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DESIGN MASTERY: UNDERSTANDING HIGH ACHIEVING ENGINEERING STUDENTS' DESIGN PROCESSES THROUGH EYE TRACKING

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Reviewed and approved* by the following:

Dr. Catherine Berdanier
Assistant Professor of Mechanical Engineering
Director of Online Programs
Thesis Supervisor

Dr. Jacqueline O'Connor
Associate Professor of Mechanical Engineering
Honors Adviser

* Electronic approvals are on file.

ABSTRACT

Engineering design is an essential aspect of the undergraduate engineering curriculum. To continually improve the ways that we understand and teach the design process, researchers often study the patterns of expert designers. In this context, I studied the design self-efficacy and design patterns of high achieving senior level mechanical engineering students. I developed an authentic design challenge specifically tailored to undergraduate engineering students and collected data using eye tracking methods. A new method of data visualization was developed specifically for this eye tracking dataset that focused on visualizing CAD-based 3D modeling processes. My visualization tool merges an area of interest timeline with cognitive workload to represent design process patterns. After analyzing data on N=10 participants, I noticed trends that indicated that high achieving students often employ a truncated version of the traditional design process. While a few participants generated productive designs, based on my twelve parameters, most of the participants failed to demonstrate mastery of the design process. As such, I concluded that current teaching methods may not be adequate in educating students to generate meaningful solutions in authentic design challenges.

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Chapter 1

Introduction

The design process is the foundation of innovation and technological advancement. Across disciplines, design thinking is essential in proposing and implementing new ideas. Design is especially important in engineering and professional organizations often include design in the very definition of engineering — describing it as the marriage of scientific reasoning and creative design thinking [1].

The design process has been a topic of literature for many decades. Engineering researchers and cognitive psychologists alike have proposed various design models that focus on the skills and knowledge that practitioners must have to design effectively [2]. While understanding these skills is important, it is also important to understand the connection between what designers do and why they do it. This connection, or the way designers combine their skills with their design approach, is often referred to as a “design lens”. This lens is the synthesis of skills, knowledge, and design understanding. To develop a foundational theory of design learning, this lens must be fully understood. Essentially, to best educate the next generation of engineering graduates and improve upon current teaching practices, a complete theory of design learning and design education is necessary [1].

Accreditation policies for current undergraduate engineering programs identify the skill of designing as a key outcome. Most programs emphasize design in the first and last years of the program [3]. While some students show improvement over this period, it is unclear how or why they improve. Without a concrete set of tools to measure the design learning progress, it is impossible to quantify if or when students are meeting the learning targets. When students exit their engineering programs, they know they possess some design skills. That said, they lack an understanding of their metacognitive, design framework. Without this understanding, it is challenging for engineers to understand the design process from different perspectives and design within a multidisciplinary team. As technology becomes more complicated (requiring cross-disciplinary teams) this gap in engineering student learning adds barriers to the design process and ultimately limits innovation [2].

To bridge the gap between where students are in the beginning of their education and where they need to be to design as professionals, researchers often conduct design challenges that compare experts and students. Notably, Atman et al. [4] tasked engineers and students to design a community playground. Data was collected by observation and talk-through methods during the design process. After, they used a coding method to determine the sequence and duration of design steps of each participant. The goal of this research was to show differences between student and expert practitioners and reveal areas of the design process where students performed poorly or neglected completely.

While qualitative methods are able to discern overarching trends during the design process, they can increase ambiguity during interpretation and analysis. Howard and Culley REF reviewed the design thinking research of engineers and psychologists over the last six decades to synthesize design thinking methodologies and propose a coherent, comprehensive model. They also attempted to understand how a creative design process can be integrated into a traditional, linear engineering design process. In their conclusion, Howard and Culley reveal the limitations of previous design study methods and suggest future research that focuses on quantitative data on how engineers design [2].

Chapter 2

Literature Review

2.1 Eye Tracking

Eye tracking methods have been used in psychology for decades to study methods of information processing such as visual perception and reading [5]. Eye tracking has also been used to study human-computer interactions and media communication [6]. Most recently, eye tracking methods have been implemented to study complex learning processes relating to science and mathematics problem solving strategies [7].

Engineering education researchers have begun using eye tracking methods in their research because it provides quantitative and qualitative data and can provide insight into a user's attention and cognitive processes without interfering with a participant's thought process [8]. This connection between visual focus and cognitive attention is often called the "eye-mind" assumption [9].

The foundation of eye tracking is human vision. A person's visual perception can be categorized into three parts: foveal, parafoveal, and peripheral vision. Of these parts, the fovea, or center of the retina, provides the most information for eye tracking researchers. People often locate and center objects in their foveal vision because it offers the greatest focus [10]. For this reason, it has been shown to be a marker of where attention is being directed [6], [11]. Raw data is captured by emitting infrared light on the eyes and using video cameras to detect the reflections. While the pupils move with the eye movement, the reflections stay in approximately the same location. Using this reflection data, algorithms are able to calculate the view angle of a user for a specific point in time [12]. This focus point is often referred to as a gaze point.

In general, eye movements can be further divided into periods of fixations and movements [13]. Fixations are brief moments when gaze is stable and eye contact is maintained for longer than 250 ms. Saccades are eye movements where a person is shifting their gaze between fixations. Researchers have shown that little information is perceived during saccades. Series of eye fixations and saccades recorded during complex information processing can provide a dynamic mapping of where a person is directing their attention [6].

Generally, eye tracking applications have either a diagnostic or an interactive role. While some computer-human interaction research is exploring an interactive eye tracking role, most fundamental research is conducted using diagnostic roles. In this method, data is collected and then subsequently analyzed [14].

While all eye tracking data is conceptualized to interpret user attention, gaze data alone is not able to fully understand a person's thought process. Some researchers have employed talk aloud methods in conjunction with eye tracking data, but research has shown that verbal stimuli changes how the eyes move [15]. Other methods have been proposed to determine cognitive activity directly from the eye tracking data. Markers such as blink rate, fixation frequency, and fixation duration have been studied, but correlations to cognitive activity have been inconsistent or nonexistent [15]. A more reliable bridge between eye tracking data and cognitive activity is pupil diameter. Diameter data can be collected using the same infrared light reflections used in gaze data collection [16].

While eye movements are not directly reflective of cognitive tasks, pupil dilation has been shown to correlate with cognitive activity [16]. The pupil consists of radial and circular muscles. The radial muscles dilate the pupil and the circular muscles constrict the pupil. While the circular muscles react to the presence of light, the radial muscles react when a person exerts mental effort. The light reflex and the dilation reflex influence the constantly changing diameter of the pupil. Light changes activate the circular muscles and inhibit the radial muscles. The dilation reflex does the opposite by activating the radial muscles and inhibiting the circular ones [16]. To distinguish between these two pupil reflexes, signal processing can be used in combination with algorithms to distinguish between both reflexes. An Index of Cognitive Workload or Index of Cognitive Activity (ICA) can be established that provides researchers a reliable benchmark to compare a participant's cognitive workload over the duration of data collection. Because different eyes may react differently based on the level of intellectual difficulty, it is best to interpret the ICA relative to a baseline reading when the user is completing the eye tracker calibration or during non-strenuous activities [16].

Even though eye tracking is a common research method, few engineering education researchers have employed it to study the student design process. Most eye tracking researchers work in psychology and computer science [17]. There are only a few papers that propose a method to analyze eye tracking data collected during a student design activity. Matthiesen et al. REF proposed a method to analyze eye tracking data to understand how engineers analyze technical systems. Their team collected preliminary data on a small number of participants to verify the method of collection and data analysis. They showed that data could be collected that offered meaningful insight into the design process. However, their study was aimed toward determining effective analysis techniques for practicing engineers. The study also was limited to eye tracking data on stationary technical drawings and physical objects. They neglected interactive analysis or active design manipulation [14].

Hess et al. REF completed an eye tracking study on students attempting to understand a technical system with multiple parts [12]. They gave each student twenty minutes to view the system and determine the function of each mechanical subassembly. This study offered insight into the student's thought process used to solve a problem. That said, the research was aimed toward providing support for a specific teaching method proposed to help students interpret a mechanical system.

Eye tracking methods have been shown to provide an understanding of the cognitive processes of engineers and students. In the context of learning, most eye tracking studies focus on conceptual development, perception, or language [17]. When discussing the learning process, most researchers focus on the acquisition of new information and neglect how students apply previous knowledge in new situations. There is need for more research in the intersection of the student design process and eye tracking methods.

2.2 Data Visualization

Visualization, an important process of data science, promotes discovery and exploration. Primarily used to promote the comprehension of dense information and to show relationships within a data set, data visualization is defined as the abstract representation of data [18].

Due to the complex nature of eye tracking data, visualizations present challenges, but also offer great simplifications to analysis. Eye tracking data is a broad category and encompasses many areas of study. For that reason, visualization of eye tracking data is highly dependent on the context of the data and research questions to be answered.

Simple visualization of eye tracking data often borrows from traditional statistical graphics such as line charts [19], [20] , bar charts [21], [22] , or scatter plots [23], even when these methods are not adapted for eye tracking data. Other simple forms of visualization constructed for eye tracking include attention maps [24], used for spatial data, and time plots [24] , used for temporal data. The ease and accessibility of attention maps or heatmaps, often included in analysis software, is an area of caution as they can be misleading in analysis [25]. Time plots present great simplifications to analysis but are only useful for temporally motivated research such as website navigation. Because eye tracking data is spatial and temporal, researchers also employ methods to visualize spatiotemporal data. Scan paths can be used to show connecting lines between fixations [26]. Attention maps, time plots and scan paths are all used for point-based eye tracking visualization techniques.

Beyond point based analysis, an area of interest (AOI) can be defined and used to show how a viewer moves between important objects and defined regions. AOI visualizations are also important for complex data sets when a point-based visualization would add visual clutter. Because regions or objects are predefined, spatial data is not as important. The importance is in the sequence of switching between AOIs or the time spent within different AOIs [27].

One method is the use of an AOI timeline, which shows the order in which the participant viewed each region [28]. This method shows temporal relationships between AOIs but doesn’t provide an intuitive qualitative analysis of spatial positioning. Unlike time plots, scan paths, and attention maps, AOI timelines eliminate the ability to show in-context relation to the stimulus. Goldberg et al. REF developed a method to construct a transition matrix to show transition frequency between regions [29]. This allows for a simpler comparison of participants moving between AOIs.

Using these methods, the analysis of static stimuli, eye tracking data is a relatively straightforward process. However, when the data is collected during dynamic stimuli, the visualization techniques become more complicated and much fewer methods exist for such analysis. At the most basic level, animated heat maps, bee swarms and recorded gaze paths are embedded features in software from Tobii and SMI [30], [31]. These options are extensions of static stimuli analysis and often offer little intuitive, qualitative analysis and require extensive manual steps to condense. One of the simpler ways to analyze dynamic stimuli are defined, dynamic AOIs. This method requires a relatively consistently placed dynamic object or the use of machine learning to move an AOI within an area of the screen [32].

Analyzing dynamic stimuli such as video data can provide a better understanding of viewing patterns in a more dynamic environment. Tien and Zheng REF studied a surgical task by measuring gaze overlaps between novice and experienced surgeons [33]. Movie scenes have also been evaluated to compare similarities in viewing patterns and to study the influence of directorial techniques on viewers [34], [35] .

One method for visualizing dynamic stimuli eye tracking data was recently proposed by Kurzhals et al. REF that adopts the space time cube (STC) [36]. The STC is used in geography [36] and 3D video content analysis [37], [38] to provide 3D visualizations. In reference to eye tracking, the STC has also been used to show eye trajectories on static stimuli [39] and Volumes of Interest on dynamic stimuli [40]. Currently in eye tracking data visualization, the most complex visualization is the STC used to compare multiple participants as they watch a passive, dynamic stimulus.

In a taxonomy of eye tracking research, Blascheck et al. REF categorizes many types of data and their matching visualization techniques. In the example of recording eye tracking data during a computer aided design challenge, the stimuli (design challenge) is one of the most complicated data types and is categorized as 2D, spatiotemporal, dynamic, active stimulus content that is asynchronous across participants. While the participants use CAD to design a 3D part, the data is still considered 2D because there is no way to collect a depth dimension of view. At the time of writing this review, no one has presented methods to compare eye tracking data of varying time length between participants. Some have used synchronization to combine multiple data streams, but each participant data was the same time length [41].

For complex data sets involving dynamic stimuli and many AOIs, a STC visualization is a helpful way to visualize time dependent data. That said, engineering education and design thinking processes often do not require a prohibitive amount of AOIs. When students design using CAD software, only a few AOIs exist on the screen and while the student manipulates the design artifact in the software, the relative position of the model is stationary. The interest to educators arises when students switch between CAD software and instructions and the corresponding cognitive workload measure associated with each step.

My research tracks and visualizes the way that students complete a design task by providing a linear time plot of the data. Because my research questions focus on the design patterns of high achieving students, I am able to simplify a complex dataset and present methods of visualization specific to the field of engineering education. Specifically, I plan to plot the five most important AOIs of CAD software in combination with the cognitive workload to answer the following research questions.

Q1: How do high achieving students demonstrate mastery of engineering design?

Q2: What heuristic patterns of design do high achieving students follow in an authentic engineering design task?

Q3: How do students’ conceptions of the design process relate to active design patterns?

Chapter 3

Methods

3.1 Recruitment and Participant Demographics

After obtaining IRB approval for this study, the participants for this study were recruited from a 400-level (senior) mechanical engineering course at Penn State University. Students who volunteered to participate were selected if they met the criteria of being senior-level mechanical engineering undergraduates, identified as domestic students, and had a cumulative GPA above 3.0. Of the ten participants selected, two identified as women and eight identified as men. Of the ten participants, all specified English as their native language. Eight of the ten participants identified as white and two identified as being from another racial demographic. Seven of the ten participants had a GPA above 3.70.

3.2 Design Prompt

My design prompt instructed participants to model a desk organizer in SolidWorks that could hold six common items. These objects were scissors, a staple remover, a USB drive, and three pencils. I instructed the participants that their, “final design should be able to rest on a flat table and should include a specific spot for each object”. I also reduced the complexity of the challenge by eliminating the consideration of material properties, manufacturability, or geometric tolerancing. Along with a written prompt, I provided unitless dimensioned drawings of the objects to aide in the design process. The full prompt can be found in Appendix A.

The most important consideration in the development of this design prompt were the constraints of the eye tracking data analysis. To simplify analysis, I constrained the design process to CAD software and did not allow participants to sketch ideas or iterate on paper. While it is possible to collect eye tracking data on sketch-based design challenges, my purpose was to study an authentic design process. In this way, I was not solely interested in the iteration process, but rather the entire process from prompt to dimensioned 3D model.

While other engineering education researchers have used similar design prompts, previous prompts have often been intended to be completed with pen and paper. Elegant solutions to these prompts encourage complex geometries. Because not all undergraduate students have ample experience designing in CAD software, my design prompt was created so that many solutions exist with orthogonal and polygon geometries.

My prompt was conducive to a variety of ability levels due to general familiarity with similar desk organizers and the simple design requirements. While participants could design a geometrically complex solution, elegant solutions exist with orthogonal geometries.

3.3 Pre-Survey Design Self Efficacy

Before each participant began the study, I asked them to complete a research consent form and answer questions about their GPA, year, major, and their design self-efficacy, measured from the Engineering Design Self-Efficacy scale developed by Carberry et al. [42]. These characteristics were correlated with results from the design challenge to add context to the findings.

3.4 Eye Tracking Data Capture

Eye tracking data was collected using a FOVIO FX3 eye tracker that was connected to the EyeWorks, Inc. Record software. This system recorded pixel coordinates of the user's gaze on the screen, cognitive workload, and a video screen capture. The software also collected blink counts, pupil diameter, and gaze data. The FOVIO FX3 eye tracker is stationary and non-obtrusive. It sits below a single computer monitor. The eye tracker did not move during the entire data collection process over many weeks. I calibrated each user individually to the eye tracker and used a chair with adjustable height to ensure that I could calibrate each user accurately without moving the eye tracker itself. While this allowed participants to move around and possibly disrupt accurate data collection, it was easier than adjusting the eye tracker. I also found that users did not move considerably when I explained the importance of beginning and ending the study in one comfortable position.

Each participant had one hour to read the instructions and complete the design challenge. Because I wanted to collect data on the participants process of reading the instructions, I calibrated the eye tracker, began recording data, and then explained the general process of the design challenge. While I limited the challenge to one hour, all participants completed the task between 20 and 50 minutes.

3.5 Post Survey

After each participant completed the design challenge, I gave them the opportunity to reflect on their process of designing. I also asked questions relating to the requirement to use SolidWorks. I asked if SolidWorks hindered their design process and if they would have iterated more if they were allowed to start their process on paper. I also asked if providing a design reference would have affected their process and if the instructions were clear enough. This survey was recorded via a typed note taking style and used to collect information to compare to design self-efficacy.

3.6 Eye Tracking Data Analysis

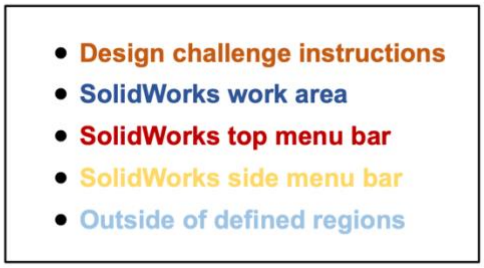
I began analyzing the data by importing the data collected from EyeWorks Inc. Record software into the EyeWorks Inc. Analyze software. While I did not use any of the included features of the EyeWorks Inc. Analyze software, I used the software to export the data into MATLAB. Based on my research questions, I used the exported pixel coordinates of the users' left eyes. This data type varies from gaze data because using one eye allows us to examine the data with discrete, similar, time intervals. Gaze data includes times when both eyes were looking at the same area. While this provides a better understanding of direct focus, it creates uneven time intervals and increases the complexity of analysis. It was also not necessary to examine gaze data since the resolution for my AOI coordinates were in the order of magnitude of hundreds of pixels. This limited resolution did not require us to examine specific and precise eye concentration.

I also exported "scaled second" cognitive workload data. This was preferred over the non-scaled second workload data as it decreased variability and outliers by taking a collective reading over an entire second. It also decreased the complexity of analysis because the time intervals for cognitive workload and eye movements were not the same. This choice made it easier to align the data as I could fit many eye tracking data points into each one second time interval of the cognitive workload data.

Because the participants could switch between the instructions and SolidWorks, the first step in the analysis was to determine the time stamps of these transitions. The eye tracker records screen capture and eye position data separately and it does not distinguish between different stimuli. The eye position data had to be linked to the instructions or the CAD so that meaningful AOIs could be defined. While these time stamps could be coded manually, it is more efficient and accurate for the computer to do so. To accomplish this task, pixel subtraction was used. Known pixel regions and values were defined for the application tabs for SolidWorks and the instruction PDF. Each video frame was read into MATLAB and the two pixel regions were compared to the known regions. After the subtraction values were read to a matrix, a simple code determined which region was most likely displayed. These switching frames were then assigned a timestamp based on the ten frames per second recording rate. Then, the closest time stamp in the eye position data was identified. This was relatively easy to align since the eye position data had time intervals of approximately 0.014 seconds compared to 0.1 seconds for the video frames. I could not use a defined number of data points for each video frame as the time intervals of the eye tracking data were not consistent with a variability of about 0.005 seconds. After this data was aligned, this matrix provided the eye position data time stamp, X and Y pixel gaze positions, and task (SolidWorks or PDF instructions).

AOIs were defined in SolidWorks as the workspace, the top bar, and the side bar. For each gaze position, the pixel coordinates were compared and the appropriate AOI was assigned. This new matrix included the time stamps and a number corresponding to one of the three SolidWorks regions, the instructions, or if no area was defined. Then, the cognitive workload values were concatenated to this matrix. Because the total duration of the design process was not meaningful, the time column was simplified so that the activity spanned a normalized one hundred time units. This simplification made it much easier to compare across participants as the data was asynchronous.

An AOI timeline was generated by a successive graphing of vertical lines. The height of each line indicates the ICA while the color corresponds to the AOI in SolidWorks or the instructions. The X-axis is a normalized time axis for one hundred time units. As seen in Figure 1, in this visualization orange represents the instructions, blue represents the workspace in SolidWorks, yellow represents the side bar in SolidWorks, red represents the top bar in SolidWorks, and light blue represents an undefined region. This method of data visualization was successful in representing the data and allowing comparisons between participants. While it may be possible to visualize data in a more effective way, my method greatly reduced the complexity of the analysis by condensing nearly 500,000 data points into a single plot.



- **Design challenge instructions**
- **SolidWorks work area**
- **SolidWorks top menu bar**
- **SolidWorks side menu bar**
- **Outside of defined regions**

Figure 1. AOI color representation

3.7 Design Artifact Rubric

To rank the designs, I created a design rubric based on twelve parameters. I weighted each parameter according to my perception of its importance in relation to our specific challenge.

The highest importance was placed on *Zero Dimensions* and *Center of Mass*. In both of these cases, failure to meet requirements removes the design's ability to exist in a physical reality, or stay standing when in use, respectively. From a user's standpoint, I judged the other requirements based on their importance for daily use. Other requirements, such as *Sharp Sides* and *Footprint* are frustrating for the end user but do not entirely remove functionality.

Then I collected *Moment of Inertia* (I_{yy}) and *Center of Mass* data from the files using the "Mass Properties" and "Measure" tools in SolidWorks. To collect this data, I had to define a new coordinate system for each object to ensure that the center of mass height was aligned properly with the vertical axis and the base of the design.

While six of the parameters are based on the design artifact, the other six are based on the assembly of the design artifact with the desk objects. To measure these parameters, an assembly was created with each design where the desk objects were arranged according to the participants' design. In many cases, building these assemblies was straight forward as the requirement of an individual location for each item made it evident where each object was meant to go. However, some participants did not follow the instructions. In these cases, I had to make judgments about where each object was intended to be placed. I made these judgements with care, but without intense speculation. The ambiguity created in their design would have to be interpreted by the end user, where the designer is not present to instruct the desk organizer's final use. The full set of participant assemblies can be found in Appendix B.

After these parameters were defined, I used Excel to normalize the values. In this way the designs were scored in relation to each other. Then each normalized grade for each category was multiplied by the weight and summed. As seen in Table 1, a complete list of the parameters, their definitions and the assigned weights are provided.

Table 1: Design Artifact Parameters

Parameter	Description	Weight
Volume of Material Used	This was used as a simple measure of how much material was used in the final design.	5
Footprint	This was the area of material that would touch the table if the organizer were in use.	5
Box Volume	This equaled the footprint * the overall height of the design	5
Material Efficiency	This was a ratio of volume used for the object spaces and the total volume used in category 1.	5
Sharp Sides	a 0 – 2 score if no, some, or all sides were sharp	3
Dimensions	This was a score out of 6 for the number of slots that were dimensioned so that the objects could easily enter the leave their spot. No “perfect” dimensioning.	10
Accessibility	This was a binary yes or no if the objects interfered when there were in their dedicated slot.	10
Follow Instructions	This was a ranking from 0-6 for how many objects had an individual spot. This category was included because many participants did not include three distinct spots for the pencils.	10
Zero Dimensions	A binary yes or no if there were zero dimension geometries.	10
Center of Mass	0-10 if the final design was likely to tip over. A 10 was for a design that would fall over with no input when all objects were in the organizer.	5
Moment of Inertia	Moment of inertia (I_{yy}) around the vertical axis	15
Lifecycle Design	This was a parameter normalized for the length of the pencil. How short could the pencil be before it was no longer accessible when it was stored in the desk organizer.	5

Chapter 4

Results

4.1 Research Outcomes

I set out to study the design habits and processes of high performing students. I designed a method of data visualization specifically tailored to show how high performing students worked through a design process. I hoped that clear trends would emerge showing parallel areas of high cognitive workload with a similar design workflow that could be used to construct a coherent design process on an authentic design task. This pursuit was intended to be prescriptive as to inform future students how to think and relate to the engineering design process.

After reviewing our design artifacts and design parameters, many of our participants failed to meet basic technical requirements and to acknowledge a complete design process. In Figure 2, I include the final assemblies from the 1st, 3rd, 9th, and 10th ranked participants from left to right. I chose to include these design artifacts, as they were the best representation of the range of design outcomes.

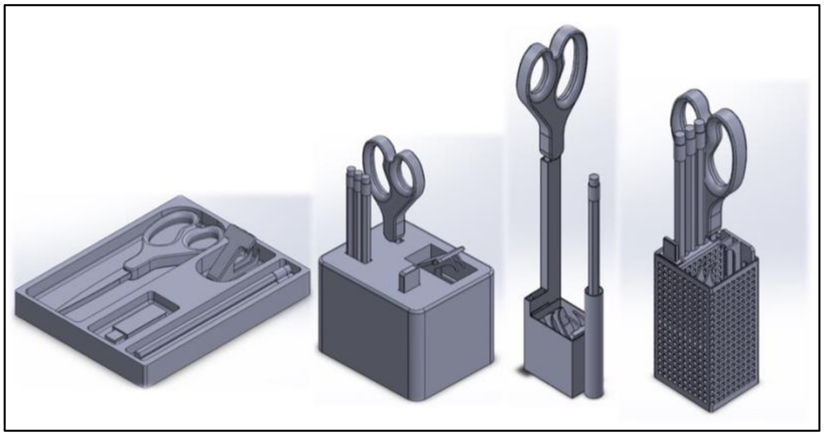


Figure 2. Design artifacts assemblies from the 1st, 3rd, 9th, and 10th ranked participants

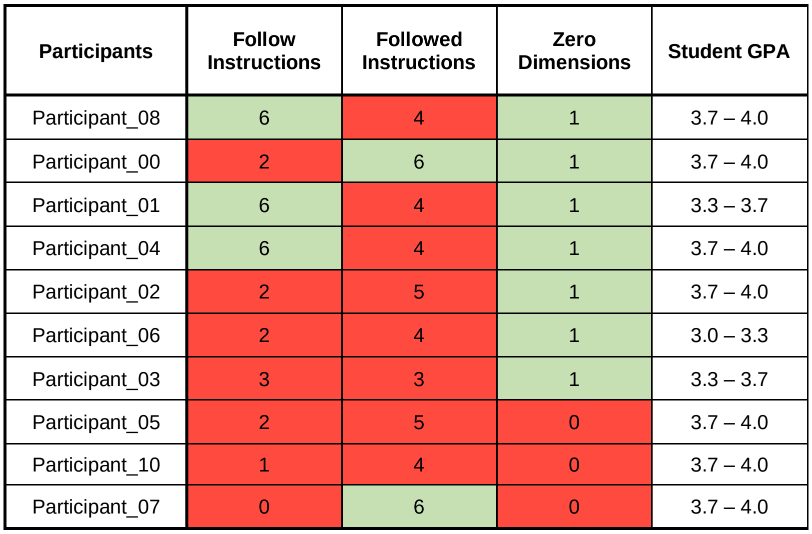
4.2 Research Q1 Results

Q1: How do high achieving students demonstrate mastery of engineering design?

After assessing each design based on the twelve-parameter matrix, not one participant demonstrated mastery of the design process. If I were expecting students to follow the instructions, dimension their design properly, and design without zero thickness dimensioning, not one participant successfully completed the design task. If, instead, I wanted a final product that could exist in a physical world and hold the objects that I mentioned without falling over, two of the ten participants would have successfully completed the design challenge.

In Table 2, I show the results of three of the twelve parameters. The participants are ranked from highest scoring (Participant_08) to lowest. Within each category, green indicates full points and red indicates less than full points. Because the instructions indicated six individual slots, the number out of six is represented in the table. The *Zero Dimension* parameter is a binary score with one representing the absence of zero dimensions. These parameters represent fundamental constraints and do not take into account mastery in any of the other parameters. While many of them did end up creating a general "form" that could meet the specified parameters and score well, often their designs looked better than they performed. Overall, out of ten participants, no participants demonstrated mastery of the design process in my authentic design challenge. The full table of results from the parameter ranking can be found in Appendix C.

Table 2: Selected Design Challenge Parameters Ranked



Participants	Follow Instructions	Followed Instructions	Zero Dimensions	Student GPA
Participant_08	6	4	1	3.7 – 4.0
Participant_00	2	6	1	3.7 – 4.0
Participant_01	6	4	1	3.3 – 3.7
Participant_04	6	4	1	3.7 – 4.0
Participant_02	2	5	1	3.7 – 4.0
Participant_06	2	4	1	3.0 – 3.3
Participant_03	3	3	1	3.3 – 3.7
Participant_05	2	5	0	3.7 – 4.0
Participant_10	1	4	0	3.7 – 4.0
Participant_07	0	6	0	3.7 – 4.0

4.3 Research Q2 Results

Q2: What heuristic patterns of design do high achieving students follow in an authentic engineering design task?

After the initial review of the design artifacts and ranking the designs, I examined the new method of visualizing the eye tracking data. After examining all the visualizations, I noticed some trends and design patterns that the participants seem to follow. In Figure 3, I show the four visualizations that correspond to the participants of the screenshots from the last section, these visualizations represent the participants who scored 1st, 3rd, 9th, and 10th in the design challenge. The full set of visualizations can be found in Appendix D.

First, every participant spends the first part of the design challenge reading the instructions: “orange/red.” Roughly five to twenty percent of the total time is spent in the beginning reading the instructions. While the participants know they need to read the instructions, they are not increasing their comprehension because many did not follow the directions. Then we see a majority of the time spent in the “blue” section designing in the main design space in SolidWorks. This is where participants sketch, dimension, and form their 3D model. Many participants spent sporadic amounts of time in the yellow areas searching for tools in SolidWorks. Most participants continue to reference the instructions as they continue to design to double check that they are meeting the requirements and copying the dimensions down correctly. While I expected there to be more of a pattern in the overall process, what we ended up with was a series of participants that all followed a similar broad structure of “read, design, read, design.” I did not see any correlations between a common area of increased cognitive workload. Based on the metrics that I chose, there is no universal design process occurring across participants.

Interestingly, one participant (Participant_03) did not even realize that I had provided dimensioned sketches. This participant’s design process showed the lowest overall cognitive workload and had many times of “undefined” AOIs. This is presumably because they were not cognitively concentrated on remembering a specific dimension and they had to look away to generate a number. However, without more data, it is impossible to say whether these results are correlated, or if perhaps the undefined AOIs were a result of a technical flaw such as eye tracker misalignment. However, since the software re-picked up the signal during the design tasks, it is more likely that this trend indicates participant behavior rather than hardware malfunction.

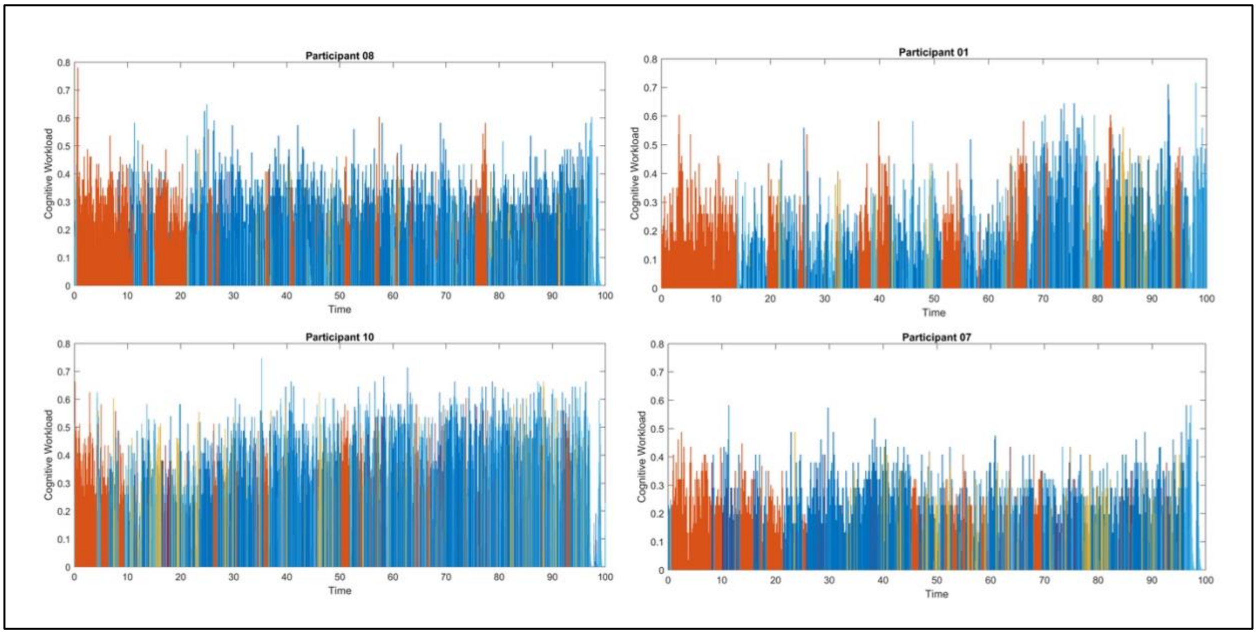


Figure 3. Cognitive workload AOI timeline visualizations from the 1st, 3rd, 9th, and 10th ranked participants

4.4 Research Q3 Results

Q3: How do students' conceptions of the design process relate to active design patterns?

After mixed results from the design challenge, I examined the data from my surveys and ran correlation plots for my design parameters, design self-efficacy, and AOIs. Figure 4 shows a qualitative summary of the Pearson correlations. Green circles denote statistically significant ($p < 0.05$) positive correlations and red circles denote statistically significant ($p < 0.05$) negative correlations. The size of each circle represents the magnitude of significance (smaller dots are significant to $p < 0.05$ and larger dots are significant to $p < 0.01$). The full Pearson correlation table can be found in Appendix C.

As seen in Figure 4, a participant's self-efficacy in *Conduct Engineering Design* positively correlated with their self-efficacy in *Develop Solutions* and *Select the Best Possible Design*. Also, overall *Design Self-Efficacy* positively correlated with *Identify a Need* and the time they spent reading the instructions during the design challenge and negatively correlated with low cognitive workload in the design space. Participants who rated themselves highly in *Conduct Engineering Design* and *Developing Design Solutions* actually spent less time designing during the challenge. Also, there is a correlation between participants who felt *Hindered by CAD* and who drafted using *Zero Dimensions*.

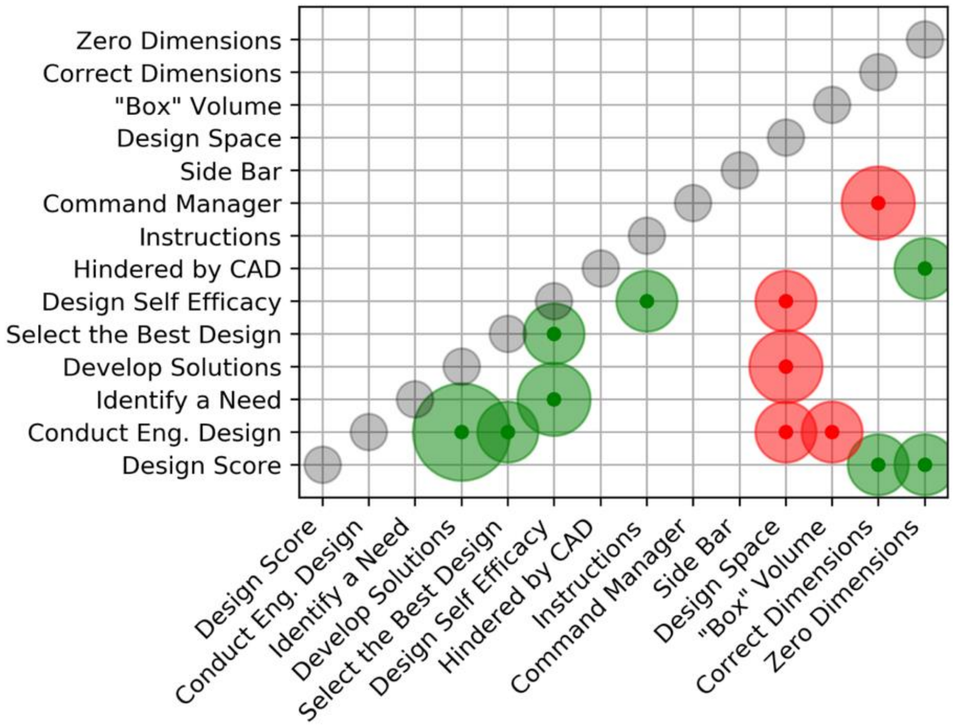


Figure 4. Qualitative correlations between design self-efficacy and performance (plot format designed by Ellen Zerbe)

Chapter 5

Discussion

Because our sample included senior level, high achieving students at a top ranked university, I expected that the participants would be able to imagine and model a simple desk organizer. With this expectation, I assumed that my metrics about *Volume of Material Used* and *Material Efficiency* would have been more important because I did not expect participants to perform so poorly in the more rudimentary parameters. Instead of judging the designs based on efficiency or creativity, the most important parameters were *Follow Instructions* and *Zero Dimensions*.

While in my prompt I did specify that the design challenge did not require geometric tolerancing, I made the incorrect assumption that students knew the difference between geometric tolerancing and basic dimensioning for fit. Also, there were no units of the length dimensions in the instructions. This was an intentional omission to encourage participants to ask about the units. Instead of asking, every participate assumed the units of inches and only one participant even noticed that the units were omitted from the drawings. Almost all the participants dimensioned the desk organizer in such a way that a 0.25 wide object would fit in a 0.25 wide slot. While this is not untrue, it completely eliminates the perspective of a user having to use such a precisely tight fitted slot every time they use their pencil. It also completely ignores simple manufacturing tolerance costs and future adaptability of the design.

Also, while I specified that each object had to have its own spot, many participants were unsure about this requirement and presumably made a judgement based on their understanding of desk organizers. While it is odd to have a separate, individual spot for each pencil, if a client requests a design parameter, it is the designer’s role to meet the request or ask about the intent of the parameter. While after the design task, many participants mentioned that they had questions about the pencil requirement, not one participant asked a question during the process.

These results may seem surprising until I realized that most design studies in literature capture sketching-style design challenges instead of authentic CAD challenges [4], [43], [44]. However, from a very practical research standpoint, we may need to start conducting more authentic design challenges. Authentic challenges ask the designer for a final, complete product instead of a ‘form’ or a concept for a design.

Also, participants are often rated based on a rubric that orders importance based on how easy different parameters are to correct [45], [46]. For example, on a class project, a dimensioning error may receive only a few points deduction if the rest of the design ‘looks’ good. While this makes sense in a classroom setting where dimensions are very easy to correct, in an authentic design challenge, the entire design could be masterful, but if the objects do not fit into their slots, the entire design is meaningless.

From this data we can start to piece together a story that students view the design process as *Identify a Need* (or in this case reading the design challenge) and *Develop Solutions*. In a sense, the students view themselves as managers. They know they should identify a problem and identify a solution, but they do not seem to connect any of the intermediary steps as essential to conducting design. This is evident in the visualizations and from my results, and we can see that their truncated design process is clearly not effective in demonstrating mastery of design.

This challenge especially shows that process because they read the instructions and then started designing in SolidWorks. When I asked them to complete a design challenge, they did not perform well and only a few of them recognized the crippling nature of their current design process. Even following the design challenge, after participants designed poor solutions to the prompt, only a couple participants complained about the constraints to use SolidWorks. If students had a cohesive understanding of their process and knew why they completed each step, one would expect them to be upset about the constraints of the challenge.

An important distinction that I need to make is that these participants were 1st semester seniors and most of them had not completed their capstone design course or were engaged in undergraduate research in replace of an engineering design capstone. This study represents their knowledge entering their senior design project. While it is unlikely that students will go from underperforming designers to masters over the course of their senior capstone, it is possible that some will improve, though outside the scope of this study. On the other hand, these participants had already completed a junior level design course that follows the design process in an authentic way where the students are expected to build a physical prototype by the end of the course.

With a small set of participants (N=10), my results cannot be generalizable, but these data do point to interesting trends in terms of the development of mastery of authentic design skills enacted in practice. These trends can be addressed in future research with larger sample sizes, especially since the present work has developed the methods for data capture and the development of metrics to evaluate design assessment criteria.

Chapter 6

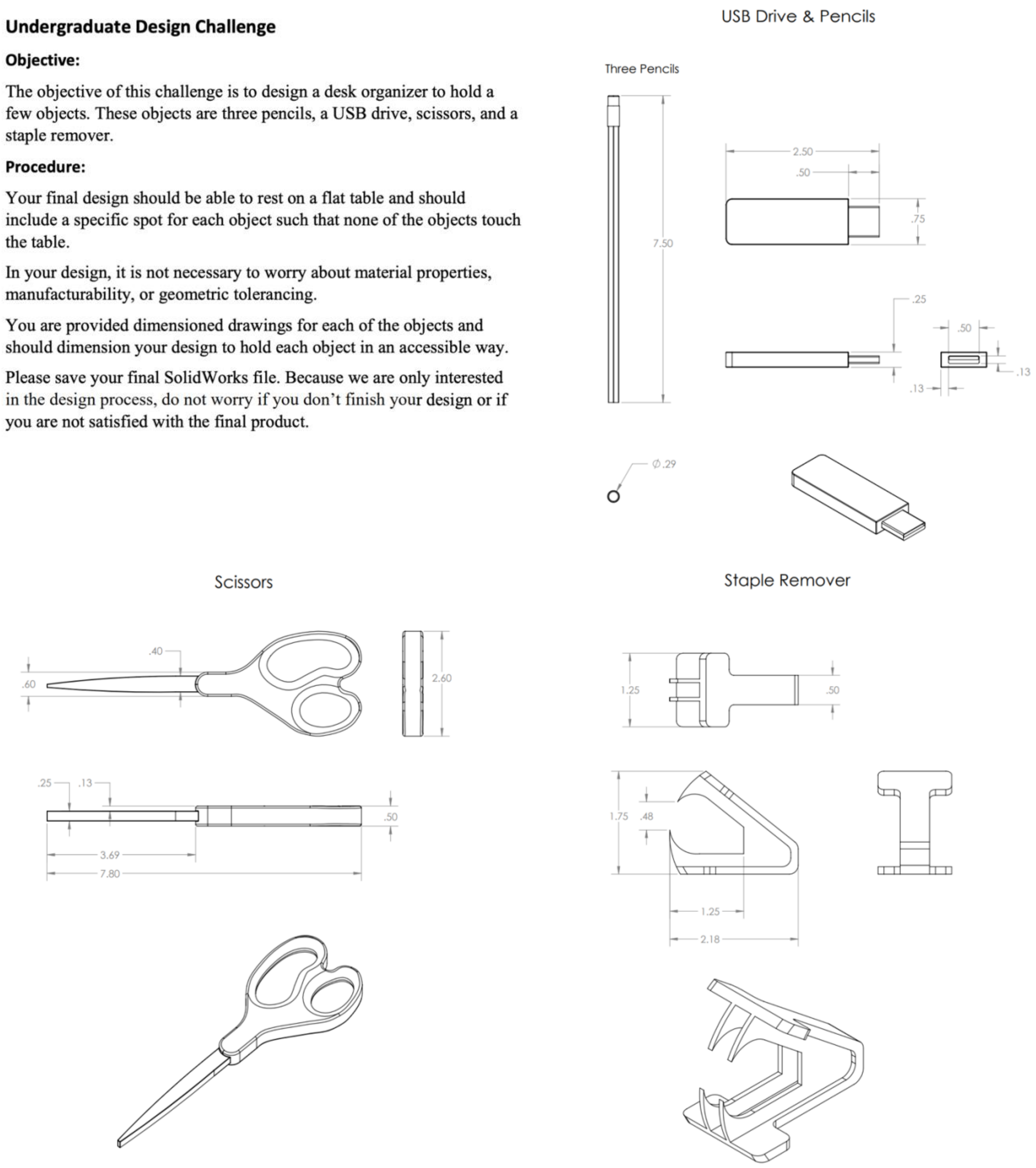
Conclusion

Based on my results, the senior-level undergraduate engineering students investigated in this study do not have the skills necessary to perform the design process successfully, despite being academic high-achievers, with many holding a GPA over 3.7.

My results indicate that while accreditation policies for undergraduate engineering programs emphasize the skill of designing, the implementation of curriculum may not be effective in educating students to transferring that knowledge to authentic settings or to retain design process knowledge from first-year engineering courses through to the senior year. As other literature has noted, the current ‘bookend’ approach to teaching design is leaving even our most high achieving students behind [3]. It seems that schools isolate design and science in curriculum as design courses are taught in a creative realm and engineering problem solving is taught in a very scientific realm. If engineering is truly the marriage of scientific reasoning and creative design thinking, we may need to rethink this ‘bookend’ design education approach and begin integrating design thinking into every class [1]. While this task seems overwhelming, it is clear from my research that students do not need to be tasked with complex, month long projects. Any small, authentic design problem that students can solve will help achieve the ultimate goal of an engineering education; to teach students how to be great engineers.

Appendix A

Design Challenge Prompt



Undergraduate Design Challenge

Objective:

The objective of this challenge is to design a desk organizer to hold a few objects. These objects are three pencils, a USB drive, scissors, and a staple remover.

Procedure:

Your final design should be able to rest on a flat table and should include a specific spot for each object such that none of the objects touch the table.

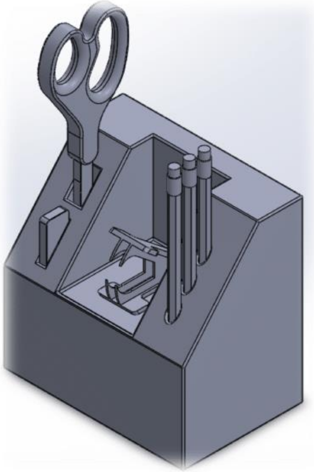
In your design, it is not necessary to worry about material properties, manufacturability, or geometric tolerancing.

You are provided dimensioned drawings for each of the objects and should dimension your design to hold each object in an accessible way.

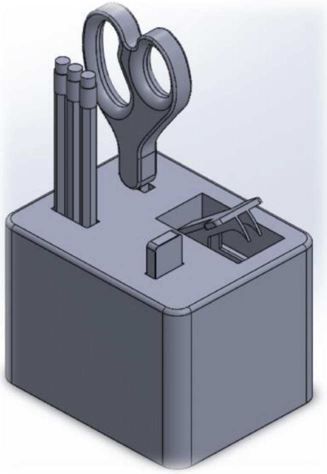
Please save your final SolidWorks file. Because we are only interested in the design process, do not worry if you don't finish your design or if you are not satisfied with the final product.

Appendix B

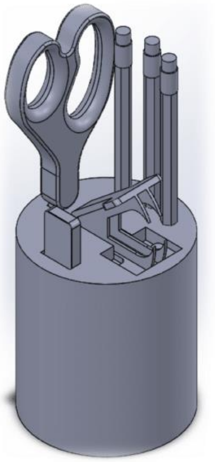
Design Artifact Assemblies



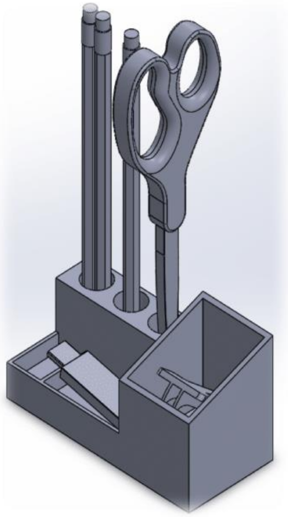
Participant_00



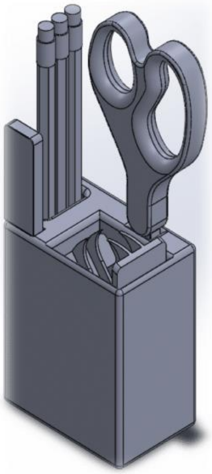
Participant_01



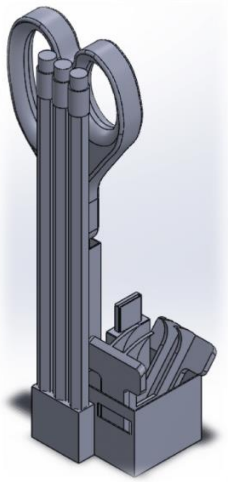
Participant_02



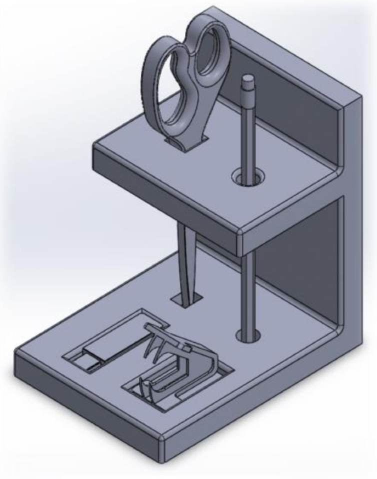
Participant_03



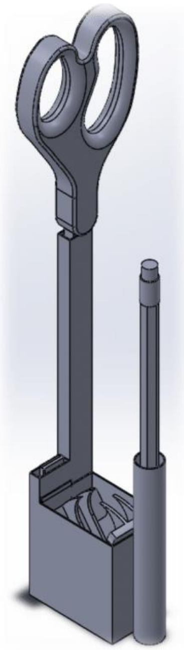
Participant_04



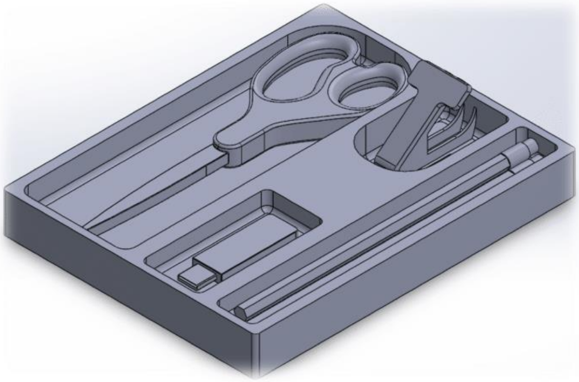
Participant_05



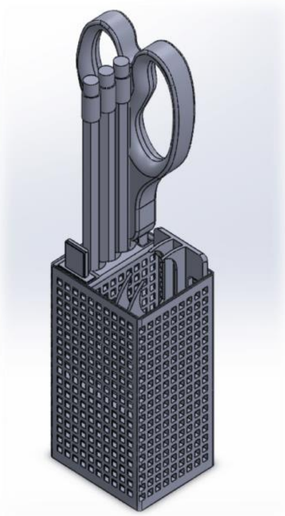
Participant_06



Participant_10



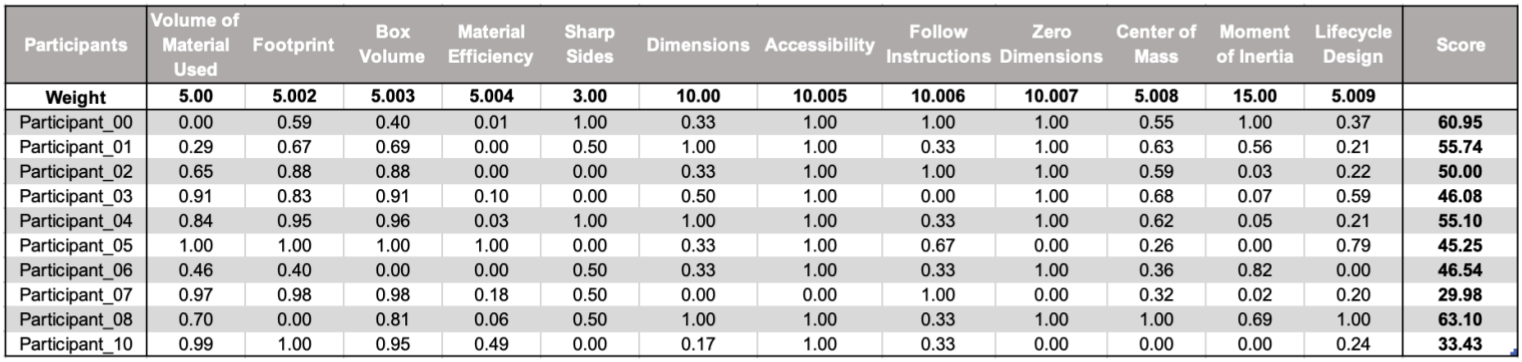
Participant_08



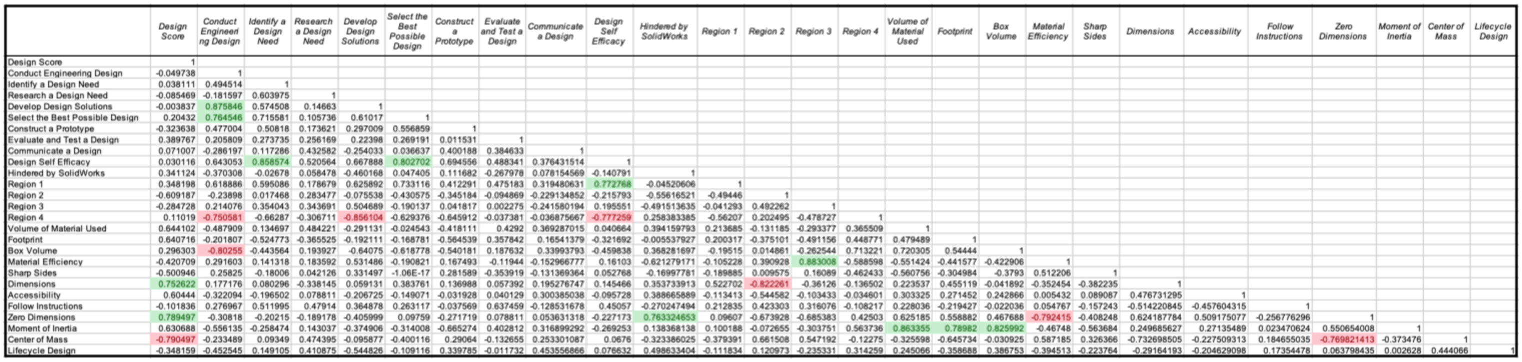
Participant_07

Appendix C

Design Artifact Scoring Table and Pearson Correlation Table



Participants	Volume of Material Used	Footprint	Box Volume	Material Efficiency	Sharp Sides	Dimensions	Accessibility	Follow Instructions	Zero Dimensions	Center of Mass	Moment of Inertia	Lifecycle Design	Score
Weight	**5.00**	**5.002**	**5.003**	**5.004**	**3.00**	**10.00**	**10.005**	**10.006**	**10.007**	**5.008**	**15.00**	**5.009**	
Participant_00	0.00	0.59	0.40	0.01	1.00	0.33	1.00	1.00	1.00	0.55	1.00	0.37	**60.95**
Participant_01	0.29	0.67	0.69	0.00	0.50	1.00	1.00	0.33	1.00	0.63	0.56	0.21	**55.74**
Participant_02	0.65	0.88	0.88	0.00	0.00	0.33	1.00	1.00	1.00	0.59	0.03	0.22	**50.00**
Participant_03	0.91	0.83	0.91	0.10	0.00	0.50	1.00	0.00	1.00	0.68	0.07	0.59	**46.08**
Participant_04	0.84	0.95	0.96	0.03	1.00	1.00	1.00	0.33	1.00	0.62	0.05	0.21	**55.10**
Participant_05	1.00	1.00	1.00	1.00	0.00	0.33	1.00	0.67	0.00	0.26	0.00	0.79	**45.25**
Participant_06	0.46	0.40	0.00	0.00	0.50	0.33	1.00	0.33	1.00	0.36	0.82	0.00	**46.54**
Participant_07	0.97	0.98	0.98	0.18	0.50	0.00	0.00	1.00	0.00	0.32	0.02	0.20	**29.98**
Participant_08	0.70	0.00	0.81	0.06	0.50	1.00	1.00	0.33	1.00	1.00	0.69	1.00	**63.10**
Participant_10	0.99	1.00	0.95	0.49	0.00	0.17	1.00	0.33	0.00	0.00	0.00	0.24	**33.43**



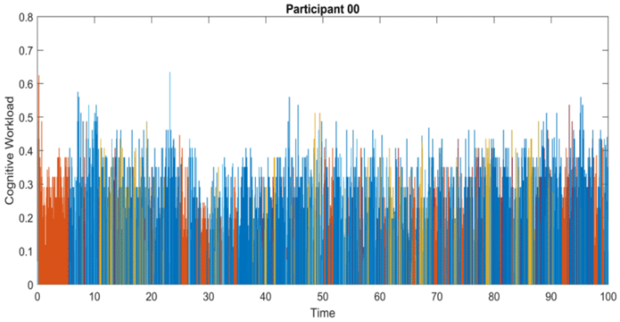
	Design Score	Conduct Engineering Design	Identify a Design Need	Research a Design Need	Develop Design Solutions	Select the Best Possible Design	Construct a Prototype	Evaluate and Test a Design	Communicate a Design	Design Self Efficacy	Hindered by SolidWorks	Region 1	Region 2	Region 3	Region 4	Volume of Material Used	Footprint	Box Volume	Material Efficiency	Sharp Sides	Dimensions	Accessibility	Follow Instructions	Zero Dimensions	Moment of Inertia	Center of Mass	Lifecycle Design
Design Score	1																										
Conduct Engineering Design	-0.049738	1																									
Identify a Design Need	0.038111	0.494514	1																								
Research a Design Need	-0.085469	-0.181597	0.603975	1																							
Develop Design Solutions	-0.003837	0.875846	0.574508	0.14663	1																						
Select the Best Possible Design	0.20432	0.764546	0.715581	0.105736	0.61017	1																					
Construct a Prototype	-0.323638	0.477004	0.50818	0.173621	0.297009	0.556859	1																				
Evaluate and Test a Design	0.389767	0.205809	0.273735	0.256169	0.22398	0.269191	0.011531	1																			
Communicate a Design	0.071007	-0.286197	0.117286	0.432582	-0.254033	0.036637	0.400188	0.384633	1																		
Design Self Efficacy	0.030116	0.643053	0.858574	0.520564	0.667888	0.802702	0.694556	0.488341	0.376431514	1																	
Hindered by SolidWorks	0.341124	-0.370308	-0.02678	0.058478	-0.460168	0.047405	0.111682	-0.267978	0.078154569	-0.140791	1																
Region 1	0.348198	0.618886	0.595086	0.178679	0.625892	0.733116	0.412291	0.475183	0.319480631	0.772768	-0.04520606	1															
Region 2	-0.609187	-0.23898	0.017468	0.283477	-0.075538	-0.430575	-0.345184	-0.094869	-0.229134852	-0.215793	-0.55616521	-0.49446	1														
Region 3	-0.284728	0.214076	0.354043	0.343691	0.504689	-0.190137	0.041817	0.002275	-0.241580194	0.195551	-0.491513635	-0.041293	0.492262	1													
Region 4	0.11019	-0.750581	-0.66287	-0.306711	-0.856104	-0.629376	-0.645912	-0.037381	-0.036875667	-0.777259	0.258383385	-0.56207	0.202495	-0.478727	1												
Volume of Material Used	0.644102	-0.487909	0.134697	0.484221	-0.291131	-0.024543	-0.418111	0.4292	0.369287015	0.040664	0.394159793	0.213685	-0.131185	-0.293377	0.365509	1											
Footprint	0.640716	-0.201807	-0.524773	-0.365525	-0.192111	-0.168781	-0.564539	0.357842	0.16541379	-0.321692	-0.005537927	0.200317	-0.375101	-0.491156	0.448771	0.479489	1										
Box Volume	0.296303	-0.80255	-0.443564	0.193927	-0.64075	-0.618778	-0.540181	0.187632	0.33993793	-0.459838	0.368281697	-0.19515	0.014861	-0.262544	0.713221	0.720305	0.54444	1									
Material Efficiency	-0.420709	0.291603	0.141318	0.183592	0.531486	-0.190821	0.167493	-0.11944	-0.152966777	0.16103	-0.621279171	-0.105228	0.390928	0.883008	-0.588598	-0.551424	-0.441577	-0.422906	1								
Sharp Sides	-0.500946	0.25825	-0.18006	0.042126	0.331497	-1.06E-17	0.281589	-0.353919	-0.131369364	0.052768	-0.16997781	-0.189885	0.009575	0.16089	-0.462433	-0.560756	-0.304984	-0.3793	0.512206	1							
Dimensions	0.752622	0.177176	0.080296	-0.338145	0.059131	0.383761	0.136988	0.057392	0.195276747	0.145466	0.353733913	0.522702	-0.822261	-0.36126	-0.136502	0.223537	0.455119	-0.041892	-0.352454	-0.382235	1						
Accessibility	0.60444	-0.322094	-0.196502	0.078811	-0.206725	-0.149071	-0.031928	0.040129	0.300385038	-0.095728	0.388665889	-0.113413	-0.544582	-0.103433	-0.034601	0.303325	0.271452	0.242866	0.005432	0.089087	0.476731295	1					
Follow Instructions	-0.101836	0.276967	0.511995	0.47914	0.364878	0.263117	-0.037569	0.637459	-0.128531678	0.45057	-0.270247494	0.212835	0.423303	0.316076	-0.108217	0.228036	-0.219427	-0.022036	0.054767	-0.157243	-0.514220845	-0.457604315	1				
Zero Dimensions	0.789497	-0.30818	-0.20215	-0.189178	-0.405999	0.09759	-0.271719	0.078811	0.053631318	-0.227173	0.763324653	0.09607	-0.673928	-0.685383	0.42503	0.625185	0.558882	0.467688	-0.792415	-0.408248	0.624187784	0.509175077	-0.256776296	1			
Moment of Inertia	0.630688	-0.556135	-0.258474	0.143037	-0.374906	-0.314008	-0.665274	0.402812	0.316899292	-0.269253	0.138368138	0.100188	-0.072655	-0.303751	0.563736	0.863355	0.78982	0.825992	-0.46748	-0.563684	0.249685627	0.27135489	0.023470624	0.550654008	1		
Center of Mass	-0.790497	-0.233489	0.09349	0.474395	-0.095877	-0.400116	0.29064	-0.132655	0.253301087	0.0676	-0.323386025	-0.379391	0.661508	0.547192	-0.12275	-0.325598	-0.645734	-0.030925	0.587185	0.326366	-0.732698505	-0.227509313	0.184655035	-0.769821413	-0.373476	1	
Lifecycle Design	-0.348159	-0.452545	0.149105	0.410875	-0.544826	-0.109116	0.339785	-0.011732	0.453556866	0.076632	0.498633404	-0.111834	0.120973	-0.235331	0.314259	0.245066	-0.358688	0.386753	-0.394513	-0.223764	-0.29164193	-0.204629098	0.17354478	0.063798435	0.002628	0.444066	1

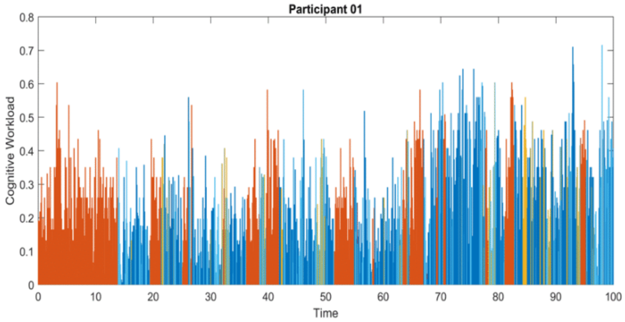
Appendix D

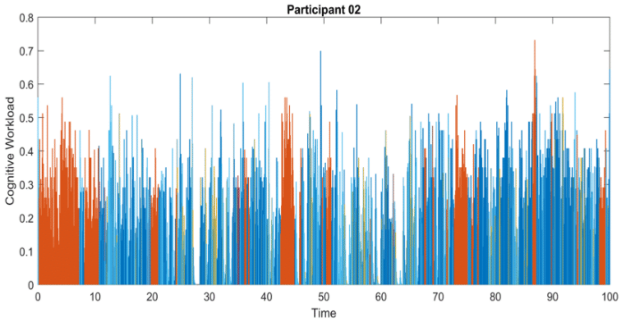
Cognitive Workload and AOI Timeline Visualizations

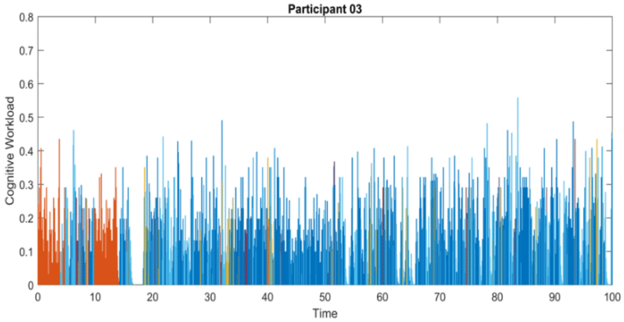
These visualizations graphically represent cognitive workload, AOI, and time. The height of each line indicates the Index of Cognitive Activity while the color corresponds to the AOI in SolidWorks or the instructions. The X-axis is a normalized time axis for one hundred time units. As seen in legend below, in this visualization orange represents the instructions, blue represents the workspace in SolidWorks, yellow represents the side bar in SolidWorks, red represents the top bar in SolidWorks, and light blue represents an undefined region.

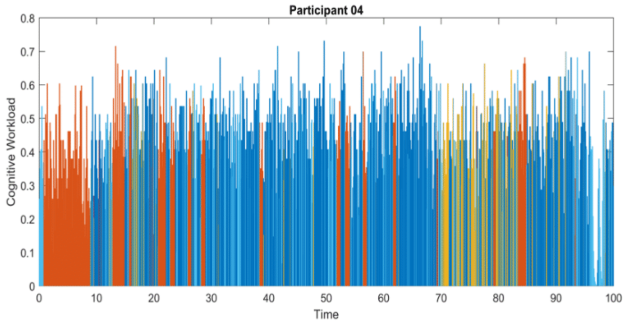
- **Design challenge instructions**
- **SolidWorks work area**
- **SolidWorks top menu bar**
- **SolidWorks side menu bar**
- **Outside of defined regions**

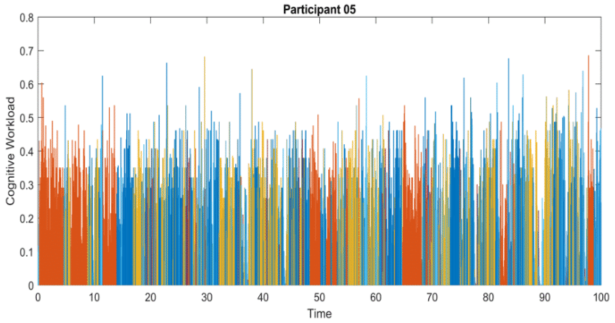


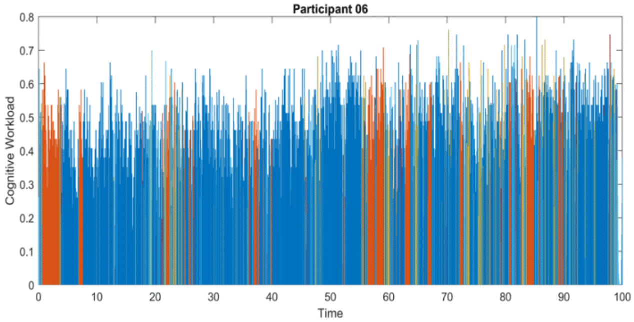


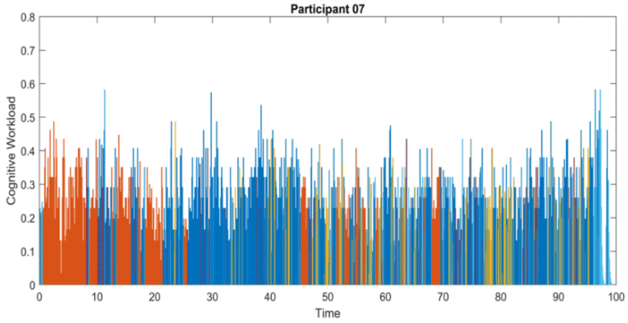


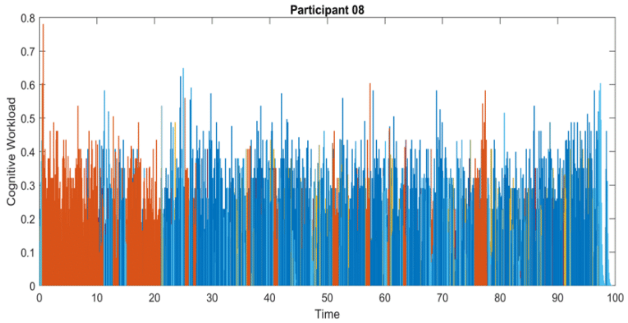


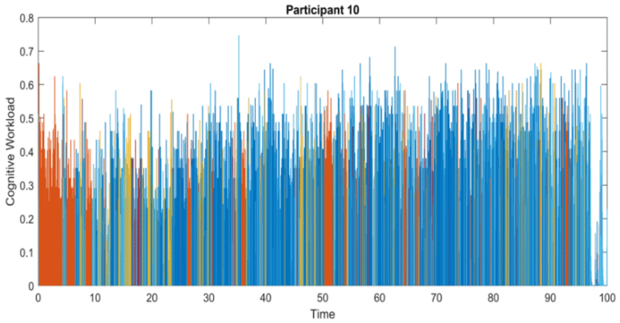

Participant 04
Cognitive Workload
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
10
20
30
40
50
60
70
80
90
100
Time


Participant 05
Cognitive Workload
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
10
20
30
40
50
60
70
80
90
100
Time


Participant 06
Cognitive Workload
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
10
20
30
40
50
60
70
80
90
100
Time


Participant 07
Cognitive Workload
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
10
20
30
40
50
60
70
80
90
100
Time


Participant 08
Cognitive Workload
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
10
20
30
40
50
60
70
80
90
100
Time


Participant 10
Cognitive Workload
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
10
20
30
40
50
60
70
80
90
100
Time

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ACADEMIC VITA

Colin Miller

Education

Schreyer Honors College

The Pennsylvania State University, University Park, PA 2020 Graduation

Bachelor of Science in Mechanical Engineering

Research

Engineering Cognitive Research Laboratory – The Pennsylvania State University

Grant Recipient / May 2019 – August 2019

- Designed a new method of visualizing eye tracking data
- Employed MATLAB to code and graph the data
- Collected, sorted and cleaned data for analysis
- Created an experiment to collect data on the engineering design process
- Communicated results through a poster and research paper

Work Experience

Graham Engineering Corporation

Mechanical Engineering Intern / May 2018 – August 2018

- Assembled 3D SolidWorks models of plastic extrusion machines
- Separated complex machines into strategic subassemblies
- Ensured that all pieces of an assembly met specifications and fit together without interference
- Converted 3D SolidWorks models into 2D drawings for assembly and legal documentation
- Designed original parts and detailed their drawings using correct GD&T to convey design intent

Leadership

Student Government Association – The Pennsylvania State University

President / August 2017 – May 2018

- Organized and led weekly senate meetings
- Established relationships with government representatives and community leaders
- Represented the campus professionally during Campus Senate and Advisory Board meetings
- Found creative solutions to campus problems and planned events in line with semester goals

Student Activity Fee – The Pennsylvania State University

Co-Chair / August 2017 – May 2018

- Structured and mediated committee discussion
- Allocated and managed a $250,000 annual budget with the committee members