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DEPARTMENT OF ENGINEERING SCIENCE & MECHANICS

ASSESSING THE IMPACT OF GRAPHICAL USER INTERFACES ON USER DESIGN PERFORMANCE
USING QUADCOPTERS IMPLEMENTING STRUCTURAL BATTERIES

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ABSTRACT

Though the energy density of batteries has been vastly improved in recent years, innovative ways of utilizing these batteries are needed in order to make them a more viable option in today's devices. This thesis aims to assess the impact that various factors have on a user's ability to optimize a quadcopter which implements structural batteries. Structural batteries can be thought of as a stack of batteries that can both support structural loads and act as a power source. If these structural batteries can be used to reduce the weight and materials required of a specific design, then the energy density will be increased. Additionally, a design tool using MATLAB was created that can be used to better visualize the relationship between quadcopter parameters and various metrics, such as duration of flight, power required, range, etc. For instance, a user may input the length, thickness, rotor radius, and velocity of the quadcopter along with the mass of the package carried, and the design tool will output an image of the design as well as graphs that show the different performance metrics. Furthermore, the design tool will have a section that outputs an optimized structure via a topology optimization program for a quadcopter with a given domain. It was found that more videogame experience significantly raises the percent error, but significantly lowers the completion time. It was also found that users who rated themselves as having more knowledge of optimization completed the optimization task significantly faster. Additionally, users who rated the design tool as more helpful in determining the relationships between inputs and quadcopter performance had significantly less error than those that rated the design tool poorly in this area. Lastly, it was found that users who rated the design tool as more difficult had significantly more error. Recommendations on future improvements in experimentation and modeling are presented based on the results of this work. The overall goal of this research is to apply innovative techniques to boost the range of quadcopters and better understand the factors that affect designers as they design quadcopters using structural battery technology.

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Chapter 1

Introduction

The following chapter discusses background information on quadcopters, structural batteries, graphical user interfaces, and my research objectives.

1.1 Problem Statement

The advances in electronics and lightweight materials over the last few decades have resulted in the popularization of quadcopters. A quadcopter is a multirotor helicopter that is lifted and propelled by four rotors. Whether for recreational, military, or commercial use, people are beginning to recognize the potential of quadcopters. One company in particular that is looking to exploit the use of drones, or unmanned aircrafts typically thought of as quadcopters, on a massive scale is Amazon through their Prime Air program. The goal of Amazon's Prime Air program is to deliver packages weighing up to five pounds in 30 minutes or less to their customers [1]. While the ultimate design or designs of the drones Amazon will use is uncertain, structural batteries could enable this technology.

Structural batteries can be thought of as a stack of batteries that can both support structural loads and act as an energy storage source. With the recent news of Samsung's issues with their phone batteries catching on fire, a concern may also arise with respect to the risks of having a battery as the frame of a quadcopter. However, the quadcopters being discussed are not designed for high-impact collisions, and therefore we assume that we can neglect this concern. The focus of this thesis is on the implementation of structural batteries into the design of a quadcopter and the use of a graphical user interface to aid in the design. To determine the relationship between quadcopter attributes, such as the length and thickness of the quadcopter arms, and performance (distance or time the quadcopter can fly), a design tool will be

implemented. Users will be able to change different variables of the quadcopter in real time to better visualize the impact each has on the quadcopter performance. Moreover, in order to create this design tool, the science behind structural batteries, dynamics of quadcopter flight, and graphical user interface assessments must be further investigated.

1.2 Quadcopter Background

Leonardo Da Vinci, who is recognized as the “Father of the Helicopter”, created the first designs of rotary-winged aircrafts. Now known as the Da Vinci Helix, displayed in Figure 1, the design embodied the basic concepts of modern-day helicopters. Although it is unclear whether he built a successful model, the idea that a spiral wing device that turned fast enough to lift the device into the air was unheard of at the time [2]. Unlike conventional airplanes, rotary-winged aircraft have a fundamental advantage in that lift and control are relatively independent of forward speed. Rotary aircraft do not need a runway and have much more freedom and maneuverability in the air. Despite early efforts to fly using rotary-winged devices as well as the freedom to take-off and land on virtually any flat surface, the first successful flight came from a fixed-wing aircraft [2]. The development of rotor technology paved the path for the creation of the quadcopter.

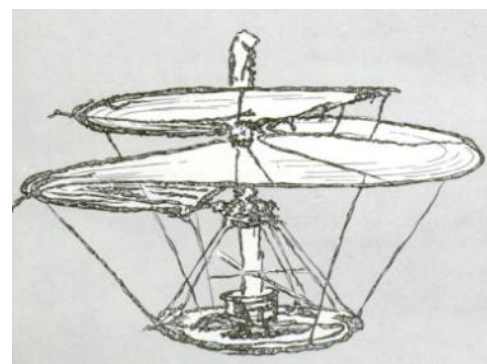


Figure 1: Da Vinci Helix [2]

Etienne Oehmichen successfully built the first quadrotor in 1922 called the Oehmichen No. 2. A single 120 horsepower engine powered the four rotors of this machine. However, due to a lack of control of individual rotors, the altitude and orientation could not be varied. To combat this issue, four additional propellers were attached to better direct the movement of the quadrotor [3]. Modern quadcopters do not

rely on additional propellers to maneuver themselves. Instead, each rotor can be manipulated to perform virtually any aerial move.

Today, quadcopters are used in many areas of industry due to their reliability, cost effectiveness, and multi-functionality. The most widely known uses are in photography and the military. More specifically, they can be seen in sports media coverage, recreational and professional filming, surveillance, and search and rescue missions. However, some lesser-developed, yet equally important, uses include agriculture and delivery systems. Farmers are increasingly making use of quadcopters to monitor and analyze large areas of land to determine the health of certain types of crops [4]. Additionally, Amazon is developing and testing a new system to deliver their products using quadcopters. Amazon's ultimate goal is to deliver a product weighing up to five pounds within 30 minutes from time of order and within a 10-mile radius from the customer [1]. As quadcopters become more accessible and reliable to the public, their use in everyday tasks will exponentially increase.



Figure 2: Amazon Prime Air Quadcopter [1]

1.3 Quadcopter Dynamics

A quadcopter consists of four equally spaced rotors arranged on a square body at the corners. According to Newton's first law of motion, for a quadcopter to hover at a fixed altitude, the vertical forces acting on it must equate to zero. Thus, the sum of the forces of all four rotors (lift) must be equal to the total mass of the quadcopter.

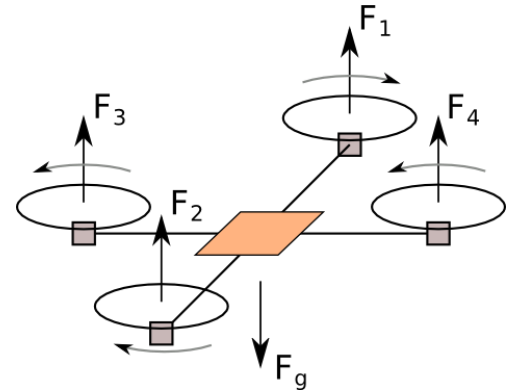


Figure 3: Quadcopter Force Model [5]

By varying the speed at which each rotor spins, the roll, pitch, and yaw of the quadcopter can be controlled. The roll angle of the quadcopter describes how the craft is tilted side to side. The pitch angle of the quadcopter describes how the craft is tilted forwards or backwards. The yaw angle of the quadcopter describes its bearing, or, in other words, rotation of the craft as it stays level to the ground [6].

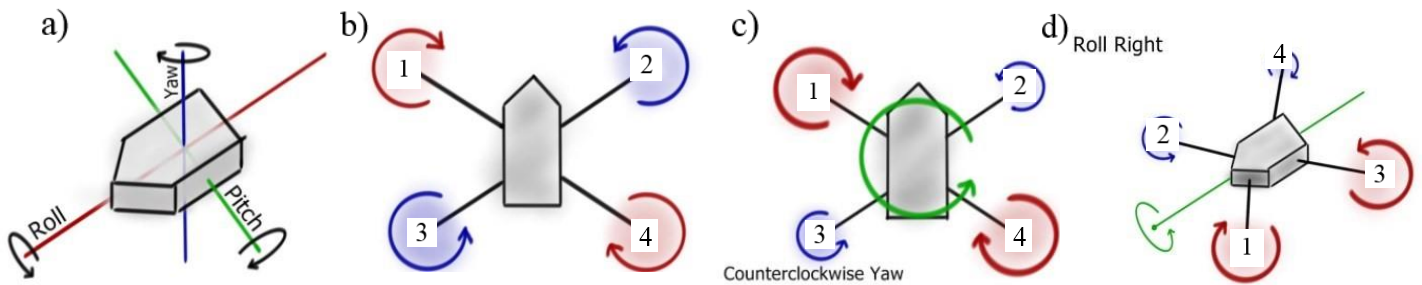


Figure 4: a) Quadcopter Orientation; b) Control of Yaw; c) Counterclockwise Yaw; d) Roll Right [6]

In order to control the yaw of the quadcopter, total angular momentum must be equal to zero, meaning the torques created by each rotor must cancel each other out. Therefore, adjacent rotors should spin in equal and opposite directions; as seen in Figure 4, rotors 1 and 4 are spinning in the clockwise direction and rotors 2 and 3 are spinning in the counterclockwise direction. If a counterclockwise yaw is desired, as in Figure 5, the spin rate of rotors 1 and 4 should be increased while that of rotors 2 and 3 is decreased [6]. This will maintain the same total thrust but an imbalance in angular momentum and the quadcopter will ultimately rotate in the counterclockwise direction to establish equilibrium. To adjust the roll of the quadcopter, the rotors on one side of the quadcopter increase or decrease so that the quadcopter

will rotate about the roll axes. For example, Figure 6 shows the quadcopter with increased thrust in rotors 1 and 3 so that it will roll right. Likewise, the same idea can be applied to adjust the pitch of the quadcopter with the only change being the front and back rotors should be manipulated [6].

Although quadcopters are extremely versatile and maneuverable, controlling them is a complex problem, especially when dealing with environmental factors. This section described the basics of quadcopter dynamics, yet there is much more that affects the flight of a quadcopter (wind, blade flapping, altitude damping, etc.) [7]. Depending on the model of the quadcopter, they need controllers and sensors, such as gyroscopes and accelerometers, to measure positioning and stabilize flight [8]. Recent research conducted by a group at Stanford University has been creating new flight control algorithms to improve maneuverability [7]. Without these algorithms, it is nearly impossible to control a quadcopter.

1.4 Overview of Structural Batteries

Typically, batteries and structures are not integrated. Electric vehicles, cell-phones, computers, and other common electronic devices separate these two key components in systems. While both energy storage technology as well as strength of materials have progressed tremendously over the past few decades, research on multifunctional materials is a relatively new topic [9]. Making use of existing technologies in innovative ways to combine non-structural and structural functions can lead to improved functionality and capabilities. This paper will focus on using structural batteries in quadcopter arms that can both support the required load while also storing electrochemical energy [10].

1.4.1 Battery Technology

There are three basic components of a battery: cathode, anode, and electrolyte [11]. In order for current to flow, a circuit must be formed. Thus, the positive side (cathode) and negative side (anode) must be connected to create a circuit. A porous separator is also placed between the anode and cathode to ensure that they do not touch each other. As the circuit is completed, chemical reactions within the battery cause a build up of electrons at the anode, which creates a voltage difference between the cathode and anode. The electrolyte keeps the electrons from travelling across the battery, so the electrons have to flow through the circuit and to the cathode. After awhile, the electrochemical processes alter the chemicals in the cathode and anode, slowly depleting the supplied electrons. Therefore, batteries have a limit to the amount of power they can supply, leading to the creation of rechargeable batteries. Rechargeable batteries charge by simply reversing the direction of current using a separate power source until the anode and cathode are restored. A simple schematic of a battery connected in a circuit is shown in Figure 8.

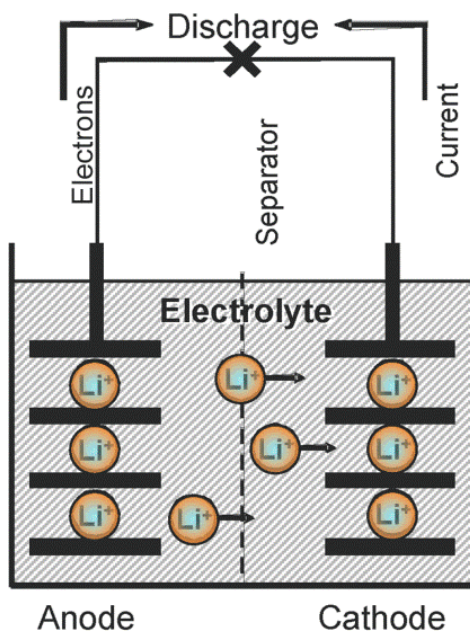


Figure 5: Schematic of a Battery

1.4.2 Structural Batteries

Multifunctional structural batteries can take on a variety of different forms. Structural batteries need the basic components of a battery (anode, cathode, electrolyte) while also being oriented in a way that supports the structural load. Much research has been conducted using various orientations to improve structural batteries. For example, [12] worked on integrating high-energy lithium-ion (polymer) battery cells into fiber-reinforced polymer composite materials for use in large-scale marine systems. This unique research had to take into account not only energy storage and structural load concerns, but also galvanic corrosion, buoyancy, and battery safety concerns as well. [13] encapsulated gel polymer lithium ion cells into a foam core sandwich structure for use in satellite devices. The primary concern for these structural batteries was to survive the extreme vibrations from the spacecraft launch. Similarly, [14] worked on creating a structural battery for spacecraft structures, but focused more on mass savings. This structural battery placed blended normal lithium-ion active materials with polymeric material into a sandwich panel core to eliminate the redundant box, which previously supported the structural load. [15] proposed a structural battery design that made use of nanofiber reinforced polymer composite structure, which achieved a modulus of 3.1 GPa and an energy density of 35 Wh/kg. Solid-state designs such as this nanofiber reinforced structural battery offer extremely high mechanical strength, which can contribute to improved safety, but they simply do not provide enough energy density for other applications such as transportation. Although these research projects show the variety of structural battery orientations, our structural batteries will take the form of beam composites, due to the vast amount of research on beams and sandwich structures and their simplicity. The structural battery modeled in the design tool is based off the structural battery developed in [10] and is summarized here.

The specific structural battery that is considered here contains copper foil for the anodes and aluminum foil for the cathodes. These electrodes are electrically isolated from each other by a microporous polymer membrane, otherwise known as a separator. Further, for proper charging and discharging, an electrically insulating, ionically conductive, organic liquid electrolyte is needed to

saturate the anode, cathode, and separator materials and allow for the exchange of Li ions through the separator. In order to have an effective structural battery, there must be a proper seal to contain the battery material. A hollow beam structure creates a perfectly closed system, while also providing the necessary structural support.

Hollow structural beams are an excellent match for structural batteries due not only to their inner void, but also their inherent flexural, compression, and torsional properties compared to their weight [16]. By surrounding a core of battery material with a metal face skin, a new multifunctional structure is achieved. While metal face skins provide the majority of the resistance to bending moments and shear forces, the transversely stacked copper current collectors augment the shear rigidity of the beam slightly. This concept was proved by [10], where a similar beam structure with aluminum C-channels and face skins, as shown in Figure 9, was mechanically and electrochemically tested.

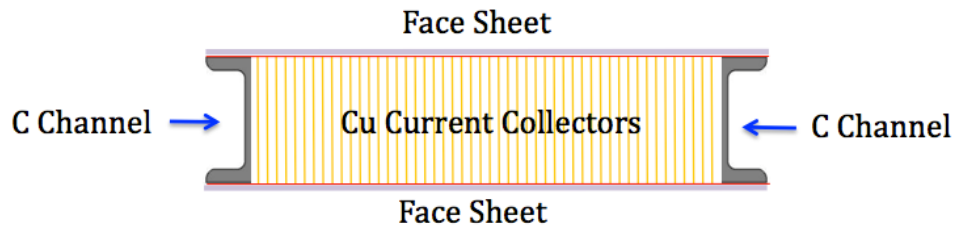


Figure 6: Tested Structural Battery with C-Channels [10]

The core battery material can be stacked in two different ways as shown in Figure 10: transversely and flat-wise [10]. In typical beam applications, the face sheets are designed to support the bending moment, while the core material is designed to carry through-thickness compression and shear loads. In the flat-wise stack orientation, each layer of the electrodes is treated as its own separate beam. Since the thickness of each layer is incredibly small (9-15 μm), the moment of inertia of each layer is also small, making the stress on the beam very large. Therefore, the flat-wise stack of battery material is not a viable option. On the contrary, the transversely stacked orientation promotes the composite behavior of the electrodes through the depth of the beam. More specifics on the core battery material and face skins will be discussed in the following chapter.

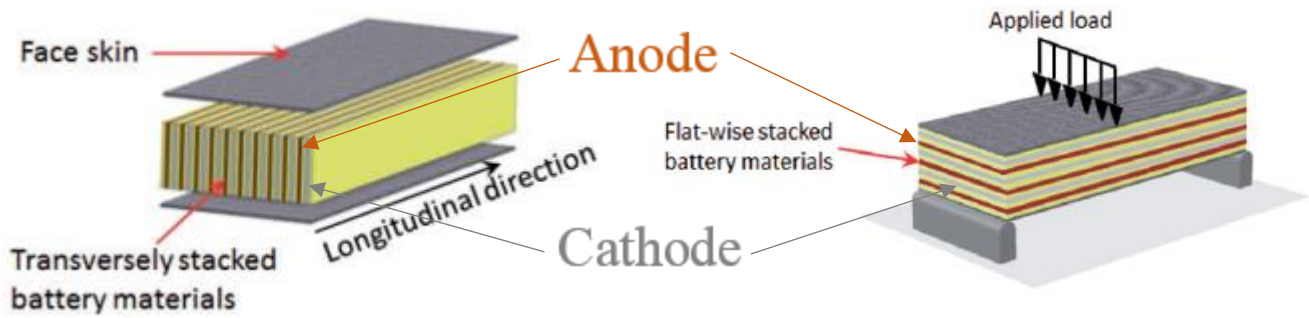


Figure 7: a) Transversely Stacked Orientation; b) Flat-wise Orientation [10]

A three-point bend test was conducted by [10] to test the flexural rigidity and the through-thickness shear rigidity. It was found that the Cu current collectors contributed to 3-7% of the flexural rigidity, whereas they contributed 16-31% of the through-thickness shear rigidity. The range of values is due to differences in thickness of the copper foils within the beams that were tested. As for the electrochemical testing, the energy density of the structural batteries (223 Wh/L) was found to be comparable to current Li-ion batteries, with the exception of a few minor design flaws that could be improved upon further testing. Thus, the mechanical tests did not adversely affect the electrochemical performance of the structural battery.

Once the mechanical and electrochemical properties of the structural batteries were determined, a model of a Tesla was created using this structural battery technology [17]. The ultimate goal of this study was to see if implementing structural batteries could extend the range of the current Tesla design while keeping the structural integrity of the frame constant. The Tesla was found to have decreased 330 kg by redesigning the Tesla's chassis with structural batteries. However, additional mass can be reduced from the Tesla design due to the vehicle mass compounding effect. Since heavier vehicles require larger and heavier wheels, brakes, suspensions, structures, and motor to maintain the same level of performance and function as its smaller counterpart, a reduction in mass leads to a reduction in all the other parts of the car. Taking this compounding effect into consideration, an additional 20 kg was saved in the redesign.

Although this technology can be further improved, the concept of multifunctional beams used as a means for both energy storage and a load-bearing structure was successfully demonstrated.

1.5 Impact of Graphical User Interfaces

A graphical user interface (GUI) is the part of a computer program that the user interacts with. Typically, a user will communicate and input information into a GUI through the keyboard, mouse, trackpad, touchscreen, or voice [18]. The GUI will then use the given input and run software in the background to provide feedback to the user. While well-designed GUIs may go unnoticed in technical programs, they play an integral role in efficiency and can save companies time and money [18].

The impact GUIs can have on performance of a task was investigated in [18]. It is reported that if a specific task required 4.8 million screens to be processed every year and it took only one second to process each screen, then 0.7 person-years would be required to complete the task in a given year. However, if the time to process each screen increased to five seconds, then the same task would require 3.6 person-years. Even though the extra four seconds per process may seem small, the time builds rapidly when thousands or millions of tasks must be completed. Another study by Cope and Uliano found that the redesign of just one graphical window would save a company around \$20,000 in its first year of operation. As technology is becoming more readily available, attention to GUIs is becoming increasingly important.

Companies such as Chrysler, Raytheon, and Boeing have been taking advantage of visualization software to improve product design and development for many years [19-22]. For example, Raytheon restructured their computer-aided design software in 1997, which reduced cycle time and eliminated parts for rework, to reduce their manufacturing costs by 30% [21]. On the other hand, Boeing competed with computing firms for programmers and developers that knew little about aerospace or manufacturing [22].

Boeing understood the importance of the people that create the software to make designing parts and equipment quicker and easier to use.

Recent technological advances, such as virtual reality (VR) and haptics, have added a new dimension to GUIs. [23] discusses the variety of benefits that VR/AR bring from an industry standpoint. VR will allow companies to design virtual prototypes, enabling engineers to analyze the shape, form, and functional behaviors in an interactive environment. Engineers will be able to more clearly understand the complexities of a design and the efficiency of the interaction between the human and computer will be improved. This will in turn improve communication in product design and production development, which could lead to a reduction in errors, number of prototypes developed, time, and money. For example, the Heinz Nixdorf Institut conducted a study on how VR can affect the product design process [24]. In this study, engineers created a mechatronic system in 3D using a set of intuitive hand gestures, as shown in Figure 9, as well as in 2D without any VR effects.

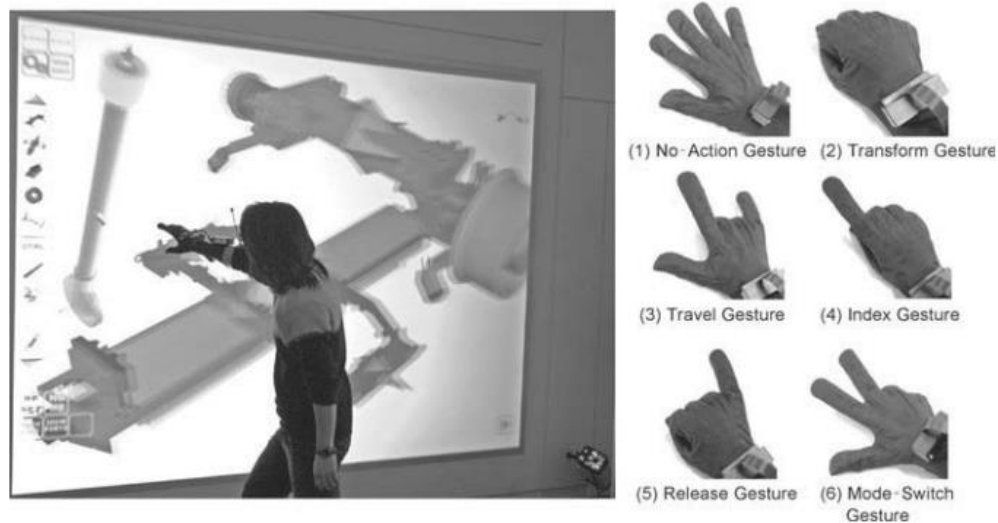


Figure 8: Composing a Virtual Mechatronic Prototype via Intuitive Gestures [24]

It was observed that engineers who used the 3D interactive model were able to understand the behavior of the mechatronic system at an earlier stage in the development process compared to the engineers who used the 2D system. While these VR systems provide users with a better understanding of the system as a

whole, haptics can assist users in using a GUI more accurately. Haptics technology brings a sense of touch to the user's experience. In [25], users used haptics to select vertices, edges, or faces of CAD models in certain sequences. Users that used the haptic feedback system completed the task 12% faster and rated the feedback as more comfortable compared to the system that offered no feedback. As costs for VR software and equipment, haptic technology, and other similar systems continue to fall, interactive GUIs will become an integral part of not only product design, but also everyday life [23].

1.6 Research Objectives

The overall objectives of this research are to create a design tool that includes a model of the maximum distance and time a quadcopter can fly, and to use this tool to better understand what factors influence people's ability to optimize designs using GUIs. The objective is achieved through completion of the following research tasks: derivation of necessary dynamic/aerodynamic/electrochemical formulas for the model, organizing the GUI into a design optimization, collecting experimental data from users, and interpreting the data. This research may eventually help extend the application of multifunctional structures and offer insight on more efficient GUI designs, which could subsequently be used to improve future quadcopter-related research designs and experiments.

Chapter 2

Description of Design Tool Exercise and Software

The design tool is a GUI that will allow us to collect information from a user quickly, while also making it simple for a user to create various quadcopter designs. It will provide us with the necessary data to determine any statistically significant correlations between a user's background knowledge and previous experiences with their performance on the optimization task. The derivations and inputs that go into the design tool are described in more detail in this chapter. Additionally, the experimental set-up and methods of data analysis are also discussed.

2.1 Derivations

The quadcopter being modeled in the design tool is based off the design of the structural batteries created by [10]. The battery core uses double-coated aluminum foils as the cathode, double-coated copper foils as the anode, and Celgard 2320 as the separator. Surrounding the battery core are aluminum 2024 alloy sheets to provide structural support for the quadcopter. The propellers are assumed to be 2-blade and made out of carbon fiber.

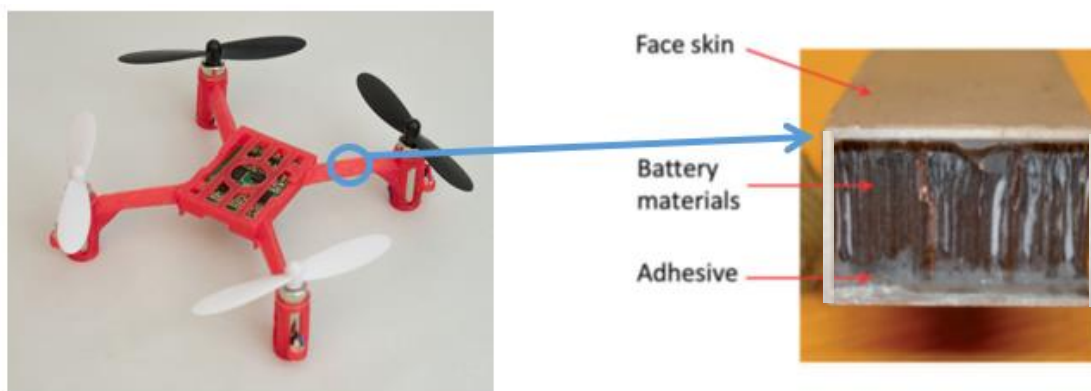


Figure 9: Structural Battery Implemented Into a Quadcopter [10]

As previously mentioned, the user inputs the arm length, arm thickness, rotor radius, mass of the package, and average velocity of the quadcopter. The first thing that is calculated is the energy capacity of the quadcopter. Assuming the length and thickness of the arms are completely battery material, multiplying the length by the thickness squared gives the volume of the battery material for each arm. Taking this value with the appropriate units and multiplying it by the energy density, 223 Wh/L (obtained from experimental results of similar structural batteries from [10]), gives the total energy of the quadcopter.

$$V_{battery} = lt^2$$

$$E = 4V_{battery}U$$

where $V_{battery}$ is the volume of battery material, l is the length of the quadcopter arm, t is the thickness of the quadcopter arm, E is the energy capacity of the quadcopter, U is the energy density of battery material, and the four represents the amount of arms in the quadcopter. Standard metrics for all units are used.

Next, the mass of the quadcopter must be considered. The mass of the battery material, faceskins, propellers, and package being carried all contribute to the total mass of the quadcopter. To calculate the mass of the battery material, the following information on the anode, cathode, and separator is provided and based on the materials used to make the structural batteries in [10]:

	Anode (Copper)	Cathode (Aluminum)	Separator (Celgard 2320)
Metallic Foil Thickness (μm)	9	15	-
Double-Sided Coating Thickness (μm)	146	160	-
Total Thickness (μm)	155	175	40 (2 Layers)
Density of Metal (kg/m^3)	2800	8900	1100
Density of Coating (kg/m^3)	2972	1631	-
E (GPa)	70	117	0

Table 1: Battery Material Properties [10]

Adding the thicknesses of these three components provides the thickness (0.00037m) of one unit of battery material. Dividing the inputted thickness of the arm by the thickness of one battery unit gives the total number of battery units. Once this is calculated, the total number of battery units is multiplied by the thickness and density of the metal and coating, respectively, and summed. Thus, the mass of battery material is now known.

$$N = t/t_{unit}$$

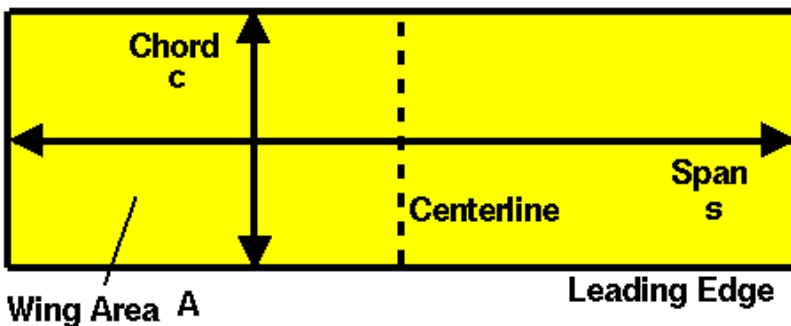
$$m_{cathode} = (Nt)[t_{Al}\rho_{Al} + t_{Al-coating}\rho_{Al-coating}]$$

$$m_{anode} = (Nt)[t_{Cu}\rho_{Cu} + t_{Cu-coating}\rho_{Cu-coating}]$$

$$m_{battery} = m_{cathode} + m_{anode} + m_{separator}$$

where N represents the total number of battery units, t_{unit} is the thickness of a single battery unit, m is the respective masses, and ρ is the respective densities. Standard metrics for all units are used.

Further, the mass of the propellers can be calculated using a few assumptions. First, the aspect ratio, or ratio between the span of the propeller to the chord, was found to be optimized at about 7:1 [26]. Designers of model propellers experimentally determined that aspect ratios around these values maximized lift and minimized drag. Additionally, according to [27], low speed aircrafts with a high lift requirement typically have a thickness-to-chord ratio of 15%-18%; therefore, the average thickness-to-chord ratio is assumed to be 15% in the design tool. Figures 15 and 16 show the relationship between chord, span, and thickness.



Aspect Ratio = AR

$$AR = \frac{s^2}{A}$$

$$AR = \frac{s}{c} \quad \text{for rectangle}$$

Figure 10: Approximation of Propeller Aspect Ratio [28]

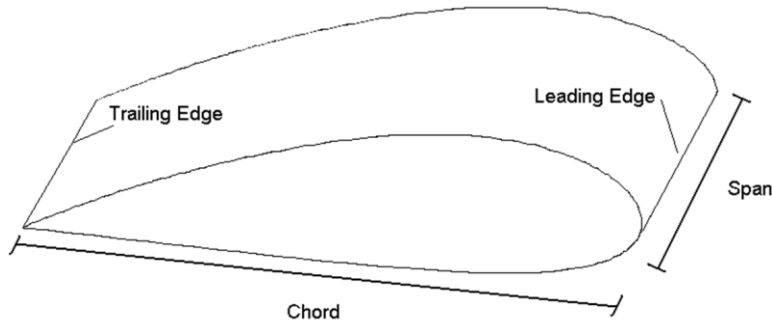


Figure 11: Cross Sectional Segment of Propeller Blade [29]

Once the ratios between the span, chord, and propeller thickness are set, the volume of material needed in the propellers can be calculated. Multiplying the volume of material by carbon fiber's density (1.55g/cm^3) will give the mass of the propellers [30].

$$c = r/AR$$

$$t_{propeller} = cTCR$$

$$m_{propeller} = 8rc t_{propeller} \rho_{propeller}$$

where c represents the chord length, r represents the radius of the propeller, AR represents the aspect ratio (7), TCR represents the thickness-to-chord ratio (0.15), and the eight represents the number of propeller blades on a quadcopter (four rotors multiplied by two blades). Standard metrics for all units are used.

Finally, the thickness of the face skins must be considered in order to determine the mass of the face skins, and ultimately the total mass of the quadcopter. Since the face skins of the structural batteries were determined to contribute to the majority of the bending stiffness in [10], it is assumed that the face skins support all stress. Each arm is treated as a cantilever beam with a distributed load for the mass of battery material and face skins and point load due to the mass of the package. To calculate the thickness of the face skins, the thickness is first set to an extremely small value (0.000001m) and incremented by 0.000001m until the bending stress and shear stress are within the yield strength (97 MPa) and a factor of safety of 1.5 [31,32].



BEAM TYPE	MAXIMUM SHEAR FORCE F	MAXIMUM BENDING MOMENT M
$P = q l b$  One End Fixed (Cantilever) Uniform Load Distribution	P	$\frac{Pl}{2}$
 One End Fixed (Cantilever) Load One End	P	Pl

Table 2: Beam Properties [33]

$$\sigma_{max} = \frac{Pl^2}{2Z} + \frac{Pl}{Z}$$

$$\tau_{max} = \frac{2PQ}{Zt}$$

where σ_{max} represents the maximum bending stress on the beam, τ_{max} represents the maximum shear stress on the beam, P_1 represents the uniformly distributed load, P_2 represents the point load, Z represents the section modulus, and Q represents the first moment of area of the beam. Standard metrics for all units are used.

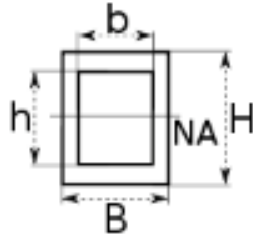


Figure 12: Cross Section of Face Skin

$$I = \frac{BH^3 - bh^3}{12}$$

$$Z = \frac{2I}{b} = \frac{BH^2}{6} - \frac{bh^3}{6H}$$

$$Q = \sum y_i A_i$$

where I represents the moment of inertia of the beam, B represents the outer width, b represents the inner width, H represents the outer height, h represents the inner height, y_i represents the perpendicular distance from the neutral axis (NA) to a given element, and A_i represents the area of a given element. The beam being analyzed in our design tool is square; therefore, B and H will be equal as well as b and h . Standard metrics for all units are used.

As the user changes the dimensions of the quadcopter arm, the thickness of the face skins continuously updates to maintain a maximum stress within the yield strength and a factor of safety. With the mass of the package given by the user, the total mass of the quadcopter can now be calculated.

$$m_{total} = m_{battery} + m_{propellers} + m_{face\ skins} + m_{package}$$

In order to calculate the power required for the flight of the quadcopter, we must assume each rotor acts as an actuator disc in hovering flight. Although the takeoff of the quadcopter does require more power than that of hovering, due to the need for greater rotor speed, the acceleration period is much shorter than the time period of hover; therefore, the energy consumed during the acceleration period is assumed to be small compared to that of the whole flight [34].

For hovering flight, the thrust from the rotors must be equal to the weight of the helicopter and the speed of the stream far above the disc is assumed to be zero [35]. Figure 16 provides schematic modeling each rotor as an actuator disc. Figure 19 provides a free body diagram of the quadcopter showing the forces due to each rotor and the weight of the quadcopter.

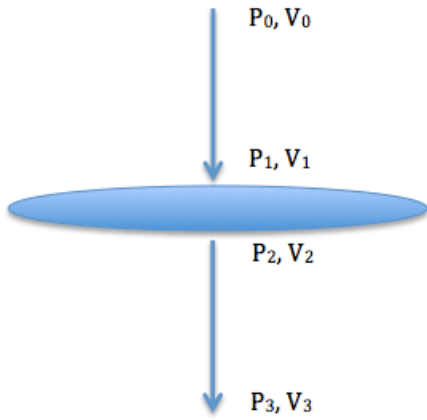


Figure 13: Simplification of Air Through a Rotor [35]

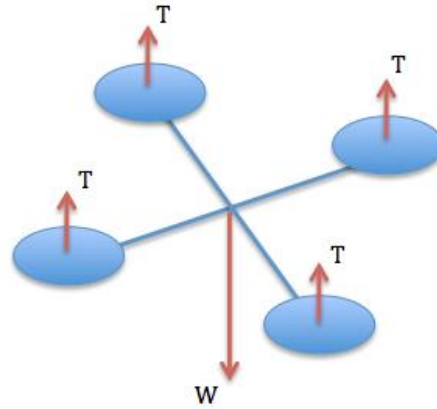


Figure 14: Quadcopter Free Body Diagram [35]

where P represents the pressure at each respective point, V represents the velocity of the air at each respective point, T represents the thrust of each rotor, and W represents the weight of the quadcopter. Looking at a single rotor with area A and air density ρ , normal notation of momentum theory can be applied as well as general momentum theory [35]:

$$\begin{aligned}
 W &= \rho A V_2 (V_3 - V_0) = \rho A V_2 V_3 \\
 V_2 &= \frac{1}{2} (V_0 + V_3) = \frac{1}{2} V_3 \rightarrow V_3 = 2V_2 \\
 W &= \rho A V_2^2 \rightarrow V_2 = \sqrt{W/2\rho A}
 \end{aligned}$$

The power supplied is equal to the rate of increase of kinetic energy of the air [35]:

$$P = \frac{1}{2} \rho A V_2 (V_3^2 - V_0^2) = \frac{1}{2} \rho V_2 V_3^2 A = 2\rho A V_2^3$$

Substituting in W leads to [35]:

$$P = 2\rho A \left(\frac{W}{2\rho A}\right)^{3/2} = \sqrt{\frac{W^3}{2\rho A}}$$

Since each rotor contributes to one-fourth of the weight of the quadcopter, the power required by each rotor and total power are [35]:

$$P_{rotor} = \sqrt{\frac{(W/4)^3}{2\rho A}} \rightarrow P_{total} = 4 \sqrt{\frac{(W/4)^3}{2\rho A}}$$

Considering the effects of air drag where A_s is the surface area of the quadcopter, C_D is the drag coefficient, and v is the average velocity of the quadcopter:

$$P_{total} = 4 \sqrt{\frac{(W/4)^3}{2\rho A}} + \frac{1}{2} \rho C_D A_s v^2$$

Using the user's input, we have all the necessary information to calculate the power required for the quadcopter to fly and can further calculate the duration of flight and range of the quadcopter:

$$\begin{aligned}
 T &= \frac{E}{P_{total}} \\
 D &= \frac{Tv}{2}
 \end{aligned}$$

where T represents the total flight duration, D represents the range of flight, and the two is necessary to change the total distance the quadcopter can travel into the range of the quadcopter (flying to a destination and back to headquarters).

Lastly, the topology optimization lets the user visualize the optimal structure based on a given domain (x,y,z) , volume fraction of material, penalization power, and filter size. The program used in the design tool is taken from [36], a compact Matlab implementation of a topology optimization code for compliance minimization of statically loaded structures. Once an initial problem is determined, a structure is discretized using the inputted domain and filter size. The domain is divided by the filter size to set up the number of elements in the structure. Each element is a cube consisting of eight nodes with three degrees of freedom each. The amount of material the program can work with is determined by the volume fraction. For example, a volume fraction of 100% would simply be a block the size of the domain. When the initial structure is loaded, the loading conditions are applied and the program uses a finite element method to find the material density distribution that minimizes the sum of the structure's deformation. Finer resolutions of the structure can be made by increasing the penalization power. The relative element densities (a number between 0 and 1) are raised to the penalization power, which penalizes the areas of intermediate densities more severely, turning them into areas of void. After the programs runs through multiple iterations, a minimum compliance for the entire structure is found and we are left with the stiffest, least weight structure. In this particular example, the constraints are the four rotor points with a force representing the weight of the package.

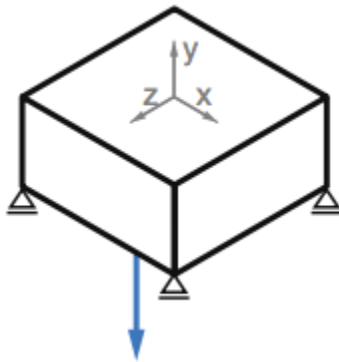
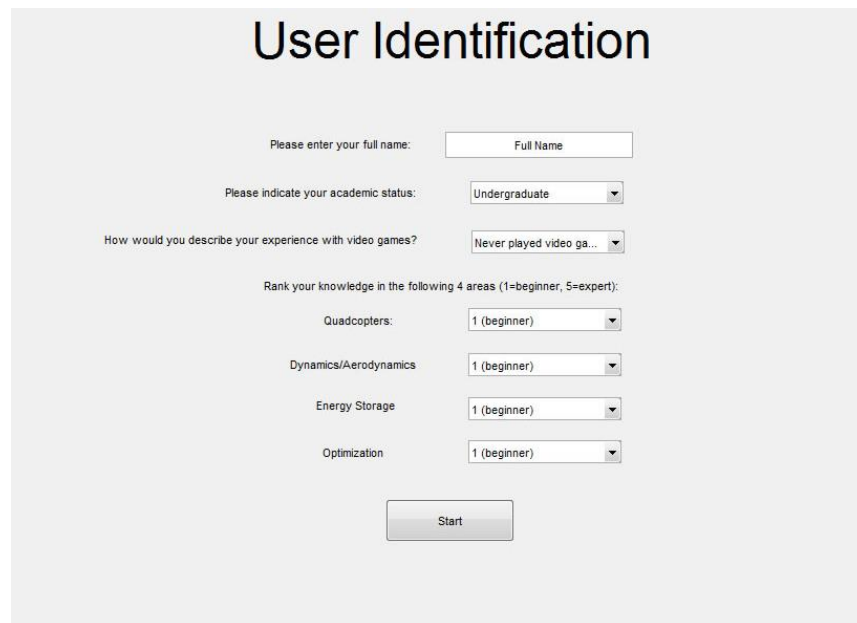


Figure 15: Domain With Constraints and Force

2.2 User Input

The design tool is divided up into four sections: *User Identification*, *Design Tool*, *Topology Optimization*, and *Feedback*. In the *User Identification* section, the user is asked to include his or her name, academic class, experience with videogames, and knowledge in four technical areas (quadcopters, dynamics/aerodynamics, energy storage, and optimization). These four technical areas were chosen because they represent a fundamental topic of either quadcopters or structural batteries. If users rate themselves higher in these areas, then we may suspect them to be better equipped for the optimization task. The user can choose undergraduate, graduate, and professor for academic class; none, some, or experienced for videogame experience; and a five-point Likert scaled ranging from 1 (beginner) to 5 (expert) for the four technical knowledge areas. Figure 11 provides an image of what the user will see when the program is initially run.



The screenshot shows a web-based form titled "User Identification". The form contains the following fields and options:

- Please enter your full name:** A text input field labeled "Full Name".
- Please indicate your academic status:** A dropdown menu with "Undergraduate" selected.
- How would you describe your experience with video games?** A dropdown menu with "Never played video ga..." selected.
- Rank your knowledge in the following 4 areas (1=beginner, 5=expert):**
 - Quadcopters:** A dropdown menu with "1 (beginner)" selected.
 - Dynamics/Aerodynamics:** A dropdown menu with "1 (beginner)" selected.
 - Energy Storage:** A dropdown menu with "1 (beginner)" selected.
 - Optimization:** A dropdown menu with "1 (beginner)" selected.
- Start:** A button at the bottom of the form.

Figure 16: User Identification Section

Upon clicking the "Start" button, the GUI will then switch to the quadcopter optimization exercise. As can be seen in Figure 12, the user can manipulate the arm length, arm thickness, rotor radius,

mass of the package, and average velocity of the quadcopter using the sliders or textboxes. As the inputs are changed, the performance metrics (to the right of the sliders) and the image of the quadcopter (to the right of the performance metrics) will also change to match the user's input. Additionally, the graphs above the sliders provide visual perspective of how changing the different variables affects the performance of the quadcopter. Within the graphs, blue crosses correspond to a user's previous designs, while the red circle is the current design based on the values of the sliders. In addition to seeing a change in number for the range or duration of flight, as the performance metrics show, the graphs allow the user to see trends in the data and more quickly predict where the optimal solution will be. Once the user believes the current design to be at the optimal point (design where the distance the quadcopter can travel is maximized), he or she will click the "Am I Close to Optimal?" button to see how far away he or she is away from the optimal design. After this button is clicked, the "Topology Optimization" button will appear and the user can move on to the next section.

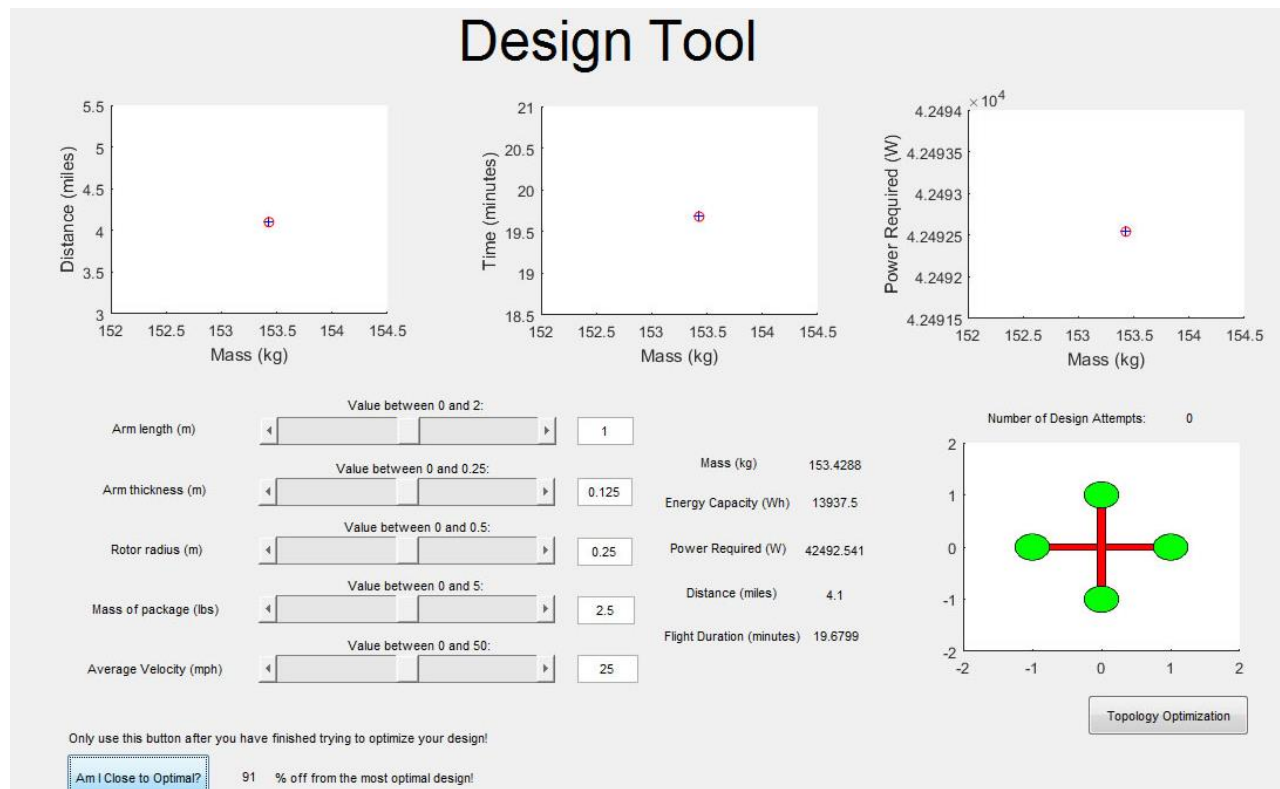


Figure 17: Design Tool Section

The *Topology Optimization* section (Figure 13) is in place to give the user an insight as to what the optimal quadcopter design would look like given a specific domain. In the case of the design tool, the domain is fixed at $(x,y,z) = (16,10,16)$. If the user were allowed to manipulate the domain, then the

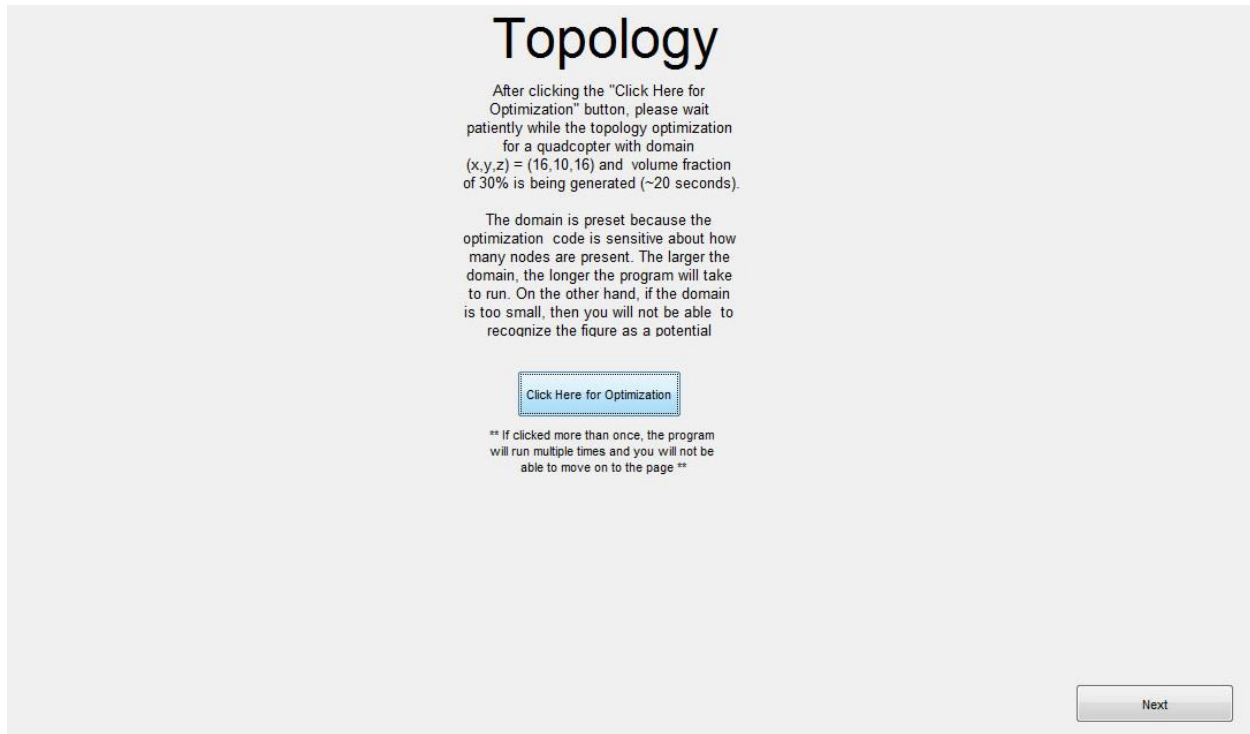


Figure 18: Topology Optimization Section

program could crash if the domain were too large or produce an unrecognizable and useless image if the domain were too small. Thus the domain is fixed in order to ease the use of the design tool for the user. The output of this program will be described in more detail in the following chapter. Once the topology optimization program is run, the “Next” button will appear and the user can move on to the next section.

Lastly, the *Feedback* section (Figure 14) allows the user to give feedback about how helpful the design tool was in visualizing the design tool as well as determining the relationships between different variables and performance. Users also have the chance to input the level of difficulty they experienced while using the design tool and any additional comments they would like to add. When complete, the user is instructed to click “Done” and email the generated Excel file back to myself for data analysis.

Thank you!

Thank you for your time and patience while completing the task!
Simply answer the final questions and click "Done".
Please email the excel file saved on to your computer to andrew.nolff@gmail.com

How helpful did you find the design tool in visualizing the design of the quadcopter? 1 (Not helpful) ▼

How helpful did you find the design tool in determining the relationships between the inputs and quadcopter performance? 1 (Not helpful) ▼

How difficult was it to optimize the quadcopter? Easy ▼

Any additional feedback?

** Please click this button to exit the program and ensure proper data storage into the Excel file **

Figure 19: Feedback Section

2.3 Experimental Setup

A design optimization task was developed to assess the impact of users' background knowledge on design efficiency and effectiveness. The following two sections will go into more detail on performance measures and the procedures used to conduct the experiment. The results and data analysis will be discussed in chapter 3.

2.3.1 Performance Measures

Three performance measurements were recorded to determine the design effectiveness and efficiency in completing the optimization exercise. The percent error between the user's quadcopter design and the known optimal design was calculated to test design effectiveness. Whereas the time taken

to optimize the quadcopter and total number of designs used to optimize the quadcopter were measured to test the design efficiency. Additionally, the natural logarithm of percent error, time of optimization, and number of designs used was taken in order to produce a more normal distribution. While these measurements were recorded based off of the users' optimization exercise, users were also required to complete a pre-test and post-test survey. Information collected from these surveys was used to test for statistically significant correlations with user performance.

2.3.2 Experimental Procedures

All test subjects that agreed to participate in this optimization exercise were sent an identical email containing all necessary information to complete the exercise. The body of the email asked users to extract the files from the zipped folder and read the instructions provided in a word document before beginning the exercise. In the instructions document, users were provided with a brief introduction to the exercise along with background information on structural battery technology and how it would be implemented. Both the instructions document and body of the email can be found in the Appendix. Users were then given specific and concise instructions on how to complete the task using the design tool and how to send the data back for analysis. No time limit was assigned to the task, but the estimated time of completion was suggested to be around 10 minutes. Pictures of the design tool itself were included to allow users to familiarize themselves with the exercise before running the program. My contact information was also provided if further assistance was needed or if the users had any questions about the design tool.

A total of 45 people performed this design optimization exercise. All of the participants were from the Pennsylvania State University and affiliated with the College of Engineering. More specifically, the participants came from Dr. Mary Frecker's Engineering Design and Optimization Group, Dr. Chris Rahn's Mechatronics Research Laboratory, Phi Sigma Rho engineering sorority, engineering students

living or studying in Atherton Hall, or other personal engineering peers. The sample population consisted of 36 undergraduate students, 8 graduate students, and 1 faculty member. Figure 21 shows an undergraduate student working through the design optimization task in the Atherton Hall Computer Lab.

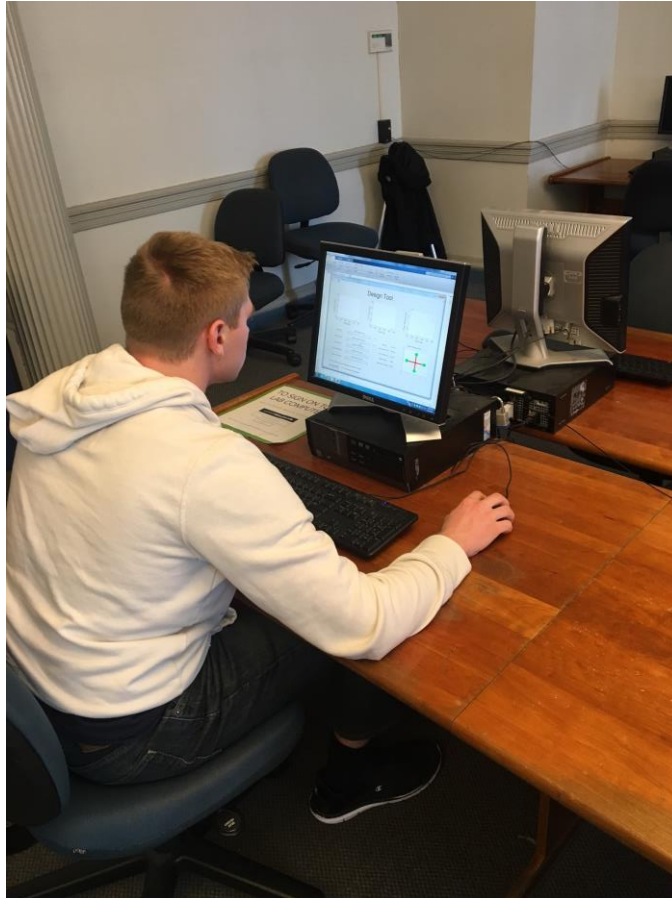


Figure 20: Undergraduate Performing the Optimization Task

2.4 Chapter Summary

In this chapter we walked through the specific features of the quadcopter modeled along with the equations used to turn user input into the performance metrics. Screenshots of various stages of the design tool were also provided to see what users experienced throughout the entire exercise. Then the experimental set up, specific information recorded by the design tool, and methods of data collection were

described. The next chapter will state the results of the experiment as well as discuss and interpret the meaning of the data.

Chapter 3

Analysis and Discussion of Experimental Results

Several hypotheses were established prior to the experimentation discussed in Chapter 2 and the data is analyzed in this chapter. The hypotheses are primarily focused on relating the pre- and post-assessment responses to the user performance. A two-sample t-test and stepwise linear regression analysis were conducted for each hypothesis as summarized in Table 3. For more detailed information on these statistical methods used to test the statistical significance of the results, refer to [37]. Additional figures on the data analysis are provided in the Appendix and will be referred to throughout this chapter.

Hypothesis	P-Value
<i>Pre-Test Questionnaire Responses:</i>	
1. Rating of Videogame Experience Affects Error	0.0405
2. Rating of Videogame Experience Affects Completion Time	0.0751
3. Rating of Quadcopters Experience Affects Error	0.3252
4. Rating of Dynamics/Aerodynamics Affects Error	0.6952
5. Rating of Energy Storage Affects Error	0.2817
6. Rating of Optimization Affects Error	0.2974
7. Rating of Optimization Affects Completion Time	0.0226
<i>Post-Test Questionnaire Responses:</i>	
8. Rating of Relationship Helpfulness Affects Error	0.0209
9. Rating of Relationship Helpfulness Affects Completion Time	0.5434
10. Rating of Visual Design Helpfulness Affects Error	0.4375
11. Rating of Visual Design Helpfulness Affects Completion Time	0.6154
12. Rating of Difficulty Affects Error	0.0127
13. Rating of Difficulty Affects Completion Time	0.4213
<i>User Performance</i>	
14. Total Number of Designs Affects Error	0.6223
15. Time of Optimization Affects Error	0.1552

Table 3: Summary of Results of Hypothesis Tests with Significant Results Highlighted

3.1 Hypotheses: Results and Discussion

In the pre-test assessment, users were asked to rate their overall experience in videogames (none, some, or experienced); class status (undergraduate, graduate, or professor); and their previous knowledge and experience in quadcopters, dynamics/aerodynamics, energy storage, and optimization using a 5-point Likert scale (1:Beginner, 5:Expert). All users rated themselves as either experienced or having some experience in videogames, therefore a two sample t-test was used to determine if this factor had any statistically significant effect on $\ln(\text{percent error})$ or $\ln(\text{optimization time})$. Out of the 45 participants in the experiment, 36 were undergraduate students, 8 were graduate students, and 1 was a professor; therefore, there were not enough data points to compare any relationships between class status and performance. Stepwise linear regression analysis was used to determine if any of the knowledge ratings had a statistically significant effect on the $\ln(\text{percent error})$. Additionally, this linear regression analysis was also performed on the user's rating of optimization to see its effect on $\ln(\text{optimization time})$.

Table 3 provides a summary of the results of the hypothesis tests. The yellow highlighted numbers represent results that were statistically significant to at least the 10% level ($p < 0.10$). As can be seen by the p-values, we found that users who rated themselves as experienced in videogames had significantly higher $\ln(\text{percent error})$ compared to those who rated themselves as having some experience ($p = 0.0405$). Although the effect of videogame experience is not significant at the 5% level on the $\ln(\text{optimization time})$, it is significant at the 10% level ($p = 0.0751$). More experience with videogames was expected to decrease both the error and the completion time of the task, but this was not the case as can be seen in Figures 33 and 34 in the Appendix. Experienced videogame players were expected to be more comfortable with graphical user interfaces and therefore be able to solve the optimization problem using the sliders more quickly and accurately than those with less videogame experience. Potential causes for this high percent error among experienced videogame users are overconfidence and carelessness. That is, those who rated themselves higher may have rushed through the task, believing it to be quite simple.

Nevertheless, the users may have not been thorough enough in their investigation of the effect each slider had on the distance the quadcopter traveled, resulting in a larger percent error.

When considering the user's knowledge ratings in the four technical areas compared to the error, none of the areas were statistically significant. This means that a user's self-rating of knowledge had little to no effect on how close their design was to the optimal design. The user's knowledge ratings were also compared to the completion time, and both energy storage and optimization ratings were statistically significant ($p = 0.0225$ and $p = 0.0226$ respectively). The stepwise linear regression analysis can be seen in Tables 5 and 6 in the Appendix. While it makes sense for users who rate themselves as better at optimization to perform the task faster, it is assumed to be a coincidence that users who rated themselves more knowledgeable in energy storage performed faster. Another note that must be made on the user's knowledge ratings is about the distribution of the ratings. As can be seen in Figure 22, all of the histograms showing the distribution of user knowledge ratings are skewed to the left. Since the majority of the users were undergraduate engineering students, they may have rated themselves as less knowledgeable because they do not consider themselves as experts in the given fields. Undergraduates may also genuinely not have the expertise in the given areas due to their inexperience, thus resulting in lower self-ratings of knowledge.

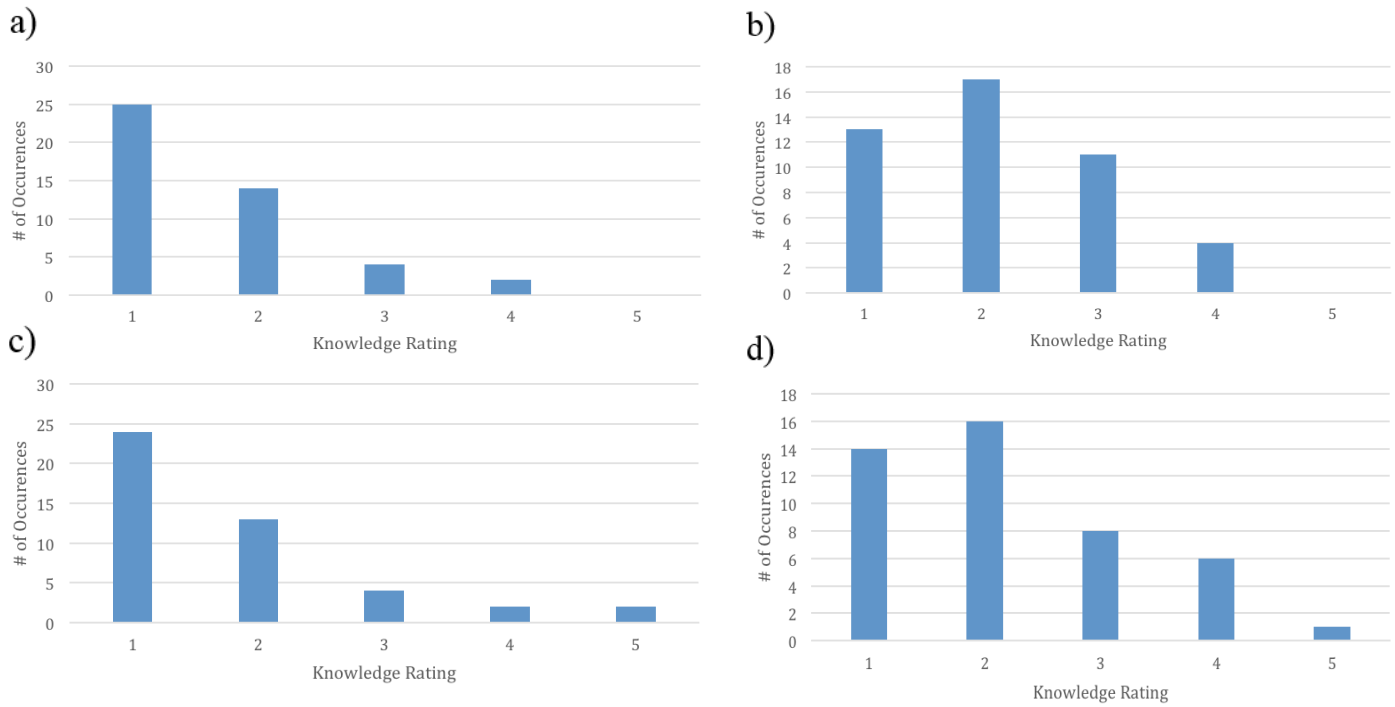


Figure 21: a) User Quadcopter Knowledge; b) User Dynamics/Aerodynamics Knowledge; c) User Energy Storage Knowledge; d) User Optimization Knowledge

The post-test assessment allowed users to provide feedback on the usability of the design tool itself. Users were asked how the design tool helped them to visualize the quadcopter design, how the design tool helped them to understand the relationships between the inputs and performance, how difficult the optimization task was, and any additional comments they had about the design tool in general. Again, a 5-point Likert scale was utilized to rate the helpfulness (1:Not Helpful, 5:Extremely Helpful) and difficulty (1-Easy, 5-Difficult). The data was analyzed using stepwise linear regression to determine if any relationships between the feedback and user performance were statistically significant.

While the effect of the ratings of relationship helpfulness on $\ln(\text{optimization time})$ was not statistically significant ($p = 0.5434$), the effect of this rating on $\ln(\text{percent error})$ was significant ($p = 0.0209$). Although the users who rated the design tool as “Extremely Helpful” were not faster or slower than those who rated the tool as “Not Helpful”, those who thought the design tool was helpful in this particular area were closer to the optimal design. Figure 30b in the Appendix clearly depicts a negative trend line, indicating that as users who rated the design tool as more helpful had lower percent error. This

result makes logical sense because those that learned how the different inputs affected the outputs were able to determine how to find a better design. Further, how well the user recognized the relationships between the variables does not necessarily mean he or she completed the task in a shorter or longer period of time, which is in agreement with our results. For instance, users who happened to identify the relationships clearly using the design tool may have only done so by taking a longer time to manipulate the variables in different ways. The general trends users should have been able to detect from the starting values using the sliders are as follows: distance increases as arm length, arm thickness, and the mass of the package decrease (up to a certain point); and distance increases as rotor radius and average velocity of the quadcopter increase. Moreover, the user's ratings of how helpful the design tool was at visualizing the design did not have any statistically significant effects on the $\ln(\text{percent error})$ ($p = 0.4375$) or $\ln(\text{optimization time})$ ($p = 0.6154$) as can be seen in Figure 32 and Table 10 in the Appendix. This result also makes sense because the graphic provides no information on whether or not the quadcopter's distance is maximized, thus users cannot rely on this graphic throughout the optimization task. The visual aid is simply meant to provide the user with a better perspective of the proportions of the quadcopter's features. Lastly, the user's rating of the difficulty of the design tool significantly affected the $\ln(\text{percent error})$ ($p = 0.0127$), but did not significantly affect the $\ln(\text{optimization time})$ ($p = 0.4213$), as shown in Figure 28 in the Appendix. It was expected that users who rated the design tool as more difficult to use would perform worse and take longer to complete the task, but the rating turned out to not have a significant effect on the completion time. This could be due to the user's motivation levels and the lack of incentive to give their full effort. Participants were simply asked to participate in the experiment with no reward beyond knowing he or she was helping out a fellow student. Therefore, if the user believed the design tool to be difficult, he or she may have spent little time on the optimization because they did not feel personally invested in the project.

Finally, the effect of the total number of designs and the time it took to complete the optimization on the $\ln(\text{percent error})$ was analyzed using the linear regression as well (Table 7 in the Appendix).

Neither of these factors was found to have a significant effect on the error ($p = 0.6223$ for total number of designs; $p = 0.1552$ for the optimization time). This lack of effect from the total number of designs was expected because the input values could be changed in a variety of ways via the sliders (arrows, sliding the slider, clicking the space next to the slider, or manually entering a value into the text box). Therefore, a value of arm length could be changed by 0.2 m in one iteration by entering the value into the text box or incrementing the slider by 0.02 m each time the arrow is clicked. Both methods would result in the same value for the arm length, but the text box method only increases the total number of designs by one, as opposed to the arrow method increasing the total number of designs by 20. Thus, the number of designs depends on the preference of the user and should not affect the user's performance. Nonetheless, it was expected that as the time of optimization increased, the error would decrease. Despite the relationship between optimization time and error not being statistically significant, the p-value is small but not statistically significant. In Figure 23, it can be observed that the two users who took the longest to optimize the design had some of the lowest percent errors.

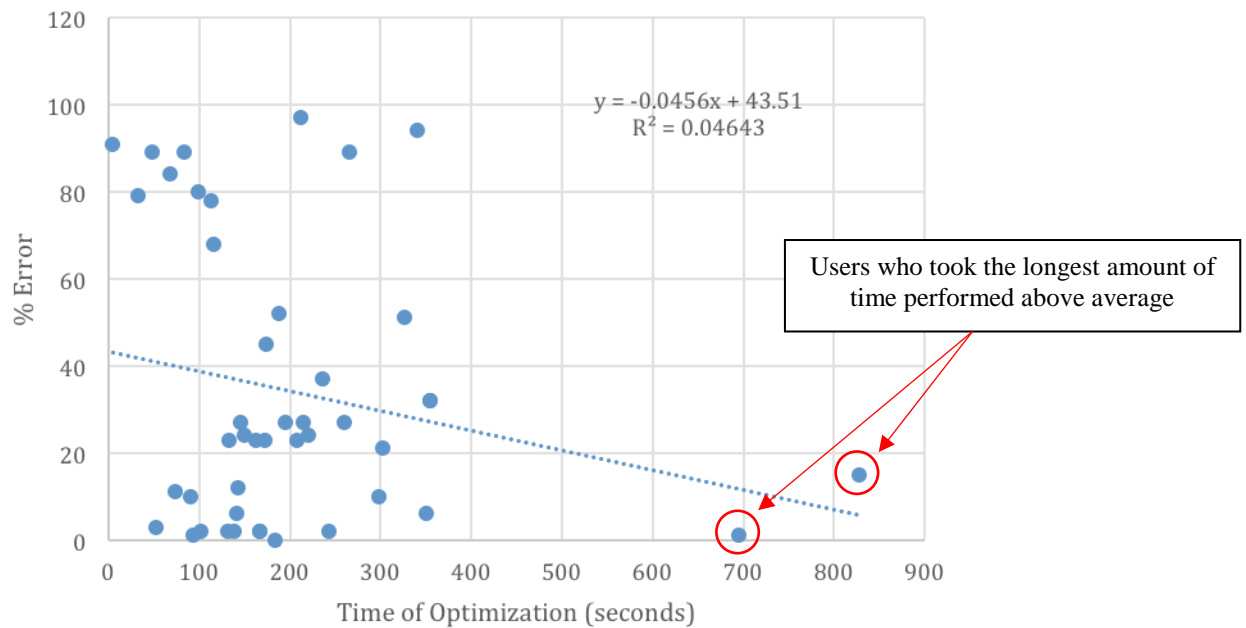


Figure 22: Percent Error vs. Time of Optimization Plot

3.2 Optimal Design

The optimal design was determined by looping through the range of each input in small increments and finding the maximum distance. The inputs and performance metrics for the optimal are as follows:

a)

Input	Value
Arm Length (m)	0.28
Arm Thickness (m)	0.02
Rotor Radius (m)	0.195
Mass of Package (kg)	0
Average Velocity (mph)	50

b)

Performance Metric	Value
Total Mass (kg)	1.35
Energy Capacity (Wh)	99.90
Power Required (W)	55.13
Flight Range (miles)	45.30
Flight Duration (mins)	108.73

Table 4: a) Input Values for Optimal Quadcopter Design; b) Performance Metrics of Optimal Quadcopter Design

Of the 45 users, 24 were able to achieve a design within 25% of the optimal design. Of these 24 users, 10 were able to get their design to within 5% of the optimal design and one user obtained the optimal design. The rest of the users' results varied up to 97% from the optimal design, which can be seen in Figure 23. This range of error is attributed to the user's motivation level. Although all the users were given the same detailed instructions that simplified the use of the design tool, not all users necessarily read the instructions thoroughly. Since there was no motivation or incentive to succeed in completing the exercise appropriately, the results could have been affected. The design tool only records the values of the inputs once the "Am I Close to Optimal?" button is first clicked; therefore, it is possible that users with relatively high percent errors (80-97%) did not read the instructions and clicked the comparison button before they attempted to fully optimize their design.

In Figure 23, it can also be seen that 11 out of the 45 users were around a 23-24% error. This fairly large number of users was expected to fall in this range when running through the potential ways users would use the design tool. All of the sliders started at the middle value of their respective range, and

depending on which variable the user changed first roughly determined the percent error. For example, if the user began with the top slider (arm length), the user should quickly recognize that decreasing the arm length increased the distance the quadcopter could travel. Although the battery material (energy capacity) of the quadcopter was being reduced, the reduced mass of the quadcopter offset this energy loss and the overall range increased. However, the arm length of the quadcopter would be unable to decrease any further once it reached the point where the rotors began to touch one another. The user might then move on to arm thickness, then mass of the package, and finally average velocity of the quadcopter to come up with their final solution. Following this method would lead to a percent error of at least 10%.

Furthermore, if the user began by changing the rotor radius input, he or she should quickly realize that the radius should be at the maximum value to maximize the distance of the quadcopter. If all the other inputs are then manipulated to further maximize the distance (e.g. decrease the arm length and thickness to reduce the mass) and the rotor radius was held constant, then the error would be about 23% off. This is due to the fact that the optimized design does not have a rotor radius at the maximum value of the rotor radius. Although the power required increases as the rotor radius decreases (area decreases), as was shown in chapter 2, the decrease in mass of the rotors due to the smaller radius offsets this increased required power, which makes the distance of the quadcopter increase. The mass of the rotors is weighted more heavily when the total mass of the quadcopter is smaller; therefore, when rotor radius was manipulated first, the area of the rotor radius was the dominant factor, but when the quadcopter is made lighter, the mass of the rotors had a greater influence.

Although users had no direct input into the *Topology Optimization* section and were only left to view the provided image, some users commented in the additional feedback response that it was interesting to see the optimal structure given a specific size design domain. The reasoning for setting the size of the design domain rather than letting the user adjust the values was to prevent the program from running for an excessive amount of time or displaying a meaningless result. For example, if the user were to enter a domain too small, then the outputted image would not resemble a quadcopter. Meanwhile, if the

user were to enter a domain too large, then the program would take an extremely long time to due to the large number of elements. Both outcomes would result in a negative experience for the user; hence, the domain was fixed to provide the user with an insight into what the optimal structure using the least amount of material would look like. Figure 24 is the optimal topology given a domain $(x,y,z) = (16,10,16)$ with four corner points fixed for the rotors and a force at the geometric center representing the weight.

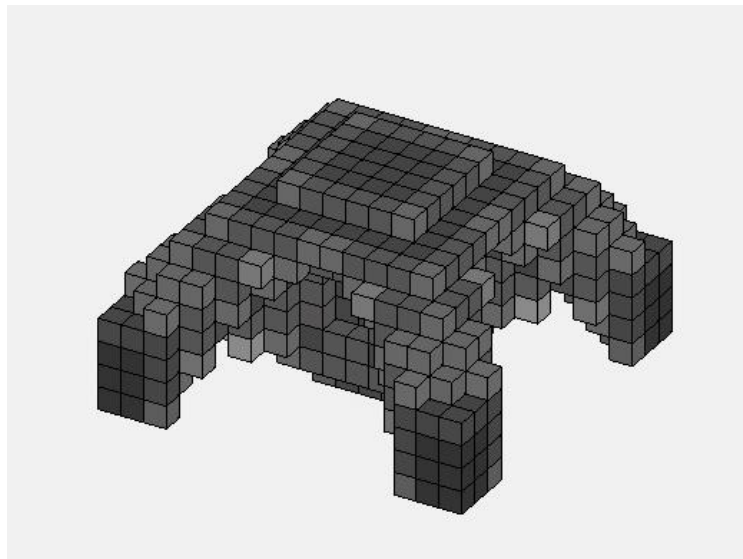


Figure 23: Topology Optimization of Quadcopter

3.3 Chapter Summary

In this chapter we analyzed the experimental results from the optimization task and determined the relationships between user inputs and optimization performance (percent error and time). Potential reasons for these outcomes were then discussed. Finally, how the optimal design was determined as well as the specific input and output values were stated along with the topology optimized design. The next chapter will summarize the work performed throughout the experiment, draw conclusions based on the discussion of the results in this chapter, and mention future work that could be performed to improve the current experiment.

Chapter 4

Discussion and Conclusions

Chapter 4 summarizes the research performed, draws conclusions based on the results from Chapter 3, and discusses future work that could be done to improve the design tool and experiment, as well as the benefits of structural battery technology.

4.1 Summary of Work

One of the goals of this work is to assess the effect of a user's background on his or her ability to perform a quadcopter optimization task. A study involving a mix of 45 undergraduate students, graduate students, and a professor was conducted to assess this relationship. For the study, a design tool was created to allow a user to manipulate the arm length, arm thickness, rotor radius, mass of package, and average velocity of a quadcopter, which implemented structural batteries in the arms as the load-bearing support and energy storage. More specifically, the user was asked to maximize the range the quadcopter can travel. The user was also asked to report on the level of difficulty and helpfulness of the design tool and these results were analyzed to determine the impact on the user's optimization ability.

Before the experiment could be conducted, a simplified model of a quadcopter using structural batteries had to be created. The dynamic, aerodynamic, energy, power, strength of material and mass equations were determined to approximate the performance of the quadcopter. Structural battery properties were adapted from [10], whereas all other formulas were taken from textbooks or handbooks [16-25]. Once the structural battery model was developed, a GUI was developed to allow a user to manipulate the various inputs of the quadcopter (mentioned above) and observe the changes in

performance. The GUI was configured in a way that users would be able to quickly and easily change the inputs of the quadcopter and visualize the output performance metrics. This was done by use of a variety of plots, sliders, and a visual representation of the quadcopter design. A topology optimization program was also integrated into the design tool to give users an idea of what the optimal structure using the least amount of material would look like.

Once this design tool was complete, a set of instructions was created and sent out to participants in the optimization exercise. All participants were affiliated with the Pennsylvania State University's College of Engineering. After the data was collected, stepwise linear regression and simple two sample t-tests were used to test for statistical significance between the user's background and optimization performance. It was found that more videogame experience significantly raises the percent error, but significantly lowers the completion time. It was also found that users who rated themselves as having more knowledge of optimization completed the optimization task significantly faster. Additionally, users that rated the design tool as more helpful in determining the relationships between inputs and quadcopter performance had significantly less error than those that rated the design tool poorly in this area. Lastly, it was found that users who rated the design tool as more difficult had significantly more error.

4.2 Conclusions

This study has provided many insights relating the impact on performance of different features of the graphical user interface and varying knowledge levels of the user. Despite none of the knowledge areas having a significant impact on a user's $\ln(\text{percent error})$ (design effectiveness), optimization and energy storage happened to significantly affect the user's $\ln(\text{optimization time})$ (design efficiency). While it makes sense for users more knowledgeable in optimization to perform the task faster, the significant effect of the energy storage knowledge rating may be a coincidence. Another interesting finding about the users' knowledge ratings was the tendency to self-rate as inexperienced. The mindset of users cannot be

fully known from the data collected, but we can infer that the lower ratings were a combination of inexperience and a high standard to be considered an expert. We also found that a user's videogame experience had a large impact on his or her performance. The correlation between videogame experience and percent error was significant at the 5% level, whereas that of optimization time was only significant at the 10% level. Users that were more experienced in videogames completed the task quicker, but their designs were farther from the optimal design. The fact that users with more videogame experience performed faster was no surprise; these users should be able to adapt more quickly to the GUI layout and therefore complete the task quicker. Nevertheless, the experienced videogame players were also expected to have a lower percent error, which is the opposite of what the results revealed. Further testing would be needed to determine the reason for this result; however, we can speculate that carelessness and overconfidence were contributing factors.

When evaluating the post-test survey responses, it was found that users who rated the design tool as helpful in determining relationships between inputs and quadcopter performance had a significantly lower percent error in their design compared to those that did not find the design tool helpful in this respect. On the other hand, the rating of the relationship helpfulness did not have a significant impact on the optimization time. These results are due to the fact that there was no incentive to complete the task to the best of one's ability. Users who learned the relationships more easily were able to design better quadcopters; however, users who did not recognize the relationship did not necessarily spend more time on the design tool because there was no motivation to do so. Moreover, users who rated the design tool as helpful in visualizing the physical design of the quadcopter did not have a significantly lower percent error or optimization time. The graphic may have been aesthetically pleasing and a confirmation for the changing variables to the user, but it did not have any effect on the user's percent error. Lastly, users who rated the design tool as difficult to use obtained higher percent errors, but this rating had no significant effect on the optimization time. Again, since there was no incentive to perform well on the optimization

task, users that believed the design tool to be difficult to use did not significantly more time on the task and performed worse.

Finally, the effect of the total number of designs and the time it took to complete the optimization on the percent error was analyzed. Neither the total number of designs nor the time it took to complete the optimization task significantly affected the percent error. Since there were multiple ways to change the values of the inputs, the number of designs may have depended upon a user's personal preference on using the sliders. A user could examine 20 designs by holding the arrow button of the slider for a few seconds, or drag the slider to the desired value in an equal amount of time and only examine one design. Further investigation would need to be performed to determine if the way a user changes the input values affects his or her error.

Aside from assessing the factors that impact user performance through a GUI, this experiment also helps demonstrate the potential for implementing structural batteries into the design of a quadcopter. Although this is a simplified model and physical testing must be conducted in order to confirm the validity of the model, the theoretical maximum range of the quadcopter is about 45 miles. The goal of the Amazon Prime Air program is to achieve a radius of 10 miles (20 miles total) in less than 30 minutes (1 hour total flight time) [1]. Our predicted range is more than double the requirement. Furthermore, these structural batteries do not have to be limited to solely quadcopters, but can be extended to cars [17], planes, trains, or other electronics that require both energy storage and structural support.

4.3 Future Work

While the current experiment helped us understand the effects of some factors on user performance using GUIs and the benefits and applications of structural batteries, there are a few modifications that could be added to improve it. The first thing would be to validate the theoretical model with a physical model. If the current model does not roughly approximate the actual data, then the model

must be reevaluated and revised until this condition is met. Further, the model could even include the cost of the current design to add an additional performance metric to the outputs.

Once the base model of the quadcopter for the design tool is validated, the sample population could be modified. Currently, the sample population includes predominantly undergraduate and graduate students associated with the Pennsylvania State University College of Engineering, but this sample could be expanded to include other universities or other areas of study to see if these additional factors contribute to a user's percent error and optimization time. Figure 22 also shows that the participants in the experiments tended to rate themselves more as beginners rather than experts. This could have been due to the inexperience of most of the participants (36 undergraduates); therefore, the sample should be expanded to include a more balanced sample of people (graduate students, professors, battery/quadcopter specialists, quadcopter hobbyists, etc.) to determine if experience plays a factor into user performance.

Next, the GUI layout could be modified to control and target specific factors that we would want to evaluate. For instance, instead of displaying three different plots all compared to mass, there could be one plot of distance and time with the point markers varying in size based on the mass of the quadcopter. This would allow a user to see three different performance metrics in one plot and would be interesting to know the effect this could have on the user's performance. Another way the GUI could be modified would be to arrange the sliders in different orders. As discussed in Chapter 2, the order in which the user manipulated the inputs to optimize the quadcopter could have affected the user's percent error. Changing the order of the sliders would allow us to better understand the thought process users go through while optimizing the design. In order to implement some of these methods, a much larger sample population would be needed in order to obtain enough data for the results to be meaningful. Lastly, the users could be grouped to input the values of the variables in a particular manner: some would manually input values into the textbox, others would use the arrows on the sliders, and the rest would drag the sliders. This would give us a better picture of users' percent error using each method.

Furthermore, the method of recruiting participants needs to be improved to ensure more focused users. The current user has no incentive to perform to the best of his or her ability; therefore, there is no guarantee that he or she did so and could have affected the results. Incentives such as a reward for completing the experiment and getting a percent error within a certain threshold might motivate participants to take the assessment seriously and read all instructions thoroughly.

Finally, structural battery technology has tremendous potential and can be used in various applications. While there is much research being performed on the energy storage side of the structural battery, our research focused on understanding what factors affect designers as they design quadcopters using this technology.

Appendix A

Data Analysis

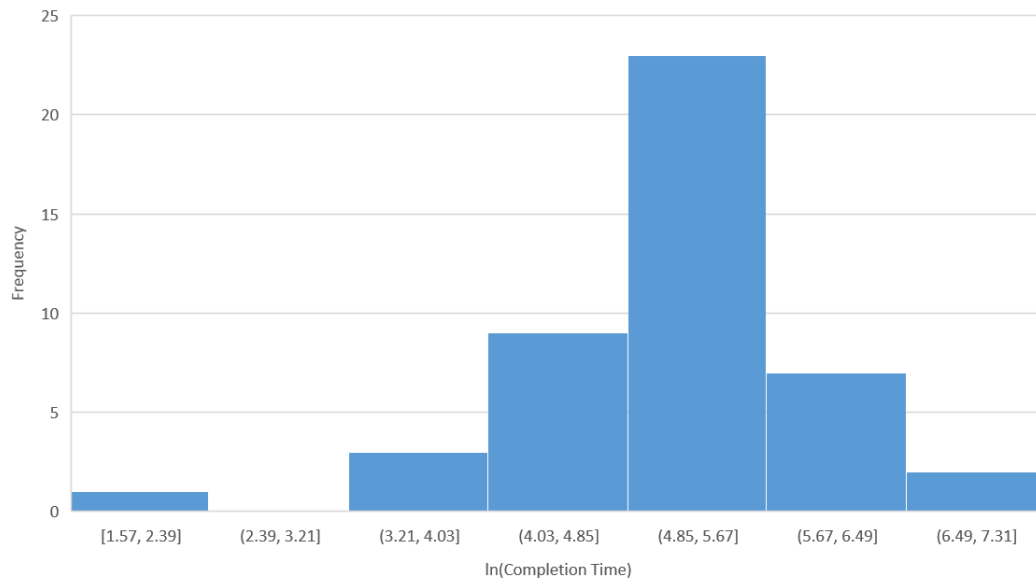


Figure 24: $\ln(\text{Completion Time})$ for All Users

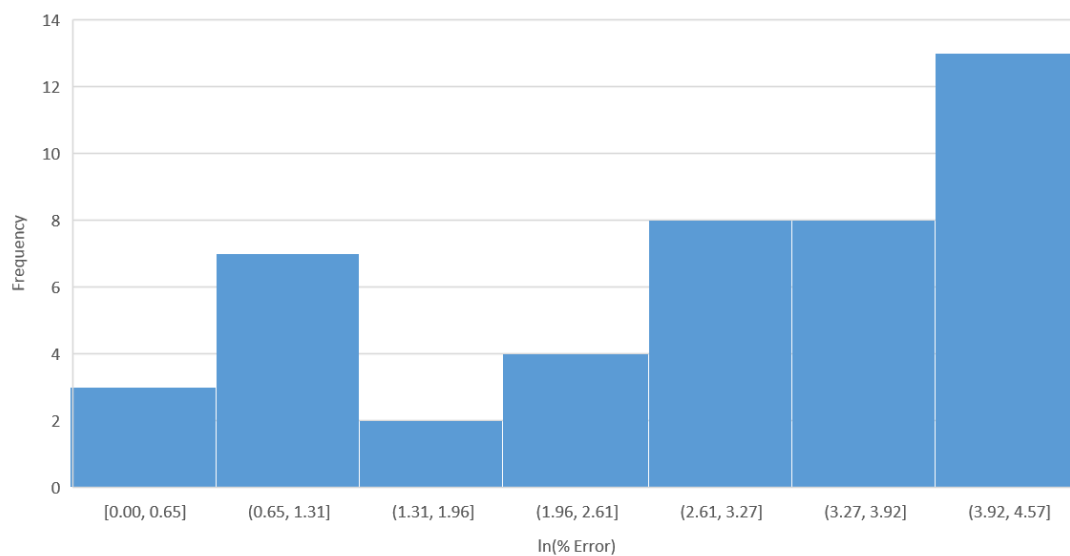


Figure 25: $\ln(\text{Percent Error})$ for All Users

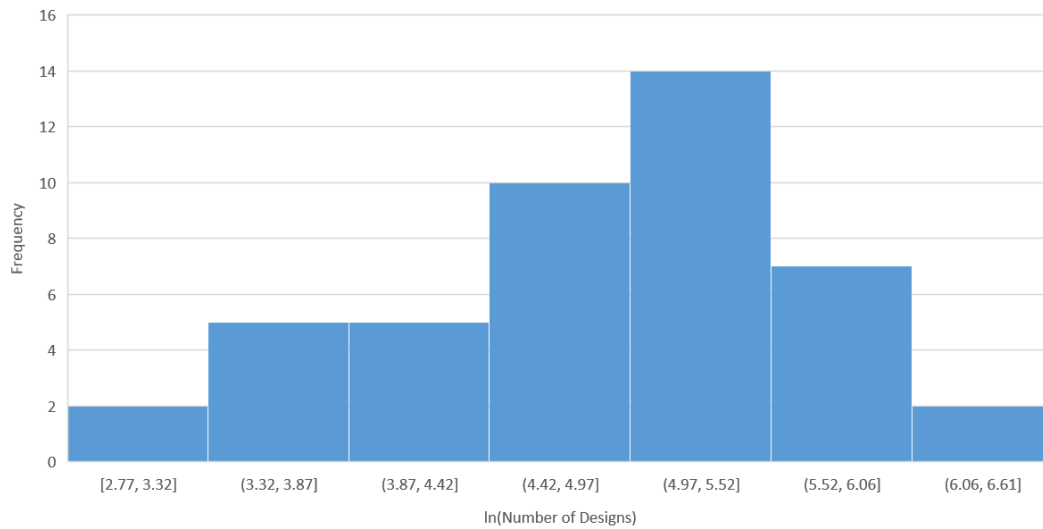


Figure 26: Number of Designs for All Users

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.297646							
R Square	0.088593							
Adjusted R Square	-0.00255							
Standard Error	1.451669							
Observations	45							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	4	8.193788	2.048447	0.972052	0.433527			
Residual	40	84.29376	2.107344					
Total	44	92.48754						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	2.227347	0.595258	3.741816	0%	1.024285	3.430409	1.024285	3.430409
Quadcopters	0.335198	0.336518	0.996079	33%	-0.34493	1.015326	-0.34493	1.015326
Dynamics/Aerodynamics	0.131569	0.33338	0.394651	70%	-0.54222	0.805355	-0.54222	0.805355
Energy Storage	0.271774	0.249068	1.091165	28%	-0.23161	0.77516	-0.23161	0.77516
Optimization	-0.32146	0.304488	-1.05573	30%	-0.93685	0.293937	-0.93685	0.293937

Table 5: Linear Regression Analysis of Knowledge Ratings on Percent Error

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.393582							
R Square	0.154907							
Adjusted R Square	0.114664							
Standard Error	143.5378							
Observations	45							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	2	158616.5	79308.24	3.849335	0.029174			
Residual	42	865330.3	20603.1					
Total	44	1023947						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	181.2281	51.40558	3.525456	0%	77.48743	284.9687	77.48743	284.9687
Energy Storage	-53.1441	22.43033	-2.3693	2%	-98.4103	-7.87784	-98.4103	-7.87784
Optimization	52.39155	22.12847	2.367608	2%	7.734482	97.04862	7.734482	97.04862

Table 6: Linear Regression Analysis of Knowledge Ratings on Optimization Time

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.07544							
R Square	0.005691							
Adjusted R Square	-0.01743							
Standard Error	32.59823							
Observations	45							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	1	261.5396	261.5396	0.246121	0.622346			
Residual	43	45693.7	1062.644					
Total	44	45955.24						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	37.42124	7.967387	4.696802	0%	21.35347	53.48901	21.35347	53.48901
Total # of designs	-0.01751	0.035295	-0.49611	62%	-0.08869	0.053669	-0.08869	0.053669

Table 7: Linear Regression Analysis of Number of Designs on Percent Error

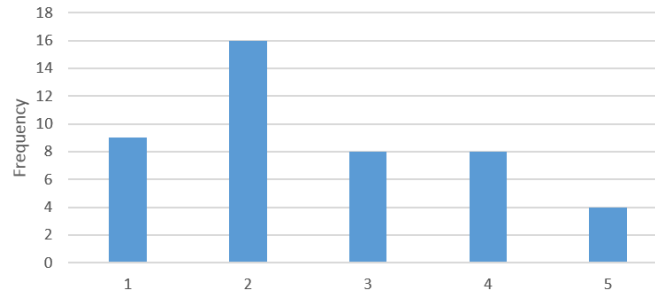
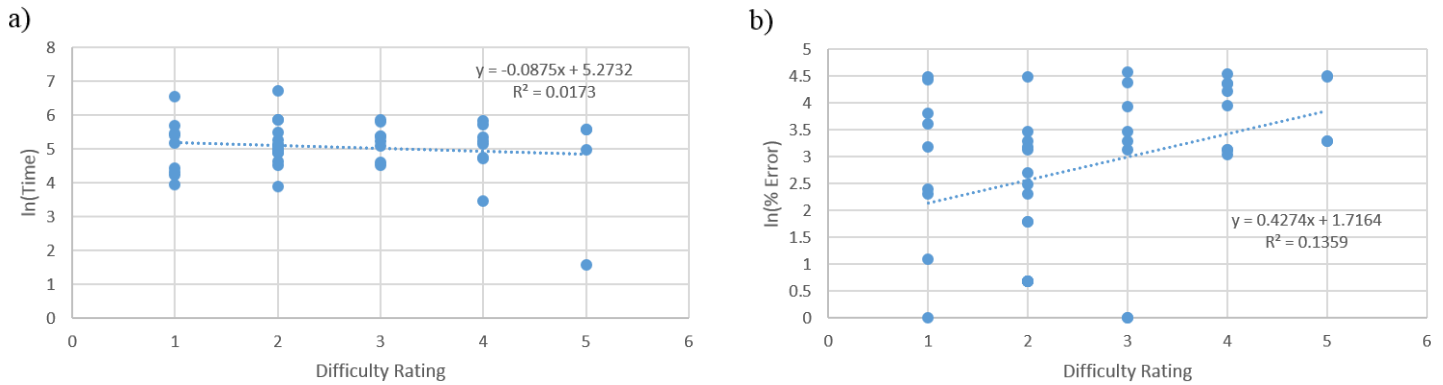


Figure 27: User's Difficulty Ratings on the Design Tool

Figure 28: a) Plot of User's Difficulty Rating vs. ln(Time) With Linear Trend Line;
b) Plot of User's Difficulty Rating vs. ln(Percent Error) With Linear Trend Line

a)

SUMMARY OUTPUT									
Regression Statistics									
Multiple R	0.131417								
R Square	0.01727								
Adjusted R Square	-0.00558								
Standard Error	0.834625								
Observations	45								
ANOVA									
	df	SS	MS	F	Significance F				
Regression	1	0.52640254	0.526403	0.755675	0.389512				
Residual	43	29.9537637	0.696599						
Total	44	30.48016624							
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%	
Intercept	5.273198	0.289697943	18.2024	0%	4.688966	5.857429	4.688966	5.857429	
Difficulty	-0.08747	0.100622998	-0.8693	39%	-0.2904	0.115454	-0.2904	0.115454	

b)

SUMMARY OUTPUT									
Regression Statistics									
Multiple R	0.368655								
R Square	0.135906								
Adjusted R Square	0.115811								
Standard Error	1.363289								
Observations	45								
ANOVA									
	df	SS	MS	F	Significance F				
Regression	1	12.56965	12.56965	6.763131	0.012707				
Residual	43	79.91789	1.858556						
Total	44	92.48754							
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%	
Intercept	1.716418	0.473197	3.627282	0%	0.762126	2.67071	0.762126	2.67071	
Difficulty	0.427432	0.164359	2.600602	1%	0.095971	0.758894	0.095971	0.758894	

Table 8: a) Linear Regression Analysis of User Difficulty Rating on Optimization Time;
b) Linear Regression Analysis of User Difficulty Rating on Percent Error

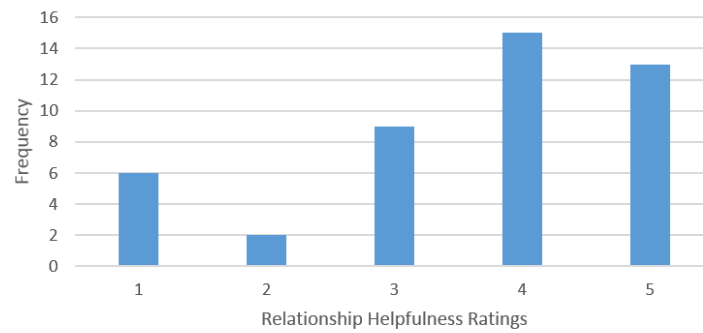


Figure 29: User's Relationship Helpfulness Rating on the Design Tool

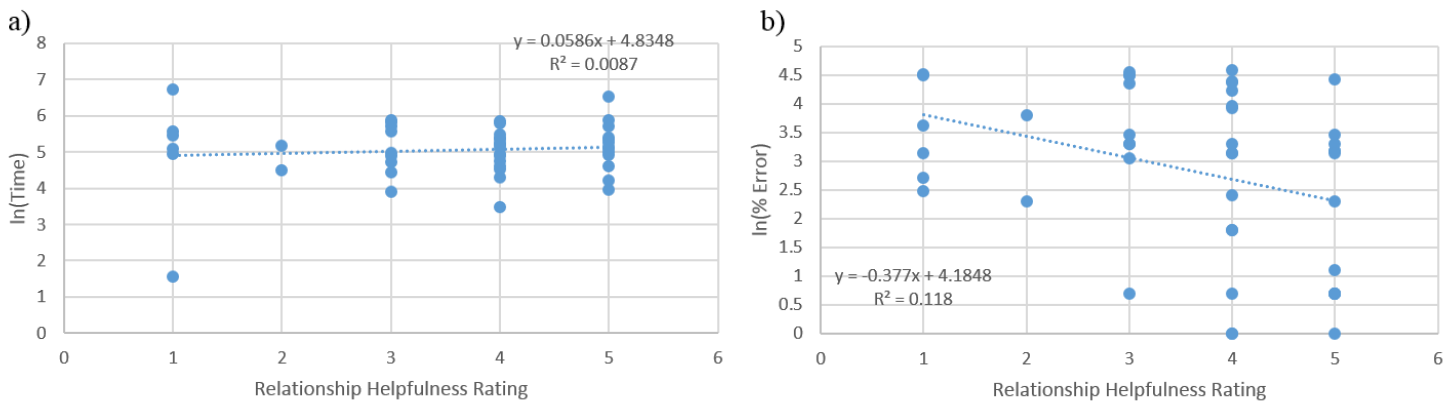


Figure 30: a) Plot of User's Relationship Helpfulness Rating vs. ln(Time) With Linear Trend Line;
 b) Plot of User's Relationship Helpfulness Rating vs. ln(Percent Error) With Linear Trend Line

a)

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.093016151							
R Square	0.008652004							
Adjusted R Square	-0.0144026							
Standard Error	0.838276911							
Observations	45							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	1	0.263715	0.263715	0.375283	0.543365			
Residual	43	30.21645	0.702708					
Total	44	30.48017						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	4.834817993	0.36633	13.19798	0%	4.0960435	5.73593	4.096043	5.73593
Relationship Helpfulness	0.058598489	0.095655	0.612604	54%	-0.134310	0.251505	-0.13431	0.251505

b)

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.343503353							
R Square	0.117994554							
Adjusted R Square	0.097482799							
Standard Error	1.377345934							
Observations	45							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	1	10.91303	10.91302658	5.752533416	0.020875			
Residual	43	81.57452	1.897081823					
Total	44	92.48754						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	4.184787882	0.601905	6.952569151	0%	2.97%	5.398646	2.97093	5.398646
Relationship Helpfulness	-0.37695716	0.157167	-2.398443957	2%	-69%	-0.06	-0.69392	-0.06

Table 9: a) Linear Regression Analysis of User Relationship Helpfulness Rating on Optimization Time;
 b) Linear Regression Analysis of User Relationship Helpfulness Rating on Percent Error

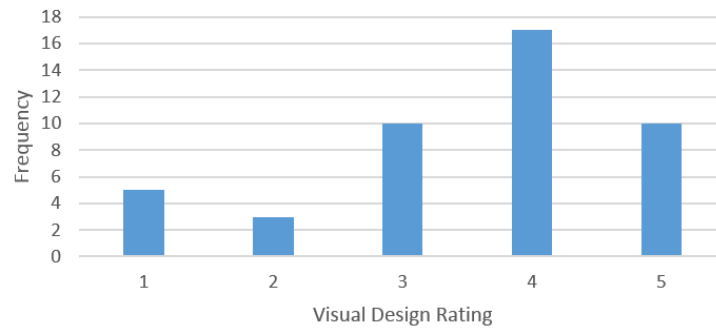


Figure 31: User's Visual Design Helpfulness Rating on the Design Tool

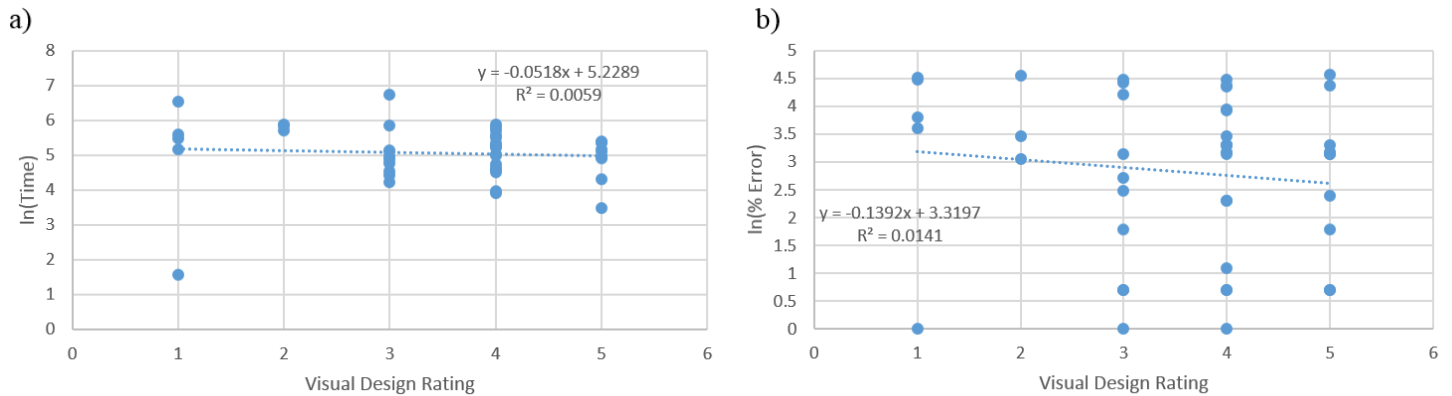


Figure 32: a) Plot of User's Visual Design Helpfulness Rating vs. ln(Time) With Linear Trend Line; b) Plot of User's Visual Design Helpfulness Rating vs. ln(Percent Error) With Linear Trend Line

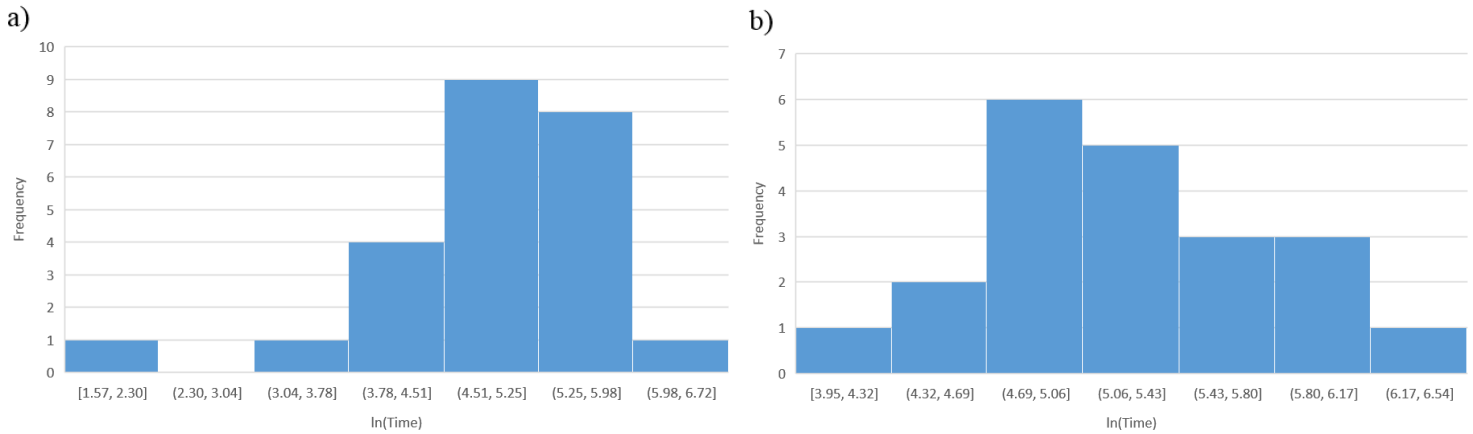
a)

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.0769438							
R Square	0.005920348							
Adjusted R Square	-0.017197783							
Standard Error	0.839431051							
Observations	45							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	1	0.180453204	0.180453	0.256091	0.615403			
Residual	43	30.29971303	0.704644					
Total	44	30.48016624						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	5.228869995	0.382841897	13.65804	0%	4.456796	6.000944	4.456796	6.000944
Visual Design	-0.05182003	0.102400103	-0.50605	62%	-0.25833	0.154689	-0.25833	0.154689

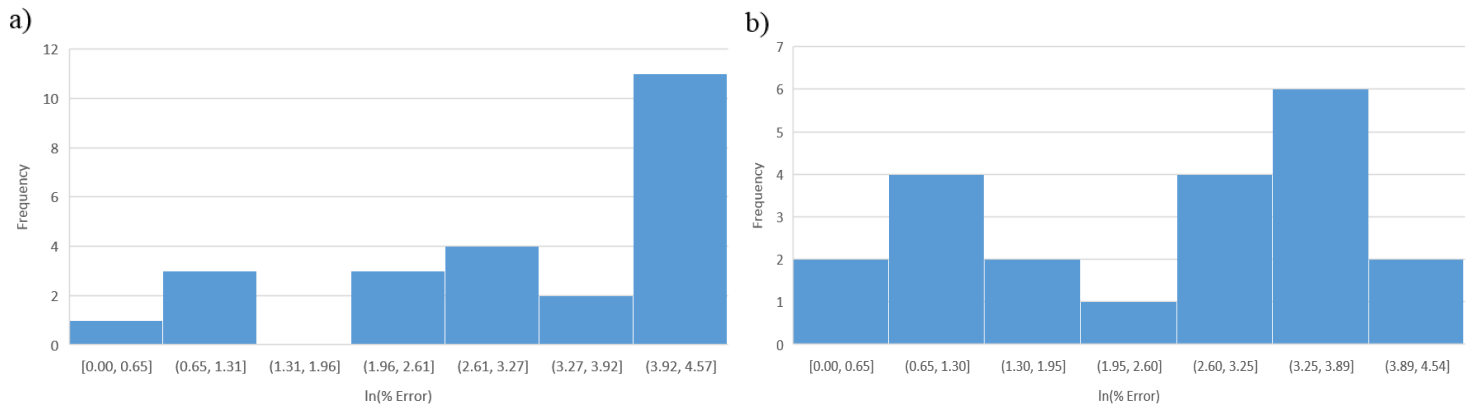
b)

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.118679199							
R Square	0.014084752							
Adjusted R Square	-0.008843509							
Standard Error	1.456220664							
Observations	45							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	1	1.302664	1.302664	0.614297	0.437471			
Residual	43	91.18488	2.120579					
Total	44	92.48754						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	3.319686716	0.664143	4.998451	0%	1.980315	4.659059	1.980315	4.659059
Visual Design	-0.139229606	0.177641	-0.78377	44%	-0.49748	0.219017	-0.49748	0.219017

Table 10: a) Linear Regression Analysis of User Visual Design Helpfulness Rating on Optimization Time; b) Linear Regression Analysis of User Visual Design Helpfulness Rating on Percent Error



**Figure 33: a) Histogram of $\ln(\text{Optimization Time})$ for Users Experienced in Videogames;
b) Histogram of $\ln(\text{Optimization Time})$ for Users With Some Experience in Videogames**



**Figure 34: a) Histogram of $\ln(\text{Percent Error})$ for Users Experienced in Videogames;
b) Histogram of $\ln(\text{Percent Error})$ for Users With Some Experience in Videogames**

a)

	Average	Std Dev
Experienced:	4.883381716	0.992936688
Some Experience:	5.231362085	0.567790425
t:	1.464848142	
p:	0.075125	
	Not Significant	

b)

	Average	Std Dev
Experienced:	3.179633064	1.432674
Some Experience:	2.425581013	1.394821
t:	1.786435777	
p:	0.040543	
	Statistically Significant	

Table 11: a) Two Sample T-Test Between Experienced Videogame Users and Users With Some Experience on $\ln(\text{Optimization Time})$; b) Two Sample T-Test Between Experienced Videogame Users and Users With Some Experience on $\ln(\text{Percent Error})$

Quadcopter Design Tool Experiment

Hi! My name is Andrew Nolff and I would first like to thank you for taking the time to complete this experiment. Your input will be used in my honors thesis on the design of quadcopters using structural batteries. These structural batteries are implemented as the arms that support the rotors as well as the power source of the quadcopter. This experiment should take about 5-10 minutes.

Figure 1: Image of a Structural Battery



Singh, A. K., Cao, L., Ma, J., Seo, J., Bakis, C. E., Zhang, Y., Hickner, M. A., and Rahn, C. D., 2015. "Design, manufacture and test of a novel structural battery based on sandwich construction". *Journal of Sandwich Structures and Materials*, p 680.

Instructions:

- Step 1: Open up the Matlab file and run the `UserInterface.m` program.
- Step 2: Enter your background information and click the "Start" button (timer will begin).
- Step 3: Move the sliders until you believe the quadcopter is optimized.
- Step 4: Click the "Am I Close to Optimal?" button to show the percentage you are away from the optimal design.
- Step 4: Click the "Topology Optimization" button, then the "Click Here for Optimization" button (wait about 20 seconds once clicked) to view what the most optimal design will look like.
- Step 5: Click "Next" and answer the final questions.
- Step 6: Click "Done" (**DO NOT "X" OUT OF THE WINDOW**) and email the Excel file named `UserData.xlsx` that was saved to the folder to andrew.nolff@gmail.com and please include in the subject line "SHC Structural Battery User Input".

Figure 2: Location of Excel File

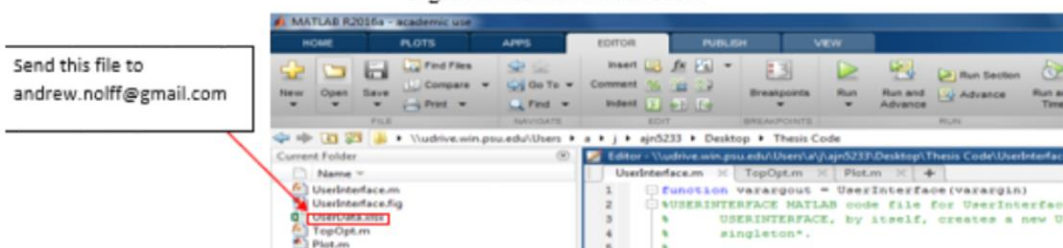
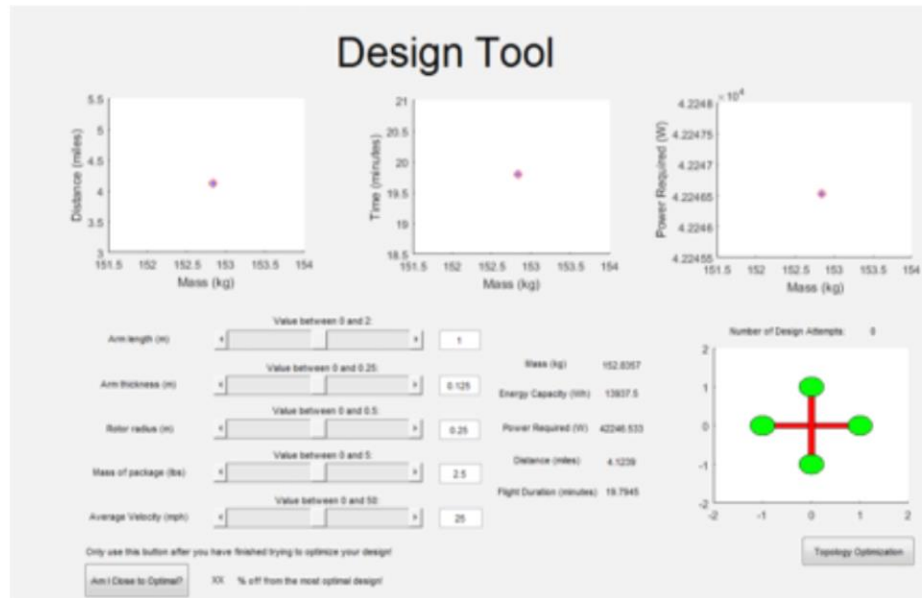


Figure 35: Page 1 of Instructions Given to Users

Additional Information:

The following experiment is to determine how your experience with the quadcopter design tool is affected by your background knowledge and qualifications. You will be trying to optimize the performance (maximize the distance) of a quadcopter by varying the different sliders. The Mass vs. Time and Mass vs. Power Required graphs are simply tools that help you to see the relationships between variables. A high power required does not necessarily mean it will produce a poor design, but rather the distance should be used to determine which design is the most optimal.

Figure 3: Design Tool



As you can see, the schematic of the design is displayed on the right as well as three graphs showing different performance metrics of the quadcopter. The blue crosses correspond to your previous designs, whereas the red circle is the current design based on the values of the sliders. Some numeric data of the current design is also displayed to the right of the sliders to help guide your optimization. Once you have arrived at what you believe to be the optimal design, click the "Am I Close to Optimal?" button to see how far off your design is from the most optimal design. Once satisfied, click the "Topology Optimization" button, then the "Click Here for Optimization" and wait patiently for approximately 20 seconds. This button runs a separate program that optimizes a structure with a given domain and set points. In this example, four points are fixed and the domain is fixed to $(x,y,z) = (16,8,16)$ to give you an idea of what the most effective structure is.

Again, I appreciate your time and if you have any questions or would like to see a copy of my thesis once complete let me know! You can contact me via email at andrew.nolff@gmail.com or my cell phone (973) 618-6359.

Figure 36: Page 2 of Instructions Given to Users

Dear Participant,

My name is Andrew Nolff and I am a senior graduating this semester and am trying to collect data for my thesis design project. I am working with Dr. Rahn and Dr. Frecker and I have created the following design tool for a quadcopter which uses structural batteries. Your task will be to maximize the distance the quadcopter can fly using the design tool. One of the things I will be looking for is if there is any correlation between a user's background experience and knowledge and their performance/helpfulness of the design tool itself. If you could please read the instructions Word document, run through the program, and email me back the Excel results, I would greatly appreciate your time and effort.

If you have any questions about the design tool, project, or any concerns, please feel free to contact me at andrew.nolff@gmail.com or by cell phone (973) 618-6359.

Thank you,
Andrew Nolff



Andrew Nolff-SHC
Quadcopte...gn Tool.zip

Figure 37: Body of Email Sent to Users

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ACADEMIC VITA

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- ❖ Performed an optimal overbuild analysis with various solar panels environments
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Interests:** **Quadcopter and Energy Storage Research**

- ❖ Used a topology optimization program to determine the optimal quadcopter design
- ❖ Created a design tool to analyze the relationship between mass, distance, and power required of a quadcopter using structural batteries
- ❖ Compared user's background knowledge and experience to the helpfulness of the design tool to see if there is a correlation