to the day care center where the individual is cared for and receives training to help manage more independently. During the visits, the team used clay to capture the preferred handgrip of the individual. Using the resulting handgrip mold, the team constructed custom utensil handles using both the Creaform handheld scanner and the Dimension 3D printer. The team made multiple iterations and refinements to their design until the individual gained the ability to eat independently. It should be noted that the team continued to work with the day care facility well after the semester ended, in order to provide a detailed design protocol so that this documentation could be used for similar projects for clients with similar disabilities at the day care facility.

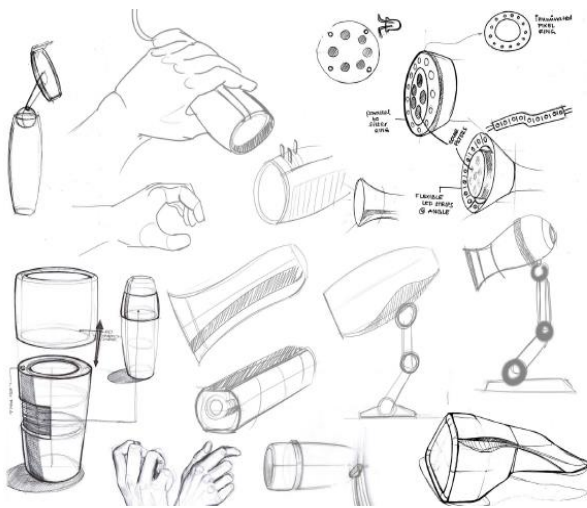


**Figure 4.8** Representative sketches, virtual and physical prototypes of eating utensils design project, as developed by team 3

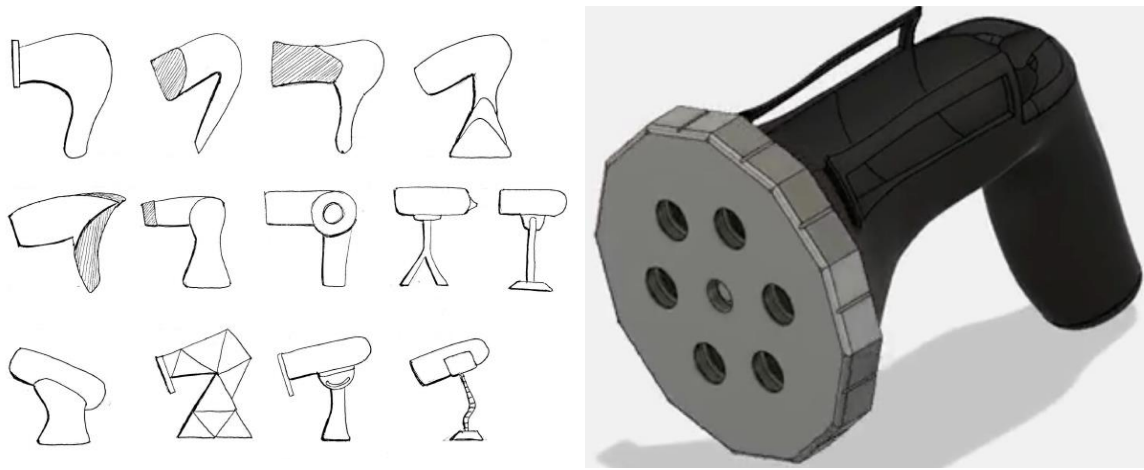


Teams 4 and 5 carried out the multispectral USB microscope design challenge. At the beginning of project, the teams were introduced to a design solution that had previously been developed by another student design team. Because that initial design solution was bulky, heavy due to the wires residing inside and hanging outside of the device, it was considered to be ineffective. Therefore, the two design teams put a special emphasis on making the USB microscope more aesthetically pleasing and considered ergonomics factors carefully in their design process. The design outcomes of the two teams turned out to be quite different from one other. They are shown in Figures 4.9 and 4.10. The design solution of team 2, as shown in Figure 4.9, consisted of a number of moving parts, potentially making the product difficult to function and to work. Team 2 produced a number of design alternatives in the early stages of the design process; however, the team selected this particular design and did not consider other design alternatives in the process.

On the other hand, team 3 made no major changes to the initially given design of multispectral USB microscope in terms of look, but made it sleeker and simpler. The handle of the device was made very comfortable to a hand grip. One novel aspect of their design was the filter wheel mechanism that allowed the filters to be changed easily by rotating the wheel. Figure 4.9 shows their design solution. Team 4 utilized the 3D printer extensively at each design iteration and testing of the physical prototype, which we believe led to a dramatic decrease in the size of the device.

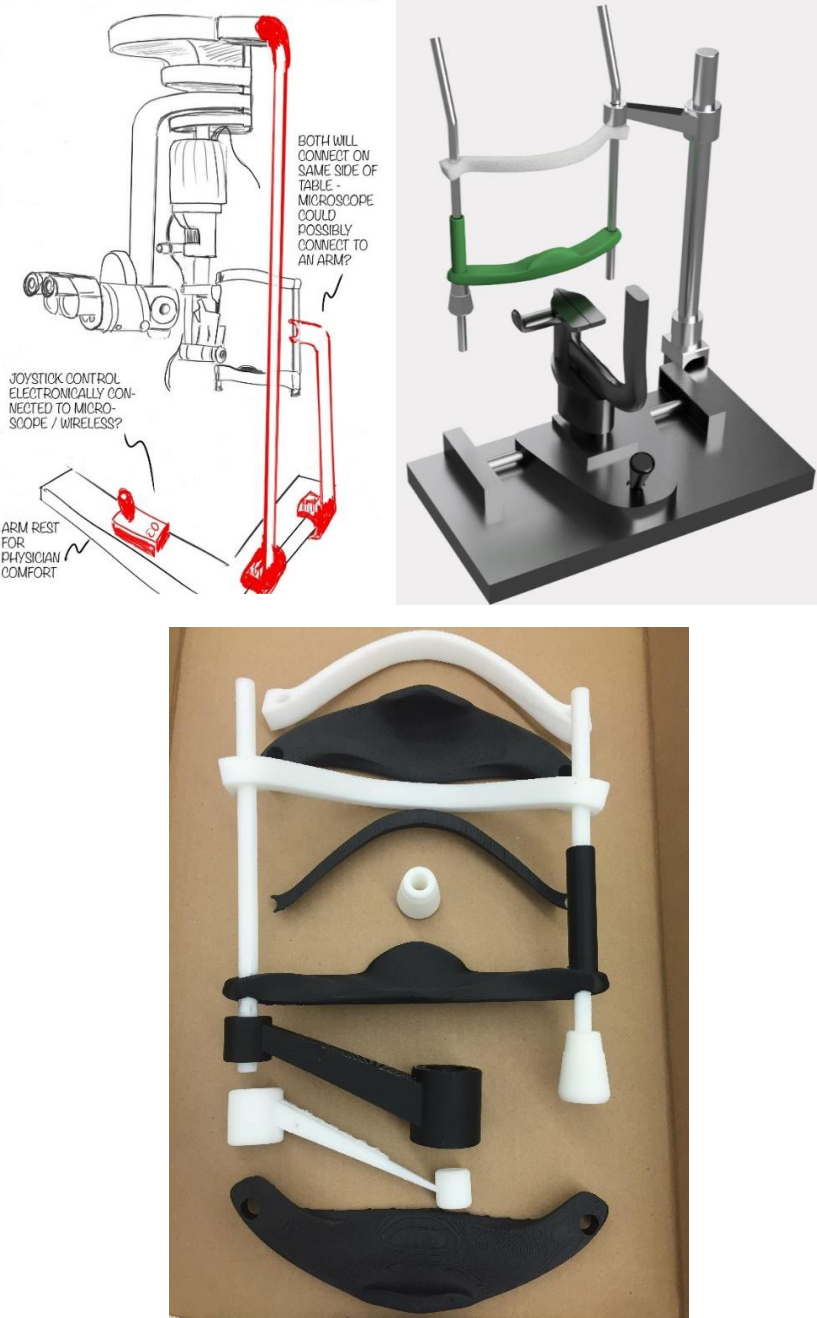


**Figure 4.9** Example concept sketches, rendered 3D CAD images and 3D printed models produced for the multispectral USB microscope design project, by team 2



**Figure 4.10** Example concept sketches, rendered 3D CAD images and 3D printed models produced for the multispectral USB microscope project, by team 5

In combination with the 3D printer, Fusion 360 was extensively used in the slit lamp design project. In particular, the sculpting environment within Fusion 360 was used to iteratively design an ergonomic chin rest for patients. The design outcome of the slit lamp project is given in Figure 4.11.



**Figure 4.11 Example concept sketches, rendered 3D CAD images and 3D printed models produced for the slit lamp design project, by team 6**

## **4.5 Literature Review Results**

The literature review resulted in the identification of twenty-four publications, as shown in Table 4.7. These works have been organized into the following six categories: design perspectives: problem solving and reflective practice, design thinking and design-based learning, CAD and creativity, prototyping, 3D printing, CAD history and next-generation of CAD.

**Table 4.7 Summary of Literature Review**

No.	Title	Author(s)	Year	Publication	Affiliations	Ref.	Times cited
<b>Design perspectives: Problem Solving and Reflective Practice</b>							
1	Revisiting Herbert Simon's "science of design"	Huppats, D.J.	2015	Design Issues	Massachusetts Institute of Technology	72	2
2	Characterizing reflective practice in design- what about those ideas you get in the shower?	Curran, R. M. ; Steinert, M. ; Leifer, L. J. ;	2011	International Conference on Engineering Design	Stanford University	20	4
3	Educating effective engineering designers: The role of reflective practice	Adams, R. S. ; Turns, J. ; Atman, C. J.	2003	Design Studies	Center for Engineering Learning and Teaching, Box 352180, University of Washington, Seattle, WA 352180, USA	22	298
4	Designery ways of knowing: Design discipline versus design science	Cross, N.	2001	Design Issues	Massachusetts Institute of Technology	34	851
5	The reflective practice of design teams	Valkenburg, R. ; Dorst, K. ;	1998	Design Studies	Delft University of Technology, Jaffalaan 9, 2628 BX Delft The Netherlands	10	302
6	Wicked problems in design thinking	Buchanan. R.	1992	Design Issues	Case Western Reserve University	55	1659
7	The reflective practitioner-How professionals think in action	Schon, D. A.	1983	-	Massachusetts Institute of Technology	220	48318
8	Dilemmas in a general theory of planning	Rittel. H.W.J. & Webber.M.M.	1973	-	University of California, Berkeley	-	9219
<b>Design Thinking/Design-Based Learning</b>							
9	Empirical studies of designer thinking: Past, present, and future	Dinar, M. <sup>1</sup> ; Shah, J.J. <sup>1</sup> ; Cagan, J. <sup>2</sup> ; Leifer, L. <sup>3</sup> ; Linsey, J. <sup>4</sup> ; Smith, S.M. <sup>5</sup> ;	2015	Journal of Mechanical Design	Mechanical and Aerospace Engineering, Arizona State University, Tempe, AZ 85287 <sup>1</sup> ; Department of Mechanical Engineering, Stanford University, Stanford, CA 94305 <sup>2</sup> ; George W. Woodruff, School of Mechanical Engineering, Georgia Institute of	190	16

**Table 4.7 (cont.)**

No.	Title	Author(s)	Year	Publication	Affiliations	Ref.	Times cited
		Hernandez, N.V. 6			Technology, Atlanta, GA 30313 <sup>3</sup> ; Department of Psychology, Texas A&M University, College Station, TX 77843 <sup>4</sup> ; Department of Mechanical Engineering, The University of Texas at El Paso, El Paso, TX 79902 <sup>5</sup>		
10	A sampled literature review of design-based learning approaches: A search for key characteristics	Puente, S. M. G. ; Eijck, M.; Jochems, W.	2013	International Journal of Technology and Design Education	Eindhoven School of Education, Eindhoven University of Technology, Postbus 513, 5600 MB Eindhoven, The Netherlands	91	24
11	Engineering design thinking, teaching, and learning	Dym, C. L. <sup>1</sup> ; Agogino, A. M. <sup>2</sup> ; Eris, O. <sup>3</sup> ; Frey, D. D. <sup>4</sup> ; Leifer, L. J. <sup>5</sup>		Journal of Engineering Education	Department of Engineering Harvey Mudd College <sup>1</sup> ; Department of Mechanical Engineering, University of California at Berkeley <sup>2</sup> ; Department of Mechanical Engineering Stanford University <sup>3</sup> ; Department of Mechanical Engineering, Massachusetts Institute of Technology <sup>4</sup> ; Department of Mechanical Engineering Stanford University <sup>5</sup>	174	1410
<b>CAD and Creativity</b>							
12	Impact of CAD tools on creative problem solving in	Robertson, B.F. <sup>1</sup> and Radcliffe. D.F. <sup>2</sup>	2009	Computer-Aided Design	Catalyst Research Centre for Society and Technology, School of Engineering, University of Queensland, 4072, Australia <sup>1</sup> ; School of Engineering Education, Purdue University, IN 47907, USA <sup>2</sup>	33	111
13	CAD and creativity: Does the computer really help?	Lawson, B	2002	Leonardo	University of Sheffield, School of Architectural Studies, The Arts Tower, Western bank, Sheffield S10 2TN, U.K.	16	60

**Table 4.7 (cont.)**

No.	Title	Author(s)	Year	Publication	Affiliations	Ref.	Times cited
<b>Prototyping</b>							
14	A study on the role of physical models in the mitigation of design fixation	Viswanathan, V. <sup>1</sup> ; Atilola, O. <sup>2</sup> ; Esposito, N. <sup>3</sup> ; Linsey, J. <sup>2</sup>	2014	Engineering Design	Department of Mechanical Engineering, Tuskegee University, Tuskegee, AL, USA <sup>1</sup> ; Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA <sup>2</sup> ; Halliburton Energy Services, McKinney, TX, USA <sup>3</sup>	60	7
15	The effects of physical prototyping and group work on the reduction of design fixation	Youmans, R. J.	2010	Design Studies	University of Illinois at Chicago, 1007 West Harrison St., Chicago, IL 60607-7137, USA	63	90
16	A study of prototypes, design activity, and design outcome	Yang, M. C.	2005	Design Studies	Daniel J. Epstein Department of Industrial and Systems Engineering, 3715 McClintock Avenue, GER 201, University of Southern California, Los Angeles, CA 90089, USA	25	132
<b>3D printing</b>							
17	The status, challenges, and future of additive manufacturing in engineering	Gao, W. <sup>1</sup> ; Zhang, Y. <sup>1</sup> ; Ramanujan, D. <sup>1</sup> ; Ramani, K. <sup>1,2</sup> ; Chen, Y. <sup>3</sup> ; Williams, C. B. <sup>4</sup> ; Wang, C. C. L. <sup>5</sup> ; Shin, Y. C. <sup>1</sup> ; Zhang, S. <sup>1</sup> ; Zavattieri, P.D. <sup>6</sup> ;	2015	Computer-Aided Design	School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, USA <sup>1</sup> ; School of Electrical Engineering (by courtesy), Purdue University, West Lafayette, IN 47907, USA <sup>2</sup> ; Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, CA 90089, USA <sup>3</sup> ; Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061, USA <sup>4</sup> ; Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Hong Kong,	348	84



**Table 4.7 (cont.)**

No.	Title	Author(s)	Year	Publication	Affiliations	Ref.	Times cited
18	Making sense of 3-D printing: Creating a map of additive manufacturing product and services	Conner, B. P. ; Manogharan, G. P. ; Martof, A. N. ; Rodomsky, L. M.	2014	Additive Manufacturing	Youngstown State University, United States	42	73
<b>Development of CAD and Next Generation CAD</b>							
20	Initiating a CAD renaissance: Multidisciplinary analysis driven design; Framework for a new generation of advanced computational design, engineering and manufacturing environments	Riesenfeld, R. F. <sup>1</sup> ; Haimes, R. <sup>2</sup> ; Cohen, E. <sup>1</sup>	2015	Computer Methods in Applied Mechanics and Engineering	School of Computing, University of Utah, Salt Lake City, UT 84112, United States <sup>1</sup> ; Department of Aeronautics and Astronautics, MIT, Cambridge, MA 02139, United States <sup>2</sup>	25	6
21	Cloud-based design and manufacturing : A new paradigm in digital manufacturing and design innovation	Wu, D. <sup>1</sup> ; Rosen, D.W. <sup>1</sup> ; Wang, L. <sup>2</sup> ; Achaefer, D. <sup>1</sup> ;	2015	Computer-Aided Design	The G.W. Woodruff School of Mechanical Engineering, Georgia Institute of technology, Atlanta , GA, 30332, United States <sup>1</sup> ; Department of Production Engineering KTH Royal Institute of Technology, Stockholm 100 44, Sweden <sup>2</sup>	68	110
22	Subdivision surfaces integrated in a CAD system	Antonelli, M. <sup>1</sup> ; beccari, C.V. <sup>2</sup> ; Casciola, G. <sup>2</sup> ; Ciaronlo, R. <sup>3</sup> .	2013	Computer-Aided Design	Department of Mathematics, University of Padova, Via Trieste 63, 35121 Padova, Italy <sup>1</sup> ; Department of Mathematics, University of Bologna, Piazza di Porta San Donato 5, 40126 Bologna, Italy <sup>2</sup> ; Former Chief Technology Officer at think3, Via C.	40	11
23	Cognitive, collaborative, conceptual and creative –four characteristics of the next	Goel, A.K. <sup>1,2</sup> ; Vattam, S. <sup>1</sup> ;	2011	Computer-Aided Design	Design & Intelligence Laboratory, School of Interactive Computing, 85	137	126

**Table 4.7 (cont.)**

No.	Title	Author(s)	Year	Publication	Affiliations	Ref.	Times cited
	generation of knowledge-based CAD systems: A study in biologically inspired design	Wiltgen, B. <sup>2</sup> ; Helms, M. <sup>1,2</sup>			Fifth Street NW, Atlanta, GA 30308, USA <sup>1</sup> ; Center for Biologically Inspired Design, Georgia Institute of Technology, 85 Fifth Street NW, Atlanta, GA 30308, USA <sup>2</sup>		
23	MCAD: Key historical development	Cohen, E. <sup>1</sup> ; Lyche, T. <sup>2</sup> ; Riesenfeld, R. <sup>1</sup>	2010	Computer Methods in Applied Mechanics and Engineering	School of Computing, University of Utah, USA <sup>1</sup> ; Centre of Mathematics for Applications, Department of Informatics, University of Oslo, Norway <sup>2</sup>	29	2
24	T-Splines and T-NURCCs	Sederberg T.W. <sup>1</sup> ; Zheng J. <sup>1</sup> ; Bakenov A. 2.; Nasri A. <sup>3</sup> ;	2003	Association for Computing Machinery	Computer Science Department, Brigham Young University <sup>1</sup> ; Embassy of Kyrgyz Republic, Washington, D.C. <sup>2</sup> ; Computer Science Department, American University of Beirut <sup>3</sup>	12	668

Most of the chosen articles are authored by leading researchers in their respective fields. To further identify the impact of the selected articles, the number of citations, according to Google Scholar, has been included in Table 4.7. Many of the articles concerning CAD technology are published in the journal *Computer-Aided Design*. On the other hand, most of the articles on design research and methods come from *Design Studies*, one of the earliest journals on design research, founded in 1979. A discussion of each category is included below.

The literature search led to a discovery of two distinct perspectives on design, that is 1) design as problem solving and 2) design as reflective practice. Design as problem solving was proposed by Nobel Laureate <sup>2</sup> Herbert A. Simon in the late 1960's, during the early years of Design Methods movement. Cross (2001) and Huppats (2015) explore and critically review Simon's view of design as a rational problem solving that deals with well-structured problems through application of scientific principles. This approach is known as the *science of design* in design literature. In the 1970's Simon's view of design as problem solving came under criticism for ignoring human judgement, intuition and creative insight as being essential in the process of solving design problems (Rittel and Webber 1979; Buchanan 1992; Cross 2001; and Huppats 2015). Rittel and Webber (1979) characterize the design and social planning problems as "wicked" due to its conflicting requirements and indeterminate nature. Rejecting Simon's view of rational problem solving, in the 1980's Schön proposed the notion of *reflection-in-action* to describe the iterative design process. Schön's ideas on reflective practice are described in his frequently cited book that spans across many research fields, *The Reflective Practitioner: How Professionals Think in Action* (1983). According to Schön, reflection is the crucial part of solving a design problem and in the context of the design task a design practitioner interactively engages with the design situation and reflects on the effects of his or her actions.

With a common goal of enhancing design education and practice, some researchers have used Schön's theory of reflective practice to investigate design thinking of designers as they worked

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<sup>2</sup> Herbert A. Simon was awarded the Nobel prize in Economic Sciences in 1978

on a team-based design task. Valkenburg (1998) developed a model of reflective practice consisting of four activity categories (naming, framing, moving, and reflecting), and then employed it to analyze multidisciplinary design team activities. Using the reflective practitioner model, Adams et al. (2003) analyzed the design activities of both first year and senior students as they worked on design problems. The results of this study indicate the importance of both effective problem setting, as well as developing the ability to engage in reflective conversation with a design situation. Another interesting approach was taken by Currano et al. (2011). They propose the concept of *reflection-out-of-action*, using it to describe to what extent individual designers engage in reflective thinking outside of the design context. They cite evidence that designers come up with new ideas through reflection while engaging in non-design related activities.

Within the design thinking and design-based learning category, three review papers were carefully selected from the large body of study available on design education. An extremely important and influential work by Dym et al. (2005) offers a detailed discussion of design thinking, engineering design teaching and learning, as well as on project-based learning. They characterize design as a decision intensive, complex process that requires designers to constantly raise questions throughout all stages of the design process. They also emphasize the importance of systematic questioning in design thinking and design learning by characterizing lower-order convergent questions that come before higher-order divergent questions. However, they argue that engineering education fails to address these characteristics of design and therefore needs to be improved. A recent study by Dinar et al. (2015) discuss design methods and tools used by design researchers in studying designer's activity and design process. The authors observe and note many limitations to design studies, including small sample sizes and the lack of standard research methods. They point out the need for the development of efficient computer tools for collecting and analyzing design data in order to draw more reliable and valid conclusions from them. A review study by Puente et al. (2012) offers comprehensive details on the characteristics of engineering design based learning. After analyzing fifty studies on the topic, they find that design projects provide open-ended and real-life design tasks in which students work in teams to

develop solutions. In this collaborative design process, instructors serve as more of a coach and act to encourage inquiry and reflection among students, and to provide constructive feedback for promoting effective design learning. The design efforts of individual students and teams, and the resulting design solutions, are assessed using a combination of methods, including presentations, self and team evaluation, and exams.

In the CAD and creativity category, two publications concerned with the impact of CAD on design were selected. It was found that design researchers and practitioners hold differing views about the effectiveness of CAD tools on the engineering design process and creativity. An early work by Lawson (2002) provides an overview of the positive and the detrimental effects that computer design tools may have on design, in the context of architectural design. He notes that computer design tools have many benefits, such as that they are good for memorization and calculation tasks. These characteristics of CAD tools help reduce the designer's cognitive load during the informationally intensive early stages of the design process. Lawson also points out that CAD tools allow for the expression of design ideas by people who do not have strong sketching skills. Lawson also observes some critical limitations of CAD tools, for example not being supportive of design collaboration and not being aligned with a designer's thought patterns and work processes. Robertson and Radcliffe (2009) identify several ways that 3D CAD tools may influence the work of engineering designers. This study is based on a case study of an engineering design team while working on a design problem, as well as on a survey administered to engineering designers of varying levels of expertise. They find that 3D CAD tools, despite their ability to enhance visualization, are not suitable in the conceptual design stage, as the designer is limited to the capabilities of the CAD tool itself and also on his or her own competency with the tool. Rather, CAD is more suitable in the detailed stages of design, Robertson and Radcliffe conclude.

Three articles were selected and placed in the category of physical prototypes in design. Yang (2005) provides a brief outline on the role and purpose of building prototypes. She studies how design teams use physical models for design. Yang concludes that spending more time experimenting with design ideas through physical prototyping can lead to more successful design

outcomes. Design researchers agree that the use of physical prototypes is beneficial in design because of the immediate feedback gained from it, and for detection of design flaws. Some also note that the physical representation of design ideas can reduce design fixation (Youmans 2010 & Viswanathan et al 2014). As previously mentioned, the phenomenon of design fixation occurs when designers produce a solution with features taken from existing designs, which detrimentally affects the idea generation process. The study by Youmans, conducted with both design and non-design students, demonstrates that the use of physical models can lead to original and novel design ideas. In investigating whether designers tend to copy from given example solutions, Viswanathan et al. find that designers are fixated on both existing designs and on their previous experiences, and that the physical construction of design solutions can help reduce the undesirable effects of design fixation. They recommend using physical models in design classrooms to improve students' design experience and to increase their innovative abilities. Further, they point to a need for more research on developing effective methods and strategies for reducing design fixation.

In the 3D printing category two publications were selected. 3D printing technology has drawn a lot of interest from academia, government and industry in recent years. President Obama's mention of 3D printing in the 2013 State of the Union address has been widely referenced by researchers, including Conner et al. (2014) and Gao et al (2015). In his address, President Obama mentioned the foundation of the Manufacturing Innovation Institute at Youngstown State University as part of the Government's effort to support future research on 3D printing. A research group at this University developed a guideline for identifying the suitability of 3D printing technology in the manufacture of different products, according to three criteria (Conner et al. 2014). These are product complexity, customization, and production volume. According to Conner et al. the benefits of 3D printing over that of traditional manufacturing lies in its ability to create custom products, as well as products with complex features in a time and cost efficient way. Gao et al. provide a comprehensive overview covering many areas of additive manufacturing, including its historical development and current status, technical characteristics, issues facing the industry, and future trends. They systematically organize the extensive existing

studies on additive manufacturing. This work is a concise, informative and all-encompassing reference work on additive manufacturing for researchers and faculty, as well as for people in the industry.

Five articles were selected in the CAD history and next-generation of CAD category. Publications in this category address the historical development of CAD, its underlying technology and surrounding issues, and future trends. Several of these publications were authored by computer scientists whose contributions have helped shape today's sophisticated 3D CAD modelers (Cohen, Riesenfeld, Sederberg). In their work, Cohen et al. (2010) and Riesenfeld et al. (2015) offer insights into the historical development of CAD since its inception in the early 1960's at MIT. Despite significant advances in the ability to represent complex geometry, researchers nonetheless criticize CAD's failure to deliver on the original vision of CAD as supporting the entire design process, from concept to detail design (Goel et al. 2012 and Riesenfeld et al. 2015). They argue that present day 3D CAD tools should be redesigned in a way that effectively integrates modern computational tools into one environment in order to support all phases of design, including collaboration. Goel et al. note that the next generation of CAD will be based on the cognitive process of designers, and will support cognitive, collaborative, conceptual and creative design.

In summary, we have reviewed and organized important works on design thinking, CAD technology, and at the interface between them. We hope that this list of publications will serve as a reference for those who are interested in exploring design education and fast developing 3D CAD technologies that are significantly influencing design practice in both academia and industry.

## CHAPTER 5: CONCLUSIONS AND DISCUSSION

### 5.1 Conclusions

The research questions addressed in this study are:

***Research question 1.*** *What activities do multidisciplinary student teams pursue in the early stages of the design process?*

The results of the linkography analysis showed that the teams were similar in terms of the activities that they engaged in, in the early phases of design. These activities included clarification, analysis, planning, “other” (non-task related) and social activity. Each activity class received varying attention, depending upon the design team. Team 1 paid considerable attention to planning, followed by clarification, analysis and “other”. Teams 2 and 3 spent the majority of their time on clarification, followed by analysis, planning and “other”.

It was observed that it was common for team members to ask one another questions concerning the design task. We assume that this is in part due to the multidisciplinary composition of the design teams, with all of the team members attempting to establish a common understanding of the design task. The team activity pattern found in this study is consistent with the results of earlier studies. Olson et al. (1992) found that design team meeting discussions revolve around activities related to the design task itself, and also with activities associated with team management and coordination.

***Research question 2.*** *What benefits and challenges with regard to the multidisciplinary design collaboration do students frequently note?*

The data obtained from the reflection journals and the survey demonstrated that the course participants highly value their experiences gained from working in a multidisciplinary team setting. Students felt that the diversity of knowledge brought by each participant accelerated the overall team design performance and contributed to a successful design outcome. No challenges,



except for the difficulties caused by scheduling conflicts when meeting outside of classroom, were noted.

**Research question 3.** *How do students view the effectiveness of 3D CAD software (i.e., Fusion 360) for team collaboration and for design concept development?*

Overall the analysis of student responses suggested that the use of the Fusion 360 software was viewed positively, in particular with respect to the cloud feature, and also regarding its effectiveness in the conceptual design stage. The course participants frequently noted in their journal entries that the cloud feature of the 3D CAD software provided an effective medium for team collaboration, as meeting outside of class time was a common challenge faced by all teams. The students often noted that the cloud feature of the software allowed them to work on their design tasks even when team members were separated by distance, thus supporting effective team collaboration. As for its usefulness for concept design, the survey data indicated that the majority of team members were able to create the geometry needed for their design projects with Fusion 360. Thus, we may conclude that the students perceived Fusion 360 to be an effective tool for concept design.

**Research question 4.** *How do students view the role of 3D printing on design concept development?*

The results of the reflective entries and the survey suggested that the students view 3D printing as being valuable in developing and testing design concepts. Specifically, all survey participants indicated that building design ideas through 3D printing is useful in improving design outcomes. Another frequently mentioned benefit of 3D printing is the instant feedback gained from the rapid prototypes.

Now, we look at the hypothesis proposed in the beginning of this work, that is: *ready access to 3D printing aids in successful design outcomes*. Based on the survey data and the entries of the

reflection journals, we may conclude that the results of this study are consistent with the hypothesis. No negative comments or feedback questioning the positive influence of 3D printer usage in design was brought out. Please note that our conclusion is based upon student feedback, and what they themselves thought about how physical models generated through 3D printing affected their design's development.

## **5.2 Discussion**

The results of this research project have been used to improve the computer-aided product realization course curriculum, and will potentially be of use to engineering design educators interested in combining design thinking with the latest advances in CAD technology. The results of the literature review conducted as part of this research consistently highlight the value of reflective practice, and experience in multidisciplinary design team collaboration in enhancing student learning and developing professional competence.

Considering the rapid advances and increased availability of various digital prototyping tools, there is a greater need for understanding and evaluating their impact on design and on a designer's creative performance. In particular, it is important to investigate the influence of current freeform surface modeling tools (e.g. T-Splines) on creative and conceptual design. With regard to the use of 3D printing, both qualitative and quantitative studies based on the changes made at each iteration of a 3D printed physical model are necessary in order to evaluate how the immediate feedback derived from the use of rapid prototypes aids the design process. Findings from these studies help inform design educators when choosing the appropriate computer design tools, and in coming up with effective teaching strategies towards the goal of preparing effective design professionals.

There are a few limitations that we would like to acknowledge in our study. The generalizability of this explorative study is restricted due to (1) a small number of participants and, (2) the qualitative approach taken in this research work. In particular, only ten out of twenty-three students took the voluntary survey. Because of the small number of participants, it is difficult to

draw a general and reliable conclusion from the results of the survey. Another limitation of this study is concerned with distinguishing the activities within the multidisciplinary design teams during protocol analysis. Team activities were determined by linking the moves of team members. For a long discussion, it is difficult to discern whether a move should be linked to the preceding move or not. Thus, in order to improve the reliability of the linking, multiple coders are necessary, along with careful observation of the actual design sessions. Additionally, it would provide more insight into the problem-solving behavior and dynamics of the multidisciplinary team interactions if the design team sessions were documented in video. It would also be interesting to analyze design team activities through the prism of the four activity categories (i.e., naming, framing, moving, and reflecting) of the reflective practice theory.

Informed by the literature review and the results of the computer-aided product realization course projects in the fall of 2015, many changes have been made and are currently being applied in the fall 2016 class. These changes include the following:

- Ten articles were selected from the literature review and are currently being used as a reading list for the course. This reading list is provided in Appendix H. The articles are discussed in class, and students are required to write one-page summary of each article.
- Additional lecture content on brainstorming and prototyping has been added to the course. In conjunction with the prototyping activity, prototyping materials such as glue guns, foam board, card, tape, pipe cleaners, playdough, etc. have been purchased and made available to the teams.
- The time allotted for the design projects has been expanded from eight to ten weeks.
- As part of the design project requirements, a logbook detailing the physical models produced by each team has been introduced. In the logbook the students are asked to photograph all physical prototypes and 3D prints produced over the course of the semester. In addition, the teams are requested to date and provide brief descriptions of the prototypes.

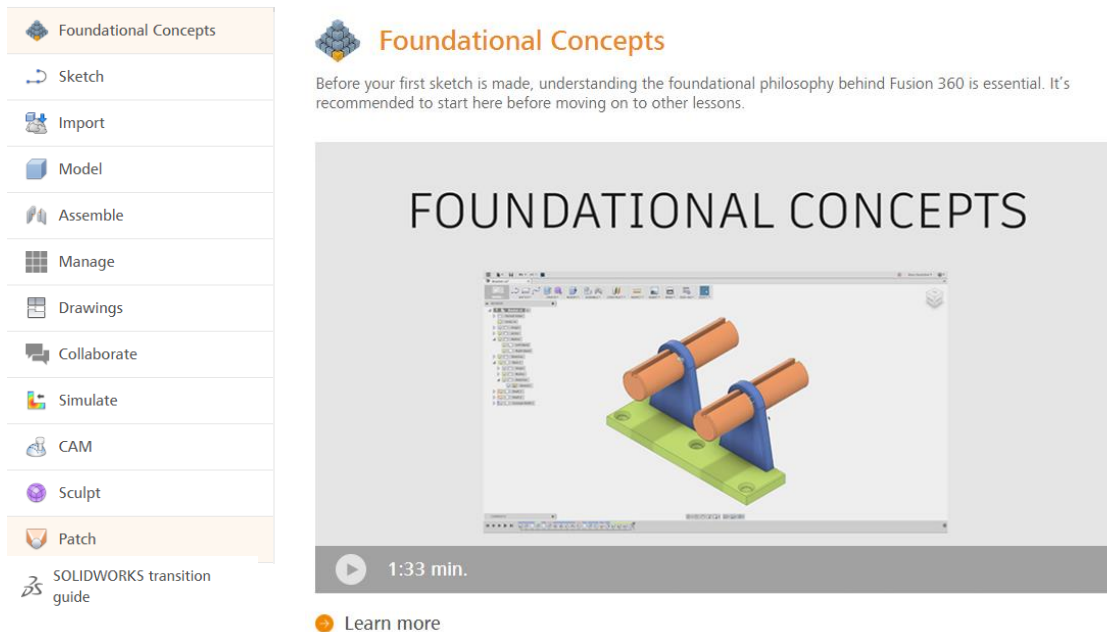
- The course has adapted a Design Quality Rubric (see Appendix I) focused on design outcome assessment, which was developed by Sobek and Jain (2004). The rubric will serve as the main assessment instrument for the evaluation of the fall 2016 design project outcomes and will be used by the evaluators (i.e., course instructors, other faculty, visitors from industry), during the final design project presentations.

The Syllabus for fall 2015 and fall 2016 class can be found in Appendix F and G. It should also be noted that the reflection journal, used for the first time in the fall of 2015 as part of this research project, continues to be an assessment component in the fall 2016 semester. In addition, a survey similar to the one used in the fall of 2015 will be administered at the end of the fall 2016 semester. It is anticipated that any improvements made to the course in the past year, as well as improvements made to the Fusion 360 platform, of which there have been many, will be reflected in a comparison of the two surveys.

### **5.2.1 Improvements of Fusion 360 Platform**

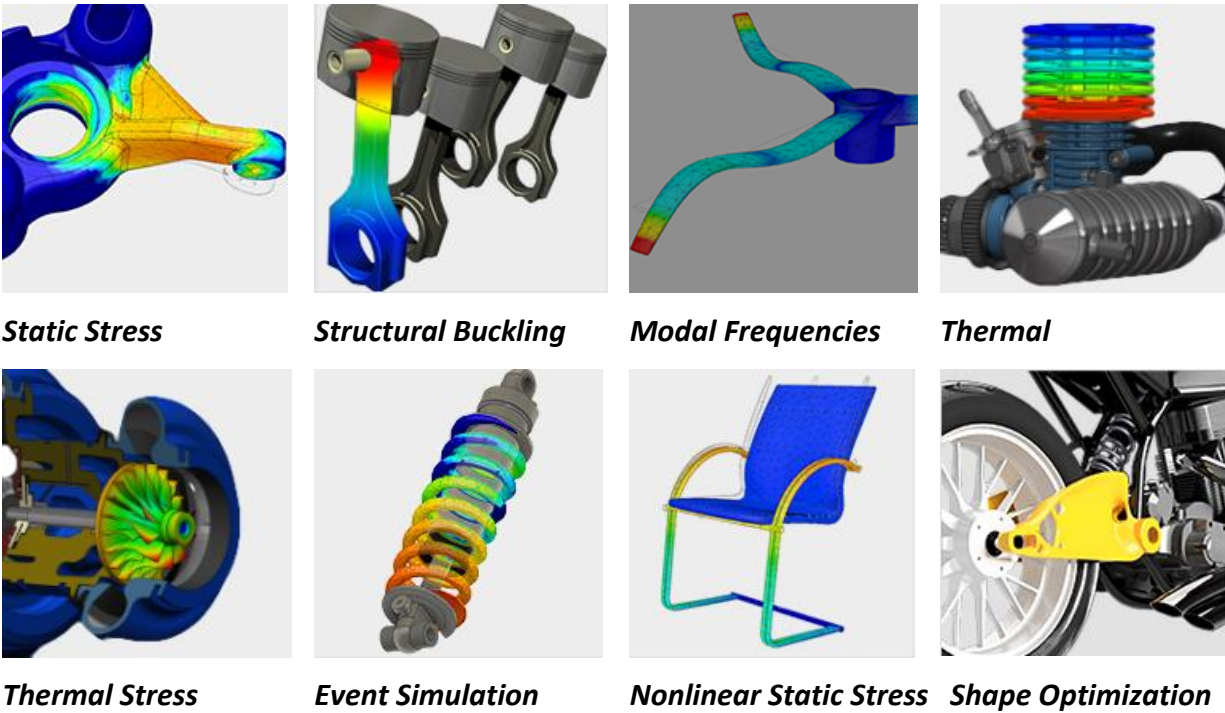
Fusion 360 has been updated frequently and undergone noticeable improvements in many areas over the last one year. Many technical issues, such as not being able to save changes and share projects through Fusion 360, and frequent occurrences of software crash, encountered during the fall 2015 semester have been eliminated for the most part and Fusion 360 has become more reliable and efficient for collaboration. Some of the improvements and the recent new features include the following:

- The online Learning Center for Fusion 360 has been vastly expanded and structured in a way that it is easy for users with varying levels of CAD experience to understand the modeling workflow and learn the functionality of the software. Many new conceptual lessons and video tutorials along with downloadable practice examples were created and are open to all users through the Learning Center. In addition, receiving technical supports and interacting with Fusion 360's online community is also available in the Learning center. Figure 5.1 illustrates the learning contents within Learning Center.



**Figure 5.1 Lesson contents and new look of online Learning Center for Fusion 360**

- Collaborating and managing data especially sharing files through Fusion 360 and A360, Autodesk’s cloud-based collaboration workspace, have become much more efficient and more reliable. CAD files can be shared and easily viewed within A360 on the web without needing to open Fusion 360.
- The number of simulation types has been increased. Now eight different analysis can be performed in the Fusion 360 Simulation workspace. These simulation types are shown in Figure 5.2. Of these, Nonlinear Static Stress, Event Simulation, and Shape Optimization were introduced as technical preview features as of now. The overview and the details about the functionality of these simulation tools are also included to the Fusion 360 Learning Center.



**Figure 5.2 Simulation types within Fusion 360**

- One of the major updates made to Fusion 360 was the integration of a new Mesh environment, which is shown in Figure 5.3. It is based on the Meshmixer scan data processing technology of Autodesk. Mesh workspace can be accessed from the drop-down menu of the modeling environment by selecting Create Mesh. The Mesh workspace allows modifying and repairing a mesh body with its editing tools such as Remesh, Reduce, Make Closed mesh, Erase and Fill, and Merge etc., The Fusion 360 Learning Center provides a detailed overview and the workflow of the Mesh workspace.



**Figure 5.3 Mesh workspace toolbar**

- The issues frequently occurred with updating Fusion 360 have been solved and maintenance update can be installed quickly and with ease.

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## APPENDIX A: THE MEETING TRANSCRIPTS OF DESIGN TEAMS

### A.1 Neonatal Pneumothorax Project

*Meeting duration:* 17 min 50 sec;

*Team members:* Kelly and Java

K001: So you are in industrial design? You probably draw a lot of sketches (laugh)

J001: I am not great at sketching, but at least some concepts that could be understood by people.  
I can sketch that much

K002: I also like sketching. I was thinking for today like it was said we will not do much. Maybe over the weekend each CAD like one part of like original design. It was kind sounded like he was OK

J002: Right, he did mention about it

K003: Yeah, so we can concentrate on making just very rough model for like each of those parts, and then like splitting the concepts and creating sketches. And then we compile that into a full PowerPoint. So today do you just want to like break up the characteristics into you know like different...em

J003: Do you have the email as well? Or, I can put it out on my phone. Oh G Illinois

K004: Oh you never looked into this?

J004: I have connected my Illinois account into Gmail. This is Gmail right? Why was it G Illinois? This is Gmail right?

K005: It's G. Illinois and it takes you to the Illinois

J005: Really? I just go to my Gmail account. It gives me all the emails from my illinois as well as the email from my gmails. I don't have to do it by myself. It is automatically done. If you send email to my Illinois account, it is automatically go to my gmail . I think there is something to do with the setting. I did it in freshman year since It has been that way

K006: Yea, I did that in freshman year too. Every time I have to reply to something professors do not really look if it is not Illinois. So I have to go into my Illinois account

J006: Ok, (Reading email) ...But it does not necessarily have to be integrated into design as it is in etube.. Does as it implied fever uncomplicated...that was the main reason I featured ... (not clear, murmuring)... depiction of one handed manual insertion followed by the instruction of stylet o

digits. But it is not possible..., when we were looking at the design it was not great right? but it could be done with one hand but so small

K007: I think that is something we can work on in terms of ergonomics

J007: What is this one?

K008: He is basically trying to say that you know there used to be a company that made that valve inside like one way valve, but they got shut down. So yeah the company did not survive. So she is not sure if they are still being manufactured. Whether like it is easy to manufacture

J008: Right. So we should not be looking into that. We can look into the market to see if it is still available or not

K009: I think I have seen duckbill valves. Because like I searched just in general. They are kind of like pretty everywhere. They do not have the same ... but that is not really necessarily. More flexible if you want to keep that way

J009: What does it exactly do? Just like passage kind of a thing?

K010: Yes. This one is like really good diagram. There is an outer passage, and the interior is made up of soft rubber. So when like air pushes in from the start, and because of this angle it pushes out, em but like external pressure nothing happens because it pushes the two sides together

J010: We are gonna be the using one which allows the air pressure

K011: Yea, this is like one thing

J011: Both are one?

K012: Yes. So this valve when air goes this way, it opens like that

J012: Oh understood. That does it by itself? Did it do the air pressure?

K013: So we're going to just like put this, I guess if he means like the cordian design was no longer being sold, then we kind of just like

J013: Yes, it does not need to be cordian

K014: It just looks like it all attached to tubes. So I think we can just like attach it to tube. But for the first CAD model we should just make exactly like what it looks. Today I would be making like em..., Oh today do you want to decide dimensions and break it into the categories? Do you have any specific part of it you would like work on?

J014: Emmm, what do we need to do part from it. See characteristic and stuff we can do it as a group. I will do the sketches

K015: Oh yeah, for the 3D model we kind of like one person makes the stylet, another person makes the duckbill

J015: Ok, I am OK with whatever part. I'm not specific

K016: I can do the duckbill. I feel like if we create like new basic dimensions and then we can send them to Kate and Matt and we can all start CAD models. We probably have to meet like once in the weekend just to come up with iterations for like different categories

J016: Yea, definitely. We are not doing different kind of design for the first time right? We are just making very general one for the first time, right? We can have slides towards the end where it says.., We will probably make some iterations probably we can have it like you know towards the end and say oh we are working in one sketches or iterations, trying to make product more ergonomic or usable

K017: Should we do it on the word doc or do you mind taking a note?

J017: Either way. Since my book is here I can take notes

K018: Let's n bstart listing bunch of things we want to achieve and then that we can characterize them all

J018: Device that can be employed by... (murmur) (taking note)

K019: It is like immediate reusable

J019: (Taking notes) immediately reusable. So like emergency kind of stuff?

K020: So in and outside of hospital settings

J020: (Taking notes) So in and outside of hospital settings

K021:It is simple, so it allows people who have low experience can use it as well. It is safe. So even if it is incorrect diagnosis, it will not harm the subject that it is used on. One way valve

J021: ( Taking note) So probably for one handed use

K022: Yeah, probably. Minimum storage space, compact, economical

J022: (Taking note)...Can be fixed to chest? Ok

K023: Inner stylet is protected. Like some sort of external shell so it does not kink. Yeah, it connects to like sewage

J023: ((Taking note) Yeah, it connects to a sewage) It compresses a side. Device also compresses a side on the right inside. Starting fifty-fourth line or fifth line. Do we need that for characteristics?

K024: I guess so, because it allows for more portals and things go through. I think it is trying to say like simplified assembly where everything is contained in one small object. This just talks about embodiments. I think those are the objectives

J024: Yeah, we have a good list of characteristics here

K025: So I think we can like group them

J025: This could be like new while designing for the iterating, right? So what we can have in the presentation is that we can have one slide for what is our device what is it used for, and then the second can the what are the main characteristics we should keep in mind. So these will be the points. Then our three CAD model three basic generic one. And then either if I will be able to do the sketches and some of the iterations and say we are working on it and we can have like future aspect slides where we can say what our future targets are

K026: I think this could be better to pick and choose couple of these characteristics that we are going to alter. Because a lot of them are in this original design

J026: So the things that we are going to keep in mind, characteristics we're going to work are based on designing it

K027: So I think we need to think about one way valve, for sure

J027: Yes, and one handedness and ergonomics

K028: And then we need to keep it very compact. One way valve because like the exact model might no longer be existed. Safe as well, we have to make sure that nothing is sharp ended when we make these alterations. Mmm, we can pretty easily keep the inner styleted. We can keep that protected. He said he wants to pull out the hub or the stylet hub with 2 digits

J028: Is it 2 digits?

K029: Yeah, two fingers

## A.2 Nose Retractor Project

*Meeting duration:* 22 min 50 sec

*Team members:* Sara, Rose, Mark, and John

S001: We can ask about general procedure from the physician

J001: Do we have a photo for this?

S002: I can share it with you

J002: You can send it to my Illinois email

S003: Sure, let me just get there. So you just put your email. Ok what should we ask?

M001: Size of each component?

J003: What is the cost? They need to suck out of blood from nose right? How do we do that? Is there an air pump?

S004: It is just like a suction machine. So it is kind of like vacuum.

M002: So it is like a needle, right?

J004: Maybe it is like a conductor tool

M003: Yeah, it is like holder. So we can just like hold a tube on it

J005: I thought there was an air tube. That goes on to the second machine

S005: It is like a tube that goes to the machine. It collects all and dump it out

J006: Also what is it made up of?

S006: Yeah, especially with the cauterizer the size of that

J007: Also there needs to be light, right? Are these LED lights?

S007: Hommage light maybe

J008: Yeah, what component of light is it? Is it running on battery or electricity?

S008: I am going to right down antiseptic. They need antiseptic region. Also when we watched that video there was like material that they have to put on, I guess we can see that in the general procedure. So like when I cauterize it all, like swapped on some dunk

J009: Essentially what we're doing is we are going to combine all of them into one. There is already a base for them

S009: Adaptability to different patients. So like children to adults. That is like unnecessary

J010: I assume they do not consider manufacturing costs. Do we consider that or no?

S010: Are we considering about the manufacturing size?

J011: No, do they consider about manufacturing size?

S011: Doctors do not care about manufacturing size

J012: Are we doing injection modeling? Or are we doing cutting metal?

S012: But they are not going to know anything about that. I am just telling you right now, but we can think about that

M004: Do we consider it is going to be one time device or like to be used em...

S013: One use or repeated use, yea sure

M005: Is there going to be hygiene?

S014: Hopefully it would be repeated use and we clean it

J013: But one time use is kind of waste

S015: We can ask them we have a lot of ideas with camera. So if camera would help, it would be better for them to have a screen to look at it. So if they like that idea. I guess, maneuverability. Like what they feel like they need to maneuver the suction or can it just stick in there

J014: Are you talking about how to deal with the nose em...

S016: Exactly, that is what we are going to ask (laugh) I have all our ideas. You want to refresh your memory on what we were thinking. Easy to move from nose. Because remember like yours like the expandable idea. See if that would be OK. If you want, we can all separate them all out. Because they are all bunch of stuff

M006: Are these buttons? What do they do?

S017: Maneuver, the cauterizer tip which is electronic or like mechanical

J015: Electronic means it will increase the weight

M007: I think we should keep them simple

S018: No, I think like these are all from brainstorming without criticizing. What do you think? I like magnifying idea

M008: How much space do they need? They just need like gate way open or like open all the way through?

S019: Right, like deep into the nose

J016: Do we have like actual photo that we can look at? Something that has been already designed

S020: With google. I would say like retractors, but typically a lot of time they are just like one of those magnifying glasses dentist use for your teeth

J017: This is what we will propose right?

S021: Actually you see that is little bulky

M009: Yeah, it takes a lot of space

S022: Do you like really need them?

M010: That is a good question. I do not know. Are we trying to combine all four into one?

J018: Well, suction is maybe. Maybe we should know their expectations, maybe two is acceptable, three is great. Because like we are making this over complicated

M011: Let's just make all these tools like maneuverable with two hands, I think

J019: I think we can combine these two into one. Because I do not think that these four can be combined into one

S023: I think that would be too hard. But I think three definitely, the light suction

J020: Yeah, I mean two is baseline here. I mean if can combine two into one, that is already improvement. Three would be really great. Why cannot we look into individual pieces to see which three are more reasonable to be combined?

S024: Sorry, I am just responding to her. I was just like we're going home in 20 min

J021: Do you know the location?

S025: Yes, I am trying to get the location

J022: Can we share it through google drive?

S026: Ok, What else? We can ask him what hurts the most?

M012: Yeah, what they do not like about

J023: Ask what they like the most and what are their favorites?

S027: Yeah, because why it has to be tomorrow. It is because he is going to conference next week? And we would to get back to him until November, which is after like all the exams done. That's why like I was pushing



J024: It would be nice if we get something from him that we can actually see. Because I have no idea what we would see

S028: That is why I am kind of like it to be in person. She is just like conference call. I think the lutina object would be better

J025: I have never encountered that thing in my life so, I have no experience. I think this should be good enough

S029: Yeah, I am just trying to think if there any other information there need to be

J026: So our deliverables. I think they are expecting us to make actual products, right? What should be accomplished by then?

S030: I am assuming first look at this information then I think we could meet this weekend and make presentation and maybe come up with... like what it is said here like narrow down with three ideas. If we have time, make a prototype out of cardboard, not even 3D printing style, just like cardboard and that would be good

J027: So what are the final deliverables?

S031: So, final deliverables of the entire project? I do not know. We are going to like 3D print

J028: Because I know exactly 3D printing material... em Is it nylon? It can directly contact with cup or food. Make it direct from the nylon, so it should expose to the product

S032: Yeah, it would not have electronic capabilities. But we can make it hollow and put wires in this

J029: Yeah, that's what I was thinking. You can have an attachment, embodiment from nylon. And then you can attach other additional items on it. We can certainly make skeletons and print the skeletons. And then LED light for example, and then buy batteries. The batteries for pocket lights ... em, no problem

S033: So what are you guys up to this weekend? (Reading Email) So on the 7<sup>th</sup>, The North Clinic, 7<sup>th</sup> floor conference room D, I will invite you once I figure out how. Well, let me just forward you guys this email. How about that? I will send you it by hot email. Because I do not have saved it on my contacts

J030: That's fine. All my University Illinois emails are forwarded to my hot email

S034: Napoleon Night is the guy. That is like a great name

J031: Wait, is his last name is Night?

M013: And his first name is Napoly (Laugh)

J032: When you said night, I was thinking about club thing (laugh)

S035: No, I was beams that serious. So good. You guys get it? Cuz I always get nervous when this invite thing. Cuz I really do not know what I learn. (browsing online) No, people do not know what the nose retractor is. Amazon does not know what the nose retractor is. Can you see like any information?

M014: I do not think I can. Because I only see the...

J033: Yeah, there is no...emm like information

S036: Going to the main lobby... ok, let me just forward this to you. So you go to the main lobby, walk 55 yards, turn rights, I guess then take a left, go down the small ramp, take the elevators down the floor, when you get out from the elevator (laugh) turn left my desk is on the right and she will show us the conference room. We will not be driving so we will not need parking lot

M015: You see the puzzle to see the Napoleon Night (laugh)

S037: (laugh) Yea, I finish class at 3:30. So you still like go with me

J034: What is the exact location?

S038: Carol. So you take 22 or silver to get there. So everyone wants to go meet up with me to go together

R001: Are we going to take a bus 22?

M016: I think 22 stops at...em

S039: Yeah, it takes you like kind of around the corner and you get off and walk rest of the way. It is like that train intersection

M017: On the University avenue?

J035: (looking at map) oh that place. Yea, I have been there many times during my second year. There was another hospital very far away

M018: Yes. I went there this morning. Yes, it is a Sports Medicine Center

J036: So, are we done here?

S040: Em... I think so

M019: So I will be driving there maybe tomorrow. I can give you guys a ride

J037: I am thinking to drive too. But probably I have to drop my girlfriend off. So basically I have to pick her up and drop here off. Maybe I will be late

M020: Oh, my class ends at 3:50

S041: Could we like meet with you at your class where you have your car at your class? And we could go. It is not like it takes 10 minutes to get there. It takes maybe like 5 min

M021: We don't have to be exactly on time

S042: I mean it is disrespectful

J038: So we are in the conference room

M022: I mean traveling there is like 5 min

J038: We will bring notebook like logbook that how does professional engineer does

S043: I mean like how much of the class you are willing to skip

M023: Like 2/3 of the class I will skip

J039: Which class are you skipping?

M024: Like 270

J040: Oh, 270 you can ignore it. Man... he can be mean

M025: Yeah, he is really mean. If you are late. He can ask you to dance in front of like a few hundred people

S044: Oh woow. So is it in the back you just do?

J041: Yep, just like two hundred people watching you

M026: He is like dance, dance, swing

J042: Yes, if you have been to his lecture. He is always on something. He is very passionate. He unstoppably talk and really fast-paced. He is very passionate. I would say he is over passionate

S045: (laugh) calm down. He needs calm down

M027: Yea, he needs calm down sometimes

J043: He is very good. His grade sometimes based on his emotions. Because it involves projects and presentations. If he is happy he can give a good grade, if he is very sad you are screwed

M028: So the whole point of the class is to make him laugh

S046: Make him laugh. Bring some chocolate and food

J044: Yeah, I take senior design. Tomorrow we have presentations

M029: Are you taking senior design with Mark?

J045: No he will be there tomorrow. My adviser is Elvis

M030: (laugh) Yeah, all the legend of our department

J046: Yeah, he is one of the legendary of our department

M031: So why don't we just meet by the door of this building? Because the lecture room is in this building. Because I will park at the parking lot

J047: So if you are driving I don't need to drive

S047: Sure, ok 3:30, done with meeting

### **A.3 Eating Utensil Project**

*Meeting duration: 25 min 66 sec*

*Team members: Matt and Julie*

Julie 001: This is team four with the utensil project. Meeting number one. So,

Matt 001: So, do we want to,

J 002: I'm setting up

M 002: What do we... want to accomplish in our conference call tomorrow? Is it today? No it's tomorrow.

J 003: Don't do that to me. It's 10:24, 10/22/15 is the conference call.

M 003: Four pm.

J 004: Through the gardner's right?

M 004: Should we introduce ourselves?

J 005: She has...thanks, oh wait. Gardner...we'll have to fill this out. Let's take a look at this. So tomorrow at least we can ask her.

M 005: What is that?

J 006: It's, uh, did you guys not get it? Did she just send it me? Oh I guess so. We have to fill out these forms. It's a waiver release. I'm assuming we're going to scan it back to her.

M 006: What is it for?

J 007: For working with the patients.

M 007: Oh, ok.

Chris 001: Yeah.

J 008: Verification on how she wants to receive the...

M 008: Is it not on?

Joanna 001: Oh I just put it on so that the noise cancels

M 009: So nothing was recorded?

Joanna 002: No, I mean it is being recorded-

J 009: It's going to cut the background noise.

M 010: Oh, ok.

J 010: I (?) to receive the...Do we want to yank out? Good we got those.

M 011: Well, first obviously, she's going to give us specific details on our clients or whatever, of their disabilities.

J 011: Are the clients already specified? That's what I'm curious about. I'm sure they are, right?

M 012: So we're going to need to actually travel up there and do this repeatedly?

J 012: This is a question that we can ask her.

M 013: Yeah, we should ask her how can we, how can we maximize or, or do this efficiently? Um, like go up there once, instead of like many, many times...minimize travel time.

J 013: So...

C 002: Or if she has...

M 014: Or travel time, just travel time.

C 003: Or if she has photos or even video of

M 015: Yeah...

C 004: of them that would probably help, that we wouldn't have to go up there. But, I think we would want to observe them first to see what their disability is, what their needs are. And then, at least once to go test our prototype.

M 016: Yeah...but yeah I guess...

J 014: I'm going to also pull up a post-it note. What else? So we got pretty in depth at one point. I think we need to use this as background, client, and then like, end-goal. Where does she see

this going? Like, what is her end result? Does she want, we want to present her with a physical prototype, but is it going to be something that we may hand off to another project?

M 017: Is this...and what is the most...does she want a spoon, a knife, and a fork

C 005: Oh yeah.

M 018: Does she want a whole set? I'm confused on the scope of...

J 015: Scope of project. That's exactly right. Scope of project, which utensil? Ok, so some of the things that we listed off were the hand size, left versus right, muscle strength, hand dexterity, um dishwasher safe

M 018: Does the hand matter? The, which hand they use?

J 016: It's going to be client specific, so...

M 019: Oh, I don't know if we make something like...

J 017: Client specific.

C 006: Yeah.

M 020: That's a question for Sal Wexler, whoever's the technical people we're talking to.

J 018: Hand capabilities. Ok. So we have, how do they currently eat? So I think this is, like, client specifics. How do they currently...and this is not something that we have to list off. It's good to reference during a phone call.

M 021: What are the solutions, like what, what are they doing now to help alleviate the issues?

C 007: Or what is the problem that they're specifically experiencing that they can't deal with?

J 019: They spell..

M 022: B-r-a-b-r-a

J 020: What did you say?

M 023: What's the problem? What's the specific problem that inhibits their eating abilities?

J 021: Um, so, another thing prototype...prototype appointments. So this will be something like dishwasher safe, um, reusable versus one-time use, you know? Some of these questions. Um we have...um...

C 008: Or like if they've had projects for them before?

M 024: Yeah, has this been an ongoing project? Or is this something where're they're like 'Yeah, we want you to receive Illinois State (? 6:51). Revolutionary?

J 022: Revolutionary, um, where'd they get their product from?

M 025: How do they eat now?

C 009: Yeah

M 025: Oh, you already said that already.

J 023: Where is their current utensil from? So I think we also talked about um, like involving mechatronics. So, an electronic component.

C 010: I guess, also like a budget, well I mean, yeah.

J 024: Yeah, very good.

M 026: Yeah, a budget would be crucial.

C 011: I mean, I think we're just doing a prototype, but we should be designing with their budget in mind.

J 025: Yeah um...

M 027: And we should definitely talk about that thing that already exists. I don't know what it's called. Here, let me go ask her.

C 012: For the shaking...

M 028: Yeah, you know what that's called. I don't remember. It has a specific name, but you should definitely bring that up though.

J 026: What is that called? Or what do you know if?

M 029: I'll look it up.

C 013: Yeah, did you put materials?

J 027: What about, I mean we're in...Does she know, do you know of patient, of clients in Champaign that we can use as...

C 014: Test subjects,

J 028: yeah

C 015: Like similar stimulus...

M 030: Here it is. It's called liftware.

J 029: Cool, is that just like a weighted spoon?

M 031: No, it's like, it uses electronics to balance the...

C 016: Oh really? I thought it

J 030: That is so sick.

C 017: I saw this stuff, oh yeah. That's amazing.

J 031: Wow.

M 032: So that's why we need to ask her, liftware. Have you heard of liftware? Liftware is a stabilizing handle/attachment soup spoon. So it's just a thing, and you can stick whatever you want on it.

J 032: You can, is that...

M 033: It's modular. You just stick a spoon, you can stick a fork, whatever.

C 018: That's cool.

J 033: Ok. Diet restrictions, we put under here.

M 034: And it is, how much is it? It's like \$300.

J 034: What do you think is...it's pretty cool.

C 019: Does it have like a gyroscope in it or something?

M 035: I'm assuming it has something like that. Probably some advanced control system can detect how the shakes and then it will, I don't know how the crap works but it will balance itself. J

035: This is like more of like the liquid component, drinking capabilities. I don't know if that's something like we want to know. So what do you think are some, some main-line items? Thank God for bringing that up, we hadn't realized that.

C 020: Um yeah. I think those three are good.

J 036: Who is the client?

C 021: And how many? Maybe if they're simple we could do.

J 037: I'm going to put customizable versus marketable because do they want us to like, for this one specific person and then never use it again? Or I think we'll talk about how she expects us to...

C 022: Like observe.

J 038: I don't know they're all very important questions.

C 023: I'm sure that's good enough, the problem the scope and budget, and I'm sure she'll cover all that stuff.

J 039: The scope of the project.



C 024: And yet how...

J 040: Ok.

C 025: And what access we have to them and how often we could test with them.

J 040: I wonder if there's any other like, you know the word like HIPPA, any HIPPA involved like knowing...

C 026: Isn't that like what the...

J 041: What'd you say? Yeah, let's take a look at that reading.

M 036: Look at this. There are so many different things that have been tried. I mean, and they're not too bad. They're only like 30 bucks, 50 bucks. I mean we might just want to, I don't know maybe we should ask her about it, these other things. I'll send you guys the links. There's like a site, that has all these

C 027: Is that just for any disability? Or is that...

M 037: I don't exactly know, rehabilitation products, yeah it's like for all different sorts of things.

C 028: Yeah, it's cool. Rehab mart.

M 038: I just got an email from Liftware, I'll forward you this. What's your email?

J 042: d-a-g-o-s-t-i-2

M 039: d-a-g-o-s-t-i-2? Dagosti?

J 043: Sure, or however you pronounce that.

M 040: How do you say your last name again?

J 044: Dagostino

M 041: Dagostino at Illinois. And then, what was yours?

C 029: Matthew Bowman 2.

M 041: Cool name.

C 030: Yeah.

M 042: T-t.

C 031: Yeah.

M 043: Matthew b-o-m-a-n

J 045: It's at like gmail

C 032: At gmail.

J 046: 2. Matthewboman2@gmail

M 044: Matthew Boman. Ok.

C 033: I thought in the presentation though, she might have mentioned amputees or disfigurement so that would be very customized.

J 047: Maybe.

C 034: Or common disabilities.

M 045: Woops, oh, I put three t's in your name.

J 048: You're an idiot. What is this called again?

M 046: Lift. Liftware.

J 049: What was that one product that you were just on?

M 047: Rehabmart. There's a lot of things that have been tried it seems.

J 058: This is it. Can I see your hammer? This is a good hammer. What was wrong about this hammer?

C 040: Huh?

J 059: Why did we split it?

C 040: What?

J 060: You should have split the hammer.

C 041: You did? Oh, you dog.

J 061: Be careful.

C 042: If you break my hammer I will...

J 062: I don't think you could shot this in any direction.

C 043: Don't try.

J 063: If it was long enough it could go just straight down there. It's so pretty.

C 044: What are you, bam bam?

M 056: Maybe it'll wake her up.

J 064: Our computer gave out at this point.

M 057: So, where are we at? We should ask them. We have the problem...

C 045: Push the button again.

M 058: Shoot, we didn't save any of that.

J 065: It's a google doc.

M 059: Ok, I'll pick it up from here. Let's go to google drive and make sure everything is ok.

J 066: I want to snapchat it. Give me a second. Ok.

M 060: Send it, don't pretend like it's not there.

C 046: Yeah, this is a normal meeting.

M 061: Sorry, we didn't laugh that hard.

J 067: What do you guys think about our...?

M 062: What is the client, how do they eat? I think that's it. That's all we need to ask. Who are they, how do they eat what are they...? Have they heard of these other things, and then we go from there.

C 047: Yeah I'm sure that will come up. Whatever's relevant.

M 063: Rehabmart.

C 048: And there's another one on here actually.

J 068: Yeah, I think those are well defined.

C 049: USA.

M 064: Woah, this looks really nice. Holy cow. Did you see this?

J 069: Turn the computer.

C 050: More utensils?

J 070: Bestic?

C 051: Is this like a robotic, pick, pick and place? Oh man...Holy...what is it? So she's just controlling it.

J071: Did she?

M 065: Yeah.

C 052: She's just like stopping the direction

J 072: Because she right now, she's not doing anything. It's that placemat. It's that placemat that's beneath the plate.

C 053: Oh, ok the placemat.

J 073: It's the placemat.

C 054: I thought it had a camera in it that was binding her mouth.

M 066: No, I think it said you could control it with anything, like your knees or any part of your body. Mealtime independence.

C 055: How much is that thing?

M 067: Buy now, a thousand, \$4,000.

C 056: Interesting.

J 074: It's just spoons make a lot, yeah, it's just spoons. What's this thing? Go down.

M 068: Maso peako-button. It's probably

J 075: It's the five button control. I don't know what it does though. There it is. What do you think those squares are that they're using them with?

M 069: What squares?

J 076: Like the plate. It looks like chicks, like the chicklets.

C 057: I don't know...

J 077: We just saw the single what's app. We want to see the...

C 058: Oh my gosh, oh my gosh.

J 078: It's funny, you go from single to five button. They are chicklets.

M 070: Sounds good.

C 059: So it's just a joy-stick.

J 079: Yeah, so the middle button would be to pick up.

C 060: That's cool.

J 080: So now it's just locating the outside of the mat.

C 061: No, I think it was just wiping it up like if there was soup so it doesn't drip.

M 071: That had to be insane to make. It must be so complicated.

J 081: Oh, dude you might be right.

M 072: Wait, what?

C 062: It just automatically wipes the bottom of any spoon to stop any drips. That's what it looks like.

J 082: It literally scrapes the bottom of the spoon. Do you know what we're trying to say?

M 073: No.

J 083: When you eat, and you go like this. And you like, you sort of like,

C 063: And if it's soup...

J 084: You scrape the spoon and then you drink it. That's what it's doing.

It's like you're wiping off the broth on the bottom. You go into the bowl, but then you do that. I going to stop doing it.

M 074: We should ask her, maybe this.

C 064: If you want to spend \$4,000.

M 075: Are we supposed to actually give them. Lake said we're just supposed to print.

C 065: Yeah, we're just supposed to print.

M 076: We're not giving them like, Ok you can use this?

C 066: I mean if it's simple, we could I'm sure. But I think the goal is just the prototype.

M 077: Can they eat off of these?

J 085: It will only be, it will be, yeah 3D.

C 067: I could make some.

J 086: The only material we work with is ABS plastic?

C 068: Is PLA, I thought we could also...

J 087: Plastic, but it has to be plastic. Like we can't print something that's of flexible material.

M 078: So you mean, for like injection molding or something. Or are we giving the design for someone else to print the flexible material?

C 068: Prototype

J 088: For like injection molding or something.

C 069: Yeah so we need recommendations probably. But I love prototyping stuff with real other material. So I could do a simpler materials.

M 079: Yeah,

C 070: If they want.

J 089: What's this one about? This is so good.

M 080: Oh yeah. I heard about that. I saw that on the wall. So we're working on the GEO thing tomorrow?

J 090: Ten to twelve. That works for you? How'd your quiz go?

M 081: Wait, what quiz? The 371?

J 091: Whatever quiz you had yesterday.

M 082: Oh, I think really well.

J 092: I heard tons of...

M 082: OK, anything else? So meet here tomorrow at 4.

J 093: Do you want me to show you where it is? Let's go upstairs real quickly.

## APPENDIX B: REFLECTION JOURNAL WRITING GUIDELINE

*“We don’t learn from experience...we learn from reflecting on experience.”*

John Dewey

**Assignment:** Write about your experiences, observations, learning, and challenges faced during project activities and team interactions. Examine and analyze your experience objectively and thoughtfully by analyzing and interpreting your experience.

**Why is reflection useful?** Most of us can learn more by reflecting and writing about what we are learning, and reflection that involves description, analysis, and interpretation will help you construct meaning from your experiences. It also enhances your learning by enabling you to (1) keep a record of your progress on the project, (2) actively integrate and apply what you’re learning, (3) improve your reflective and analytical writing skills, and (4) develop new insights and perspectives. Submit journal entries to Compass by 11:59 p.m. on the following due dates: 10/30, 11/20, and 12/18. Journal entries must be a minimum of one-page each-300 words. The average grade will count 5 percent towards the final grade.

**Prompts that may help you examine your experience,**

- What important technical and logistical challenges are you or your team facing?
- How do you think your team should address cooperation, communication, leadership, decision-making, and conflict?
- What have you learned by collaborating with others?
- What have you learned about yourself and/or your role on the team?
- How have you adapted, set goals, and taken initiative during the project?
- In what ways has diversity been a challenge and an asset to your work?
- In what ways have you developed your teamwork skills (e.g., collaboration, conflict resolution, leadership, maintenance of group dynamics, project management, etc.)?
- How have you changed as a result of this experience?

## APPENDIX C: SURVEY QUESTIONNAIRE

1. What department are you in?
  - A. Industrial Design-The School of Art and Design
  - B. Department of Mechanical Science and Engineering
  - C. Department of Industrial and Enterprise Systems Engineering
  - D. Department of Bioengineering
2. Rate your 3D CAD proficiency prior to taking GE 402?
  - A. No experience
  - B. Minimally proficient
  - C. Moderately proficient
  - D. Proficient
  - E. Very proficient
3. How many team design projects have you participated prior to taking this class?
  - A. None
  - B. 1
  - C. 2
  - D. 3
  - E. 4 or more
4. Our team was able to geometry needed for our designs using Fusion 360 software.
  - A. Strongly disagree
  - B. Disagree
  - C. Neutral
  - D. Agree
  - E. Strongly agree
5. Rate the usefulness of Fusion 360 as a communication and collaboration tool.
  - A. Not useful
  - B. Somewhat useful
  - C. Neutral
  - D. Useful



- E. Extremely useful
6. Rate the usefulness of 3d scanning in improving design outcomes.
- A. Not useful
  - B. Somewhat useful
  - C. Neutral
  - D. Useful
  - E. Extremely useful
7. Rate the usefulness of 3D printing in improving design outcomes.
- A. Not useful
  - B. Somewhat useful
  - C. Neutral
  - D. Useful
  - E. Extremely useful
8. Describe your experience using 3D printing for your design project. Do you think 3D printing aided your team's ability creatively develop your design ideas? If so, why?
9. Describe your experience using 3D scanning for your design project. Do you think 3D scanning aided your team's ability to creatively develop your design ideas? If so, why?
10. What technical challenges did you face in using digital prototyping tools (i.e. Fusion 360, 3D printer, 3D scanner etc.) in your design project?
11. Describe your experience working with students from different disciplines. What were the most challenging aspects of collaborating with students from different disciplines?

## APPENDIX D: DESIGN PROJECT BRIEF

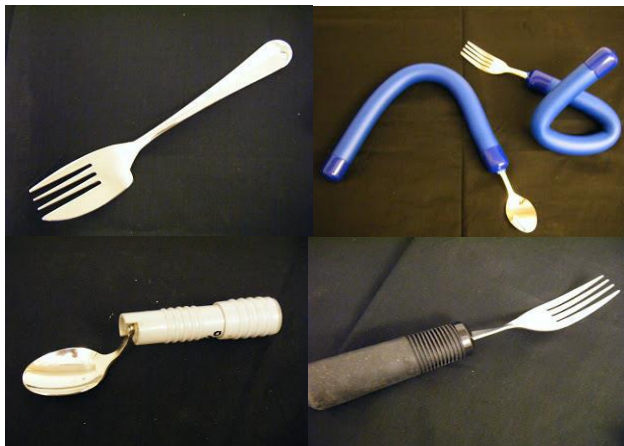
**Slit Lamp:** Improving the aesthetic and efficiency of a slip lamp, as shown in Figure D.1.

**Issues:** Obese, short stature, children have difficulty fitting in the lamp. Variability in forehead protrusion leads to angles in viewing.



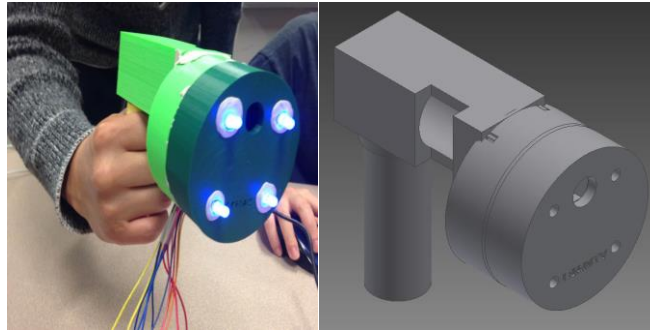
***Figure D.1 Existing designs of slit lamp***

**Eating Utensils:** Developing custom eating utensils for dexterity limitations and allowing people with mental/ physical disability to eat independently. Example customized utensils are shown in Figure D.2.



***Figure D.2 Example eating utensil designs***

**Handheld USB Microscope:** Building a handheld, portable, USB powered microscope that have multispectral imaging capability. The device is used in developing regions where traditional arm scope is not accessible or too expensive. The previous design solution is given in Figure D.3.



**Figure D.3** The previous design of handheld USB microscope

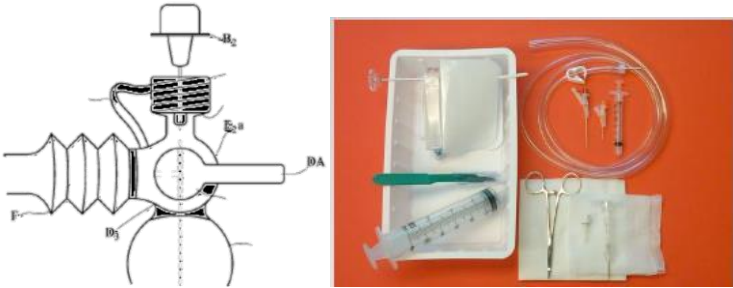
**Nose Retractor:** Eliminating the need of involvement of multiple people during operation.

**Issues:** for a common nosebleed, many tools need to be inserted into a very small space with two hands. Figure D.4 illustrates the existing design.



**Figure D.4** The previous design of nose retractor

**Neonatal Pneumothorax Device:** Improving the functionality and the ease of use and reducing the potential harm on the subject. The proposed design is shown in Figure D.5.



**Figure D.5** The proposed conceptual design of neonatal pneumothorax device

## APPENDIX E: DESIGN PROJECT POSTERS

# NOSE RETRACTOR

GE402 Chen Zhong, Margaret Barbone, Jin Yan, Weyi Song



### PROBLEMS



When a patient comes to the hospital in an unconscious or sedated state, the physician has to retract the nose when using endotracheal tubes. This is required so that the tube can be inserted into the trachea without the patient's tongue blocking the airway. However, this is a difficult task to perform, especially in emergency situations. The tongue and the epiglottis are soft, fleshy tissues. Therefore, a nose retractor device is needed to hold the tongue and the epiglottis away from the airway. Our mission is to design a hands-free retractor device that is easy to use and effective, thus alleviating the need for an assistant and allowing the physician more visibility.

### PRODUCT DEVELOPING



**NYLON 680**  
FDA approved  
Fast to get to a nice balance of strength and flexibility

**OPTICAL FIBER**  
Lightweight  
Low cost  
Great performance in conducting light  
Adjustability

### SOLUTION



Our device consists of two predominant components. A retractor with an integrated fiber optic which directs a laser light. The retractor is fabricated from a FDA approved polymer of polypropylene. The most important is as much as possible. The fiber optic wire is incorporated as the retractor to allow for illumination of the nasal cavity. The integrated components of a jack for the fiber optic wire to be plugged in. Then an LED is up against the fiber optic wire, serving as the light source. Finally, the battery and charging components are housed into the back of the device. Since the retractor and fiber optic wire are removable, they can be disposed of or reused, and if the retractor is reusable, making our solution device to be used for multiple patients or components.

Figure E.1 Nose retractor project poster, team 2

# Custom Utensil Grip

### Problem Statement

Individuals suffering from motor impairment require assistive devices to lead a more independent life. Eating is an important aspect to developing physically and socially.



### Objectives

Design a utensil handle to improve user's control and manipulation to allow a more independent eating and encourage proper eating habits.

### Features

- Flat base
- Bosses for mating
- Magnetic closure
- Textured grip
- Dishwasher safe
- Weighted handle

### Design process











Figure E.2 Eating utensils project poster, team 3



# SPECTRAL USB MICROSCOPE

A streamlined, simple, & affordable solution for spectral imaging

Spectral microscopy is prevalent in both research and clinical diagnostic settings. The Spectral USB Microscope is a small, portable alternative to traditional scopes. Each filter is individually locked into position for imaging by a simple pull-and-slide motion.

The Spectral USB Microscope includes a stand to provide extra stability during imaging, but can also be used as a handheld device as well. The design overcomes the current limitations of the spectral microscopy in a sleek yet functional form.

## KEY FEATURES

### USB

Connects microscope to computer imaging software

### BATTERY & SWITCH

Concealed battery pack and switch powers external LED ring

### USB MICROSCOPE MAGNIFICATION CONTROL

Access window for existing USB microscope magnification control

### MAGNETIC SLIDING JOINT

Allows for easy transition between handheld and table top use

### CONTROL TABS FOR COLORED FILTERS

Simple slide and lock mechanism correctly positions specific filter for use

### EXTERNAL LED RING

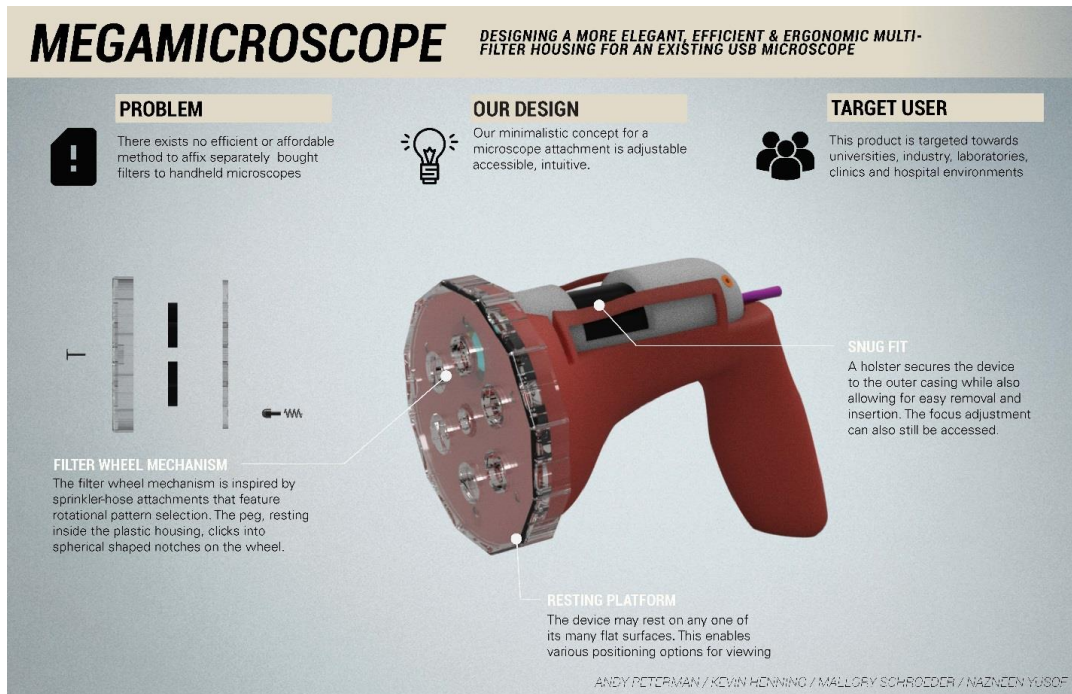
Illuminates sample

### 360 ROTATING CLIP STAND

Provides stable yet flexible platform for accurate imaging

Caro Fahy / Dylan Babb / Erik Salinas / Rajeev Rastogi

Figure E.3 Multispectral USB microscope, team 4



# MEGAMICROSCOPE

DESIGNING A MORE ELEGANT, EFFICIENT & ERGONOMIC MULTI-FILTER HOUSING FOR AN EXISTING USB MICROSCOPE

## PROBLEM



There exists no efficient or affordable method to affix separately bought filters to handheld microscopes

## OUR DESIGN



Our minimalistic concept for a microscope attachment is adjustable, accessible, intuitive.

## TARGET USER

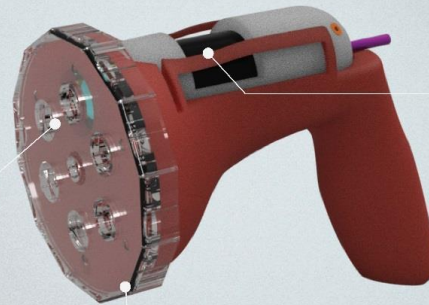


This product is targeted towards universities, industry, laboratories, clinics and hospital environments



### FILTER WHEEL MECHANISM

The filter wheel mechanism is inspired by sprinkler-hose attachments that feature rotational pattern selection. The peg, resting inside the plastic housing, clicks into spherical shaped notches on the wheel.



### SNUG FIT

A holster secures the device to the outer casing while also allowing for easy removal and insertion. The focus adjustment can also still be accessed.

### RESTING PLATFORM

The device may rest on any one of its many flat surfaces. This enables various positioning options for viewing

ANDY PETERMAN / KEVIN HENNING / MALLORY SCHROEDER / NAZNEEN YUSOF

Figure E.4 Multispectral USB microscope, team 5



**Table F.2 Grade distribution**

Pre-assignments (5)	5%
Fusion/other assignments (5)	15%
Digital shape sampling and processing projects (2) (in pairs)	10%
Paper (on <i>The Art of Product Design</i> )	5%
Online exam	10%
Self-reflection journal (design project collaboration)	5%
Product design project (team)	50%

**Course Goals:**

- Expand upon existing CAD skills using parametric and direct solid modeling.
- Use T-Splines to develop sculpted, watertight geometry.
- Understand the various capabilities and weaknesses of parametric solid, direct solid, NURBS, and T-Splines modeling.
- Gain hands-on experience using 3D printing and 3D scanning.
- Gain experience using digital prototyping tools used for visualization and simulation.
- Promote multidisciplinary collaboration between engineering and industrial design.
- Use cloud-based 3D CAD for collaboration.



## APPENDIX G: GE 402 COURSE SYLLABUS, FALL 2016

**Instructors:** Jim Leake                      309 Trans                      244-0401                      jmleake@illinois.edu  
David Weightman                      139C A&D                      333-0855                      diw@illinois.edu

**Credit:**                      3 or 4 credit hours

**Meeting Times:**   Monday, Wednesday 4:00 – 5:30PM

**Course Description:** In the first half of the course students are introduced to a variety of design tools, including cloud-based, freeform CAD for modeling and design collaboration, 3D printing, 3D scanning and scan data processing, simulation for design engineers, and rendering and animation. Working in teams, students then use these digital prototyping tools to design and prototype a medical product or device.

**Text:** No text required; several journal articles on topics relevant to the course will be assigned during the course of the semester

**Table G.1 Digital prototyping tools**

Software	Hardware
Autodesk Fusion 360	Dimension SST 1200 3D printer
Geomagic Design X	Autodesk Ember DLP SLA 3D printer
Autodesk ReMake	Creaform handheld laser scanner
SketchBook Pro	DAVID SLS-2 structured light scanner
KeyShot, Showcase	Wacom Cintiq 21ux interactive pen display
ANSYS Workbench 15	iPad Airs (15)
Alias & Rhinoceros	HP T1100ps 44" DesignJet Printer
Inventor, SolidWorks, Pro/E	Collaboration tables (4)

**Table G.2 Grade distribution**

Pre-assignments (Fusion/other)	10%
Assignments (Fusion/other)	20%
Written summary of assigned readings (10)	10%
Online exam	10%
Product design project (team)	50%

**Course Goals:**

1. Expand upon existing CAD skills using parametric and direct solid modeling.
2. Use T-Splines to develop sculpted, watertight geometry.
3. Understand the various capabilities and weaknesses of parametric solid, direct solid, NURBS, and T-Splines modeling.
4. Gain hands-on experience using 3D printing and 3D scanning.
5. Gain experience using digital prototyping tools used for visualization and simulation.
6. Promote multidisciplinary collaboration between engineering and industrial design.
7. Use cloud-based 3D CAD for collaboration.

## **APPENDIX H: READING LIST FOR COMPUTER-AIDED PRODUCT REALIZATION COURSE, FALL 2016**

- Engineering Design Thinking, Teaching, and Learning; Dym, Agogino, Liefer, 2005
- The Reflective Practice of Design Teams; Valkenberg, Dorst, 1998
- Designerly Ways of Knowing: Design Discipline versus Design Science; Cross, 2001
- CAD and Creativity: Does the Computer Really Help; Lawson, 2002
- A study of prototypes, design activity, and design outcome; Yang, 2005
- MCAD: Key Historical Development; Riesenfeld (Utah), Lyche, 2009
- T-splines and T-NURCC's; Sederberg, Brigham Young, 2003
- Making sense of 3-D printing: Creating a map of additive manufacturing product and services; Youngstown State, 2014
- The status, challenges, and future of additive manufacturing in engineering; Purdue, 2015
- Cloud-based design and manufacturing: A new paradigm in digital manufacturing and design innovation; GTech, 2015

## APPENDIX I: DESIGN QUALITY RUBRIC

*Table I.1 Course rubric, fall 2016*

<b>Basic</b>	<b>Requirements</b>	The design meets the technical criteria and the customer requirements	
	<b>Feasibility</b>	The design is feasible in its application and fabrication/assembly	
<b>Advanced</b>	<b>Creativity</b>	The design incorporates original and novel ideas, non-intuitive approaches or innovative solutions	
		The design is simple, avoiding any unnecessary sophistication and complexity, and hence is:	
	<b>Simplicity</b>	Practical	Usable
		Reliable	Ergonomic
		Serviceable	Safe
	<b>Overall</b>	Overall impression of the design	

NOTE: This rubric is adopted from *Two Instruments for Assessing Design Outcomes of Capstone Projects*, Sobek, D.K., Jain, V.K., Proceedings from 2004 ASEE Annual Conference, 2004