THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF ENGINEERING

THE STRUCTURAL INTEGRITY OF CYLINDRICAL LITHIUM ION CELLS IN MULTI-ROTOR QUADCOPTERS

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ABSTRACT

Rechargeable Lithium-Ion batteries are a relatively new type of battery that is constantly being introduced in various industries. They provide a high energy density while being only slightly larger than typical alkaline batteries. In addition, they can be reused, unlike the alkaline batteries, which makes them more attractive in a social atmosphere where ‘going green’ is becoming very important. While it is widely known that these batteries are a great energy source, there is not much analysis or investigation on the amount of strength or stiffness that the batteries can provide to a given assembly. This analysis builds upon the previous research of Professor Hollinger regarding Lithium-Ion Battery integration in multi rotor quadcopter drones.

In particular, this report will explore the potential benefits of battery integration in a topologically optimized quadcopter arm based on expected flight loading conditions. Furthermore, the finite element software, ANSYS, was the main source of modeling during this research as it allowed a variety of settings and boundary conditions to accurately model the loading scenarios. Ultimately, the batteries did provide a significant amount of strength and stiffness to the quadcopter arm as expected, and the magnitude and implications of those results is explored further.
# TABLE OF CONTENTS

LIST OF FIGURES ........................................................................................................ iii
LIST OF TABLES ........................................................................................................... iv
ACKNOWLEDGEMENTS .................................................................................................. v

Chapter 1 Introduction .................................................................................................. 1

Chapter 2 3D Modeling ................................................................................................. 2
    18650 Lithium Ion Batteries ....................................................................................... 2
    Quadcopter Arm ....................................................................................................... 5
    Combined Model ...................................................................................................... 8

Chapter 3 Finite Element Analysis ............................................................................. 9
    Boundary Conditions ............................................................................................... 9
    Mesh ....................................................................................................................... 11
    Stress and Deformation Results ............................................................................. 12

Chapter 4 Further Research and Validation ............................................................... 18

Chapter 5 Conclusion ................................................................................................ 20

Appendix A Various Quadcopter Arm Assumptions ............................................... 21
Appendix B Material Properties used during ANSYS Analysis ............................... 22

BIBLIOGRAPHY ............................................................................................................ 23
LIST OF FIGURES

Figure 1: Panasonic 18650 Lithium Ion Batteries ......................................................... 2
Figure 2: Interior View of Lithium Ion Batteries ................................................................. 3
Figure 3: Interior Section View of typical Alkaline Batteries .............................................. 4
Figure 4: Inventor Model of Lithium Ion Batteries ............................................................. 5
Figure 5: Quadcopter Arm with Topological Optimization ................................................ 6
Figure 6: Redesign of Quadcopter Arm .............................................................................. 7
Figure 7: Combined Battery and Quadcopter Arm Model .................................................. 8
Figure 8: Loads and Boundary Conditions ....................................................................... 10
Figure 9: Mesh Nodes and Elements (Quadcopter Arm with Batteries) ............................. 11
Figure 10: Plot of Mesh (Quadcopter Arm with Batteries) ................................................ 11
Figure 11: Mesh Nodes and Elements (Quadcopter Arm without Batteries) ..................... 12
Figure 12: Mesh Nodes and Elements (Quadcopter Arm without Batteries) ..................... 12
Figure 13: Equivalent Stress of Quadcopter Arm (no batteries) ....................................... 13
Figure 14: Equivalent Stress of Quadcopter Arm (with batteries) .................................... 14
Figure 15: Total Deformation of Quadcopter Arm (no batteries) ..................................... 15
Figure 16: Total Deformation of Quadcopter Arm (with batteries) .................................. 16
Figure 17: Quadcopter Arm Assumptions Spreadsheet .................................................... 21
LIST OF TABLES

Table 1. Summary of Maximum Stress and Deformation ............................................. 17
Table 2. Material Properties used in ANSYS ............................................................... 22
I would like to thank Professor Hollinger for his guidance on this research project and this thesis. His mentorship has assisted me greatly both inside and outside of the classroom and I greatly appreciate it. Professor Hollinger was who offered me the ability to complete this research project and that has helped refine my academic career and grow as an undergraduate.

I would also like to thank Paul Lutz Jr. who was a co-researcher on this project from Professor Hollinger. Paul was responsible for creating the battery model that was an integral part of this project in addition to several other aspects. His assistance with the project was critical in achieving completion.

I would also like to thank Professor Chris Rahn and Jun Ma. They were our correspondents from University Park while Paul and I worked on this project from Penn State Behrend. They provided great insight on the quadcopter arm redesign and how we should pursue experimental testing as a way of validating the model.

Finally, I would like to thank my parents, Amy and James Kassimatis, who have given me the ability to pursue a degree in mechanical engineering and have supported me throughout my whole undergraduate career. I attribute a lot of my success as an undergraduate student to their support.
Chapter 1

Introduction

Recently there has been a general increase in activity and technology regarding quadcopters and other drone devices. These devices require some form of energy to power the motors and control system so that they may achieve flight. The most typical form of energy that the quadcopters use is some type of battery power. Those batteries are usually in an external power pack, similar to that of a laptop computer, which is situated in the middle of the drone. With the battery pack in this setup, there is a centralization of weight in the drone which is essentially a “dead space”. The research contained within this report explored the idea of removing a battery pack from the drone and replacing it with 18650 Lithium-Ion Batteries that were located in the arms of the drone.

With batteries located in the drone, the weight would be distributed more evenly across the whole assembly of the drone. Also, this would effectively allow the batteries to act as a stiffening and strengthening agent to the overall drone. This research focuses on finite element analysis of a hypothetical drone arm with set boundary conditions to analyze the amount of stress and deformation in the part. Two major scenarios were considered, those being: (1) a drone arm without 18650 Lithium-Ion battery integration and (2) a drone arm with 18650 Lithium-Ion battery integration. It is important to note that the analysis with battery integration is only valid with rechargeable 18650 Lithium-Ion batteries and not a typical alkaline battery. The main reason for this limitation is the difference in internal geometry and chemistry that alkaline batteries have which will be discussed in the Chapter concerning 3D Modeling.
Chapter 2

3D Modeling

The two main components of this analysis were the 18650 Lithium Ion Batteries and the quadcopter arm. The batteries were complicated to model as there are several different sections of the battery that make exhibit vast differences in mechanical properties. In particular, the “jelly-roll” of the battery required exploration of previous research conducted that attempted to quantify those mechanical properties. Lastly, the initial dimensions of the quadcopter arm are derived from previous research and experimentation by Professor Hollinger as this research was largely a continuation of his previous work. The modeling of both the 18650 Lithium Ion Batteries and quadcopter arm are further discussed below.

18650 Lithium Ion Batteries

Figure 1: Panasonic 18650 Lithium Ion Batteries
An example of the 18650 Lithium Ion battery can be seen above in Figure 1. These batteries have a thin plastic sleeve around them that acts as an insulator and protection from people as the battery will become dangerously hot when in use. This thin sleeve was neglected from modeling as it contributes a non-negligible amount of strength or stiffness to the battery. The next layer was a thin stainless-steel shell that surrounded the length of the battery. The thickness of this shell was measured by hand using calipers. Inside of this stainless-steel shell was the “jelly-roll” substance that was mentioned earlier. The “jelly-roll” is a common component of lithium-ion batteries and rechargeable batteries in general. This “jelly-roll” material consists of a long sheet of anode and cathode material on the front and back of this sheet respectively. This sheet is then wound extremely tight around the inner core of the battery. Figure 2 shows the general interior anatomy of a cylindrical lithium-ion battery that is very similar to that used in the analysis of this research. It is important to note from Figure 2 the complicated interior that includes the aforementioned series of a cathode, anode, and a separator material.

Figure 2: Interior View of Lithium Ion Batteries
The setup of a lithium-ion battery’s interior chemistry is slightly different from a typical alkaline battery’s interior chemistry which utilizes a manganese dioxide cathode and a zinc anode. Most typical alkaline batteries also do not exhibit the same tightly wound sheet of cathode and anode characteristic but rather have a conventional rod-paste-tube design. Figure 3 below provides a good section view of an alkaline battery and all of its components.

![Figure 3: Interior Section View of typical Alkaline Batteries](image)

Due to the difference between alkaline and lithium-ion batteries regarding their geometry and internal consistency/chemistry, this analysis is only valid for lithium-ion battery integration in quadcopter arms. However, this concept could apply to all potential quadcopter arms observing induced strength and stiffness increases due to cylindrical battery integration.

Figure 4 below shows the Inventor model of the batteries that were used in the ANSYS analysis.

This model maintains the most critical parts that contribute to the strength and stiffness of the battery and those are: the ‘jellyroll’ (orange), the stainless-steel cap (gray), and the stainless-steel shell (green).
There are some features, such as the gasket, cap, and shell that are made of stainless steel and those material properties are readily available. The “jelly-roll” material, on the other hand, does not have much data on necessary mechanical properties that are required for a finite element analysis. As a result, this area had to be researched to find any existing literature on the mechanical properties of this section. Ultimately, the material properties chosen for this analysis was that the jelly-roll material properties were similar to that of clay at typical operating temperatures [1].

**Quadcopter Arm**

As described in the introduction, the objective of this research was to observe the abilities of a battery integrated quadcopter arm in decreasing weight while increasing or maintaining an acceptable level of stiffness and strength. As a result, the initial design of the quadcopter arm needed to be developed such that it was in the most weight reduced state. In order to find this
design, a feature on ANSYS (a finite element analysis software) called topological optimization was utilized. The topological optimization software analyzes the stress state of the specific part under a set of boundary conditions and removes sections that show no stress. An input of the topological optimization software is the ‘retention rate’ which will limit the amount of material that ANSYS removes from the geometry. In this analysis, the retention rate was kept at 60% because any smaller amount resulted in sections of the quadcopter arm that were ‘floating’ in space. Figure 4 below shows the design of the quadcopter arm that resulted from topological optimization.

![Quadcopter Arm with Topological Optimization](image)

**Figure 5: Quadcopter Arm with Topological Optimization**

As can be seen in Figure 4, the overall structure of this design is very crude but there is a general pattern that can be distinguished. The pattern can be visualized as a triangular/arrow head shape that is on parallel sides of the cylinder along the axial direction. Initially, this project was intended to use a three-point bending machine to experimentally test the quadcopter arm. This data was to be used in validating the ANSYS analysis along with contributing an experimental
confirmation of the increased strength of the quadcopter arm. However, this design is extremely complicated and inquiries with machinists at Penn State Erie decided that this would be nearly impossible to design. As a result, the overall quadcopter arm had to be redesigned in order to account for limitations in the machinists’ ability to fabricate the parts. Figure 5 below is the redesign of the quadcopter arm.

Figure 6: Redesign of Quadcopter Arm

The redesign was created with a few considerations to make it more viable to be fabricated by use of the CNC milling machines at Penn State Erie. For example, the radiiuses were large enough such that, using the smallest tool available, the shapes of the part could still be made. Ultimately, the redesign of the quadcopter arm was the exact model that would be used in the finite element analysis for both the battery integrated and non-integrated analyses.
Combined Model

Once the models for the quadcopter arm and batteries were created, the combination of these models would be used in the ANSYS analysis to show the difference in stress and deformation between the single quadcopter arm and the quadcopter arm with battery integration. All of the models were created in Autodesk Inventor, so the combined model was an assembly of three batteries axially constrained inside of the quadcopter arm, as seen below in Figure 7.

![Combined Battery and Quadcopter Arm Model](image)

**Figure 7: Combined Battery and Quadcopter Arm Model**

In addition to the batteries and the quadcopter arm, there are two holders on the ends of the batteries. In practice, these holders are meant to ensure that the batteries do not slide out of the arm during operation if the tolerance between the batteries and the quadcopter arm was too much that relative motion between the two occurred. Relative motion between the quadcopter arm and the batteries could lead to an improper connection between the batteries that does not complete the circuit. As a result, the electrical system could be compromised and appropriate power may not be supplied to adequately rotate the rotors to lift the quadcopter.
Chapter 3

Finite Element Analysis

The 3D models that were created in Autodesk Inventor were then imported into ANSYS so that assembly could be simulated under specific loading conditions. This simulation is meant to show the affects on stress and deformation of the quadcopter arm with and without the lithium ion batteries. Further discussed in the following sections are some of the settings and the boundary conditions used in this analysis. In addition, the final results will be discussed regarding the stress and deformation plots.

Boundary Conditions

The configuration of the quadcopter model is an X-wing formation. This means that the arms of the quadcopter insert themselves into a central housing of the quadcopter. There can be no relative motion between the quadcopter arm and the central housing to ensure that the quadcopter would function properly during flight. As a result, one end of the quadcopter arm was constrained with a fixed support. In ANSYS, a fixed support does not allow translation or rotation of that end relative to any direction. This will not over constrain the model, however, because it is the only support used in this system.

In order to simulate the lift force that is created by the rotors/motor assembly, a point force load was applied to the outer face of the quadcopter arm at the end that was opposite of the fixed support. This lift force was calculated by considering the standard amount of lift required by
many quadcopter manufacturers. That standard lift is that at 50% throttle of the motor output, the quadcopter should be able to hover. In other words, the lift force that a motor must be able to produce must be twice the weight of the entire assembly. Using some assumptions about material density, volume, and a general model of an entire quadcopter, the presumptive weight was calculated and the motor lift force extrapolated from that value. A summary of the assumptions can be found in Table 2 in Appendix A. Figure 8 below shows a plot of the boundary conditions.

**Figure 8: Loads and Boundary Conditions**

The loads and boundary conditions are summarized as follows: the red section is the application of the force load of 5 N, the yellow arrow denotes standard earth gravity, and the blue section denoted by the letter C is where the fixed support is located.
Since the geometry of the quadcopter arm was very complex, the mesh used during the analysis was critical to ensuring that the finite element analysis was valid. The mesh was refined several times so that there would be no problems with singularities in the model. Singularities are locations where the stress in the model increases to infinity at a single point when the mesh is refined. Below in Figures 9 and 10 are the number of nodes and elements of the model, as well as, the plot of the mesh for the model of the quadcopter arm with batteries. The more nodes and elements in the model results in a tighter mesh and, typically, more accurate results. However, it will result in a much longer solve time.

<table>
<thead>
<tr>
<th>Statistics</th>
<th></th>
</tr>
</thead>
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<td>121282</td>
</tr>
<tr>
<td><strong>Elements</strong></td>
<td>55449</td>
</tr>
</tbody>
</table>

**Figure 9: Mesh Nodes and Elements (Quadcopter Arm with Batteries)**

**Figure 10: Plot of Mesh (Quadcopter Arm with Batteries)**
The mesh is slightly different for the model that does not have batteries. Most notably is that it will not take nearly as many nodes and elements in order to create a tight mesh because the geometry is much simpler. This is shown below in Figures 11 and 12.

<table>
<thead>
<tr>
<th>Statistics</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Nodes</td>
<td>23314</td>
</tr>
<tr>
<td>Elements</td>
<td>10672</td>
</tr>
</tbody>
</table>

**Figure 11: Mesh Nodes and Elements (Quadcopter Arm without Batteries)**

**Figure 12: Mesh Nodes and Elements (Quadcopter Arm without Batteries)**

**Stress and Deformation Results**

After determining the appropriate boundary conditions and ensuring that the mesh would be sufficient for this analysis, the model was evaluated to find the stress and deformation of the quadcopter arm. The stress evaluated in this model was equivalent stress or Von-Mises stress because the quadcopter arm was analyzed as an aluminum alloy. As a result, equivalent stress was used to evaluate failure criteria. Also, the area on the model that resulted in the highest
stress amount was the outer edge of the quadcopter arm. This is correct since the bending stress caused by the point force load on the quadcopter arm created the highest amount of stress. Since the stress considered was equivalent stress, evaluating the potential failure of any of the components is only applicable to the aluminum quadcopter arm. Additional analyses could be conducted using maximum and minimum principal stress values to better understand the stress occurring in the lithium ion batteries because they were modeled as clay [1]. Brittle, ceramic materials such as clay require the use of principal stresses for the Tresca failure criteria.

Figure 13 below shows the stress of the quadcopter arm without battery integration. The model shows several areas of higher stress (red/yellow regions) towards the fixed end of the quadcopter arm. Other sections such as the rounded sides of the arm show very minimal stress (predicted by ANSYS at 13924 Pa). If further weight reduction is needed for this part, those side sections could be removed to increase the topological optimization.

Figure 13: Equivalent Stress of Quadcopter Arm (no batteries)
As shown above in Figure 13, the quadcopter arm shows several sections of stress that could be decreased by using battery integration. The purpose of this research was to model the potential strength and stiffness reduction from including batteries in the arm. Therefore, below in Figure 14 is the stress plot of the quadcopter arm with battery integration. There is great stress reduction in the quadcopter arm due to the integration, especially in the region that is close to the fixed support end of the quadcopter arm.

![Stress Plot of Quadcopter Arm](image)

**Figure 14: Equivalent Stress of Quadcopter Arm (with batteries)**

The areas of high stress (red/yellow regions) was decreased tremendously with the battery integration. This is most notably due to the increased moment inertia since the arm is no longer hollow when it is filled by the batteries. The resultant maximum stress of the quadcopter arm is not enough to cause yielding of the arm sleeve to occur. As a result, further topological optimization could be used to increase the overall stress in the quadcopter arm that would cause it to be closer to yielding. In addition to the stress analysis, this research was also focused on the added stiffness. In order to evaluate stiffness, deformation plots were created for both scenarios.
Figure 15 shows the total deformation plot of the quadcopter arm with batteries. Due to the fact that the only load applied to the quadcopter arm was an upward force, the deformation of the quadcopter arm is predictably vertical. This plot is similar to the stress plots regarding the color of the quadcopter arm and how that refers to the amount of deformation. The areas or red/yellow are the areas that show significant deformation relative to the sections that are blue. The areas of high deformation occur where the force was applied.

![Deformation Plot](image)

**Figure 15: Total Deformation of Quadcopter Arm (no batteries)**

As seen in Figure 15, the maximum deformation of the is 0.00015 meters or 0.15 millimeters. In general, the deformation is very low because the applied force of the motor is not very high. As a result, the quadcopter arm is not deflecting. However, the deformation of the quadcopter arm with no batteries relative to the deformation of the quadcopter arm with batteries will show the increase in stiffness. Figure 16 below is the total deformation of the quadcopter arm with battery integration.
Figure 16: Total Deformation of Quadcopter Arm (with batteries)

The result from the finite element analysis concluded that the maximum deflection of the quadcopter arm was 3.59e-5 meters or 0.036 millimeters. This is approximately a 76.0% reduction in the maximum deformation of the quadcopter arm. As a result, battery integration resulted in a much stiffer quadcopter arm. This is important in ensuring that the electrical connection of the batteries would not be disconnected during flight of the quadcopter. With such a small amount of deformation, disconnection would be very unlikely.

Quadcopter arms have the potential to be greatly improved regarding strength and stiffness when integrated with lithium ion batteries. From this analysis, the quadcopter arm shows an order of magnitude improvement in both stress reduction and maximum deformation reduction. Table 1 below shows a summary of the maximum results of equivalent stress and maximum deformation in these models.
Table 1. Summary of Maximum Stress and Deformation

<table>
<thead>
<tr>
<th>Quadcopter Arm</th>
<th>Max Stress</th>
<th>Max Deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>With Batteries</td>
<td>5.81 MPa</td>
<td>0.036 mm</td>
</tr>
<tr>
<td>Without Batteries</td>
<td>10.85 MPa</td>
<td>0.150 mm</td>
</tr>
</tbody>
</table>
Chapter 4
Further Research and Validation

This research showed that there is great potential for lithium ion battery cell-stiffened quadcopter arms. There is much to be gained by weight and material production by potentially increasing battery duration and lowering costs for production. There are potential areas of this type of optimization that can be explored in the future to gain a better understanding of the affects of lithium ion battery integration. For example, further research on the mechanical properties of lithium ion batteries would result in more accurate modeling and better predictions to the response of the batteries to loading. Also, in direct comparison to this analysis, there could be additional models created to see the difference between two, three, and four battery integration and that effect on additional strength and resistance to deformation.

The model created in this analysis can be used as a starting point for further finite element analysis research into cell stiffened quadcopter arms. Further validation should be considered as well in order to confirm the effects of cell stiffening. For example, hand calculations would be useful but would most likely need to be approximated due to the very complex geometry of the designed quadcopter arm sleeve. Also, the original purpose of the quadcopter arm redesign was to have the parts fabricated in order to do experimental tests via a three-point bending machine.

This would be a more viable option to show the strength difference of the cell stiffened quadcopter arms. Feedback from other Pennsylvania State University Professors suggested that Metallic Additive Manufacturing could be a way to create the quadcopter arms out of a metal. Additive Manufacturing may also allow the use of the actual topology optimized part to ensure that the weight is reduced to its maximum possible value. However, the material properties of
additive materials change drastically with the usual aluminum alloy so the model would have to be adjusted.
Chapter 5

Conclusion

In an environment where obtaining weight and cost reduction to improve efficiency and revenue are crucial areas to improve upon, cell stiffened quadcopter arms is an interesting concept that could apply to other products. In this case, the batteries provided additional strength and reduced the overall deflection of the quadcopter arm while also providing a more balanced weight distribution. The modeling of the Lithium-Ion batteries was very difficult to accurately capture all of the small parts with varying mechanical properties. Further research may be able to create a better model which could result in a more accurate simulation in ANSYS. The finite element analysis created in this report showed that batteries could contribute a significant amount of stress and deflection resistance. In the future, custom batteries could be used instead of a quadcopter arm to even further reduce the weight of the quadcopter. Furthermore, quadcopter arms such as these have the potential to be implemented on a custom quadcopter drone to observe any affects to payload capacity and flight time.
Appendix A

Various Quadcopter Arm Assumptions

<table>
<thead>
<tr>
<th>Assuming the Three Cell Assembly</th>
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</thead>
<tbody>
<tr>
<td>Mass of Aluminum Sleeve</td>
<td>17 grams</td>
</tr>
<tr>
<td>ABS Plastic Sleeve Density</td>
<td>1210000 g/m³</td>
</tr>
<tr>
<td>Volume</td>
<td>5.9429E-07 m³</td>
</tr>
<tr>
<td>Mass</td>
<td>0.719052472 g</td>
</tr>
<tr>
<td>Lithium Ion Battery Mass</td>
<td>48.5 g</td>
</tr>
<tr>
<td>Mass of Reinforcing Disk</td>
<td></td>
</tr>
<tr>
<td>Total Mass</td>
<td>145.5 g</td>
</tr>
<tr>
<td>Overall Mass of one arm</td>
<td>163.2190925 g</td>
</tr>
<tr>
<td>Total Weight of one arm</td>
<td>1.60179297 N</td>
</tr>
<tr>
<td>Total Weight of one arm</td>
<td>0.359959517 lb</td>
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<tr>
<td>Overall Mass of all arms</td>
<td>652.8764 g</td>
</tr>
<tr>
<td>Total Weight of all arms</td>
<td>6.404717 N</td>
</tr>
<tr>
<td>Total Weight of all arms</td>
<td>1.439838 lb</td>
</tr>
</tbody>
</table>

| Mass of potential motor         | 25 g              |
| Total Mass of all motors        | 100 g             |
| Thrust Force from one motor     | 446 g             |
| Thrust Force from all motors    | 17.2656 N         |
| Thrust Force from all motors    | 3.881462 lb       |
| Total Mass of Flight Controller | 7 g               |
| Thrust Force from all motors    | 176 g             |
# Appendix B

Material Properties used during ANSYS Analysis

Table 2. Material Properties used in ANSYS

<table>
<thead>
<tr>
<th>Material</th>
<th>Density</th>
<th>Yield Strength</th>
<th>Ultimate Tensile Strength</th>
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</thead>
<tbody>
<tr>
<td>Jelly-Roll (inside of battery)</td>
<td>2800 kg/m³</td>
<td>N/A</td>
<td>1x10⁷ Pa</td>
</tr>
<tr>
<td>Aluminum Alloy (quadcopter arm sleeve)</td>
<td>2770 kg/m³</td>
<td>2.8x10⁸ Pa</td>
<td>3.1x10⁸ Pa</td>
</tr>
<tr>
<td>ABS Plastic</td>
<td>1040 kg/m³</td>
<td>4.14x10⁷ Pa</td>
<td>4.43x10⁷ Pa</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>7750 kg/m³</td>
<td>2.07x10⁸ Pa</td>
<td>5.86x10⁸ Pa</td>
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</tbody>
</table>
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Panasonic, 1 Nov. 2011. Web. 26 July 2017
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Education
Major(s) and Minor(s): Bachelor of Science in Mechanical Engineering
Thesis Title: The structural integrity of cylindrical lithium ion cells in multi-rotor quadcopters
Thesis Supervisor: Professor Adam Hollinger

Research Experience
May-August 2018
MC REU Undergraduate Research Assistant
• Collaborated with graduate students under the supervision of Dr. Adam Hollinger and Dr. Christopher Rahn
• Calculated the optimal length and reinforcement of a quadcopter’s arm utilizing ANSYS’ topological optimization feature
• Modeled the optimized arm with and without battery integration to examine the additional strength the batteries provided
• Designed a quadcopter using the newly optimized quadcopter arms with lithium-ion battery integration
• Created a poster and presented our results at the year-end research symposium

Pennsylvania State University, University Park and Erie PA
Adam Hollinger

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MCREU Summer 2018 Research Symposium

Community Service Involvement:
Volunteer at the American Heart Association Heart Walk in November 2015