FINAL REPORT

Team 3-D Delivery
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Executive Summary

The 2014-2015 Calvin College senior design 3-D Delivery (Team 2) consists of members Jeff DeMaagd, Kemal Talen, and Ross Tenney. All three team members are senior mechanical engineering students. This report details development, prototyping, and testing of the unmanned aerial vehicle (UAV) that the team designed. The UAV was designed to carry and deliver a 3 lbs package across the Calvin College campus with enough energy left to return back to its starting point. The frame of the drone was made of 3-D printed ABS plastic and carbon fiber tubing due to their lightweight and cost-effective properties. Two prototypes were built and the second was tested to ensure that it met the performance standards the team set for it. The UAV successfully carried and delivered a package a half mile with enough energy to fly an additional half mile.
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1 Introduction

1.1 Senior Design and Project Introductions

This year for the Calvin College Engineering department, Team 2, 3-D Delivery, will be working on a drone designed for small package delivery. Professor Nielsen (M.E.) and various cross-disciplinary engineering faculty members will supervise the project. The main goal of this project is to build and design a drone that is safe, functional, and capable of performing the task of remotely picking up and delivering a package.

The senior design course ENGR 339/340 is aimed to develop undergraduate senior engineering students in areas of team building, project design and implementation, and oral/written communication. During the duration of the course, the team will develop a Project Proposal & Feasibility Study, a team website and poster, a final report/presentation, and display the final design at the Engineering Senior Design Fair in May 2015. The engineering department at Calvin College hosts the fair which exhibits all of the senior design projects.

1.2 Biographies

1.2.1 Jeff DeMaagd

Jeff DeMaagd is a senior engineering student in the mechanical concentration. He lives in Grand Rapids, Michigan with his wife and two daughters. His engineering interests lie in rapid prototyping and new product design and development, especially in industries where form and function meet.

1.2.2 Kemal Talen

Kemal Talen is an engineering student in the mechanical concentration with a math minor and is pursuing an honors designation. His hometown is Bethesda, Maryland. He is interested in learning about the utilization of mechatronic systems in engineering, specifically 3-D printing. Some of his engineering skills include stress and deflection analysis of beams, control systems design and optimization, and thermodynamic analysis of power cycles.

1.2.3 Ross Tenney

Ross Tenney is an engineering student in the mechanical concentration with a math minor and international designation. His hometown is Shoreview, Minnesota. After graduating from Calvin College, he desires to enter the career field of the automotive, aerospace, defense, or biomedical industry. His interests correlating to the senior design project are additive manufacturing, flight aerodynamics, machinery dynamics, plastics properties, and stress and deflection analysis.

2 Problem Definition

2.1 Problem Statement
The Federal Aviation Administration (FAA) is scheduling to integrate UAVs (drones) into U.S. airspace by 2017\(^1\). Currently, drone technology has been limited to governments and hobbyists; however, with the upcoming opening of U.S airspace to commercial UAVS, UAV technology will likely become very popular. One of the reasons companies want to utilize UAV technology is that they are able to go places where it is not necessarily safe or economical for people or large machines to go.\(^2\) UAVS have many commercial applications because of their relatively small size and ability to fly without an on-board pilot.

There are many future possibilities for UAV’s commercial applications. One of the main applications is the delivery of small packages. UAVs would allow businesses to ship and send packages of their products directly to their customers without the need of human interference. Another application would be internet service provided by solar-powered drones. The solar-powered UAVs would provide wireless internet all around the world acting as movable wireless access points. UAVS can also be used for covering news stories. The UAV’s could cover news events that normally would be a high-risk situation for news reporters. Also, commercial UAVs have a large application in photography and video documentation. UAVS would be able to acquire photos and video footage that normally would be impossible to gain. Agriculture would also benefit from the capability of UAVs to monitor large areas of land remotely. Finally, UAVS would be very beneficial for the public services domain of search and rescue missions that are normally very dangerous for law enforcement\(^3\).

Currently the design for drones is very one-dimensional and does not meet the variability associated with commercial applications. For example, for commercial photography and video documentation, different UAVs are needed for varying camera sizes and weights such as 4 arm/propeller drones for lighter cameras and 8 arm/propeller drones for heavier camera setups. As a result, customers would need to invest in different drones for different lifting capabilities. Furthermore, the current designs of drones are not fully optimized in areas of material science, manufacturing/production, assembly, customization, ease of use, impact strength, and modularity. In addition, the production of UAVs does not fully utilize the capabilities of 3-D printing in producing the structural parts. 3-D printing is a growing field that currently is used in industry for rapid prototyping, but some manufacturing facilities are using 3-D printing because of its efficiency, customization tailoring capabilities, and sustainability. In conclusion, there is increasing demand for UAVs in commercial industries to which drone engineering can be tailored for certain applications.

2.2 Objectives

In order to meet the requirements of the customer and respond to the up-and-coming field of commercial drone use in the United States, our design team plans to design and manufacture a user-friendly multi-copter incorporating 3-D printable parts capable of carrying and delivering a package. Creating a revolutionary design drone involves technical hurdles that can be overcome by engineers.


\(^3\) Dussault. “7 commercial uses for drones.”
Our main project requirements are listed below:

- **Multi-copter drone with capability of being a quadcopter or octocopter**

  A main design function of the drone is to have a modular design. This entails that the drone will have the ability to easily transform into multiple different rotor configurations to meet the lift needs of the consumer based on previously stated commercial applications. The drone would be able to transform from a quadcopter to an octocopter.

- **10 minute flight time**

  The drone shall be designed in order to achieve a mixed flight time of 10 minutes. A mixed flight time incorporates an average flight time of hovering and maneuvering.

- **1 mile flight range**

  The drone will be able to fly for a minimum range of one mile. The one mile range will incorporate a half mile of carrying the package load and another half mile without the package load, thus simulating a package delivery. The one mile range is an estimate trip distance for package delivery within Calvin College’s campus.

- **Lift, carry, and deliver a 3 lb package**

  The drone would also have the function of package delivery for commercial use. The drone will be able to lift, deliver, and drop off a 3lb. package of goods directly to the customer. The drone will be able to release the package from the control device without human physical assistance. As a result, a package attachment mechanism (PAM) will need to be designed.

- **Survive a 2 foot vertical impact strength**

  In addition, safety of the drone will also be a main objective in the aspect of strength. The multi-copter drone will be designed to be durable enough to withstand moderate landing impacts and will be tested using both computer and physical models. A two foot vertical impact test will be used to assess the strength of the drone. A two foot vertical impact is defined as a vertical drop of the drone from a height of two feet.

- **Stable flight in up to 10 mph winds**

  The drone will also be designed to be safe to control and maneuver. The drone design will be stable in flight during moderate wind conditions (wind speeds of 10 mph or less).

- **Interchangeable and 3-D printed parts**
For producing the drone, the team believes that the use of a 3-D printer would be very beneficial. The structural parts will be designed and produced using a 3-D printer. The parts can easily be reproduced if broken or worn out. Also, parts can be updated and further optimized without expensive tooling changes allowing for easy design iteration. The use of a 3-D printer allows for iterative design and complex geometries that are not easily achieved through traditional manufacturing methods. Finally, the structural drone parts would be compiled in an online library for commercial use.

3 Project Management

3.1 Team Organization

The 3-D Delivery team consists of three senior level mechanical engineering students. The team broke up the tasks based on the interests and experiences of each team member as shown in Figure 3.1.

![Figure 3.1 Team organization chart](image)

3.2 Team Meetings

Team meetings were held each Monday to review the project schedule and go through the meeting agenda. The previous week’s meeting minutes were used as the agenda and all of the action items assigned the previous week were reviewed and documented. New action items were then added to the minutes. These action items were assigned to one or more of the team members and the agreed upon due date was noted. The project schedule was used to inform what new items needed to be added to the meeting minutes. Action items that were completed the previous week were removed. These meeting minutes were kept in the team’s Google Drive folder.

3.3 Schedule
Microsoft Project was used to schedule the required activities and was managed by Jeff. The project was broken into major topics; each major topic was broken into sub-topics when appropriate. The required duration of the work was then estimated and the critical path was mapped out using the “Predecessor” function. The team reviewed the project schedule each week at the team meetings, and upcoming items were noted in the meeting minutes with action items assigned to team members. Contingency days were added to each major section of the project for unforeseen circumstances. Schedule issues were addressed in team meetings and the team made schedule adjustments during meetings. The schedule from Microsoft Project is shown in Appendix A.

3.4 Budget
A budget was determined by the team and was maintained by Ross. The team reviewed the budget during the Monday team meetings, and any budget problems were addressed at those meetings. The budget was kept in a Microsoft Excel spreadsheet. Both predicted and actual numbers were kept on that sheet, and the actual cost of items informed changes to the predicted cost of items.

3.5 Method of Approach
The team decided to use a method of collaboration to inform all individuals of each other’s activities. The team met before any major research or design work was done and agreed upon the direction. Individual team members were then assigned work; they did this work while keeping in mind the direction agreed upon by the team.

The project was broken into sections, including materials, rotor and electronic configurations, safety and sustainability. The individual team members were tasked to do the research for their respective sections. Team members would then present their findings to the team, and the team would decide which design direction to go. A team member was then tasked to pursue that design.

An atmosphere of openness and respect was important to the team. The team did not want to stifle ideas by being overly critical. All ideas, no matter how “out there” they were, were received by the team with respect and were discussed. This was done to ensure no team member felt like they had to keep their ideas to themselves for fear of being ridiculed.

4 System Architecture
The system breakdown is shown in the block diagram of Figure 4.1. The system is comprised of three main sections, the electronics, frame, and PAM. The electronics involve aspects that give the drone the power to fly, control attitude, and control the relay switch. The electronic interface is broken down into further design sections of flight control configuration, PID tuning, and code modifications. The frame design is heavily dependent on the weight-to-thrust ratio of the drone. The frame also incorporates the use of 3-D printed plastic materials for the sections of the body, motor mounts, and landing legs. The PAM involves the main function of the drone for picking up, carrying, and releasing packages. The PAM design breaks down further into areas of the package and electromagnet.
5 Design Norms

There are three main design norms that apply to the scope of this project: cultural appropriateness, trust, and stewardship/sustainability.

5.1 Cultural Appropriateness

In the last couple of years, the general public has been exposed to news about military drone attacks and more significantly, the covert operation of these drones. Therefore, there is a certain negative predisposition towards the use of drones for delivery. Therefore, with the current push for the implementation of package delivery drones, our design needs to respect the communities involved with concerns with privacy and safety. For example, when delivering packages, the UAV must not fly directly over people’s houses, and the drone must also be quiet enough not to disturb the community. In addition, based on current FAA laws, the drone must be designed to follow the restrictions of being controlled within line of sight and outside of restricted airspace. Furthermore, the UAV must have an extremely safe PAM that ensures the package does not detach from the UAV during flight.

5.2 Trust

A trustworthy design is the last design norm that influenced the design decisions for this project. The safety of the users and others around the drone is paramount. The drone design needs to meet the performance specifications and objectives previously stated. The user needs to trust that the drone will function as stated by having stable flight with and without the package, user-friendly controls, and a resistance to impact collisions.

5.3 Stewardship/Sustainability
Finally, our design takes into account the design norm of stewardship and sustainability. As stated earlier, the drone will have a modular design which is has two major components in regards to stewardship. First, the modular design involves interchangeable parts which can be easily replaced individually without needing to replace the entire drone and wasting unnecessary material. Secondly, the modularity encompasses having a multi-copter that is a quadcopter and octocopter in one single frame design which allows for a broader application range. Therefore, it is unnecessary to need to attain the materials and money for both a quadcopter and an octocopter to accomplish these various tasks. Furthermore, a majority of the multi-copter is composed of 3-D printable ABS plastic which is recyclable. Accompanying this fact is that users who own 3-D printers can easily print out their own drone parts without needing to drive to the store to purchase parts or order parts online. As a result, there will be a diminishing need for shipping costs and materials required.

6 3-D Printing

6.1 Reason/Requirements

A critical component of the team’s desired outcomes for the drone design is that it incorporates 3-D printing for a significant portion of the drone.

3-D printing facilitates an iterative design approach. Parts can be designed on the computer and printed over the course of a few hours. The part can then be reviewed and tested in its final form. Any changes can then be made, and the part can be printed and reviewed again. This also allows for replacement parts to be quickly made when parts fail or break. This means that the replacement parts do not need to be kept in stock and only parts that need to be replaced are made.

A second reason for using 3-D printing is its ability to make complicated parts without needing expensive tooling, or without needing to spend a lot of time and money having a machinist make it. This works really well for parts that are low volume or highly customizable.

According to many 3-D printing proprietary resources, including Proto Paradigm’s research, “For a material to prove viable for 3-D Printing, it has to pass three different tests: initial extrusion into Plastic Filament, second extrusion and trace-binding during the 3-D Printing process, and finally end use application.”  

In order to pass the first test, each plastic’s material properties must allow the plastic to form properly into the 3-D Printer feedstock called the plastic filament. Once inside the plastic filament, in order to pass the second test, the plastic must process well during 3-D printing to produce accurate parts. Finally, passing the third test requires that the completed 3-D printed plastic piece matches the requirements of its desired application, which in our design includes elements such as strength, durability, temperature-resistance, modularity, sustainability, and aesthetics.  

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5 “The Difference Between ABS and PLA for 3D Printing.”
6.2 Material Comparisons

There are three main 3-D printable plastics to consider when implementing into the drone design: ABS, PLA, and acrylic. Each type of printed plastic has certain advantages and disadvantages.

Acrylonitrile butadiene styrene (ABS) is a recyclable thermoplastic made from petroleum-based products. As a thermoplastic, the plastic can become soft and moldable when heated while returning to a solid when cooled. ABS can produce very accurate parts, however, there can be some part warping characterized by the surface of the part curling upwards. This occurs when the part is in direct contact with the print bed and the print bed is not heated and/or smooth. ABS can also have warping at surface edges if there is not sufficient air-cooling on the part. ABS has characteristics of high strength, flexibility, machinability, and higher temperature resistance when compared to PLA.⁶

Polylactic Acid (PLA) is a thermoplastic made of cornstarch and sugar cane. It is also a thermoplastic that reacts similar to the heating and cooling behaviors of ABS. There are a few differences between ABS and PLA in terms of part accuracy. PLA generates much less part warping when compared to ABS because it melts at a lower temperature. A lower melting temperature provides sharper details when cooled as well as stronger layer binding during the printing process. PLA has characteristics of high strength, rigidity, fast printing speed, sharper printed corners, and pleasing aesthetics. A summary characteristic comparison table for ABS and PLA is shown in Table 6.1.

<table>
<thead>
<tr>
<th>ABS</th>
<th>PLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrude at ~225°C</td>
<td>Extrude at ~180-200°C</td>
</tr>
<tr>
<td>Requires heated bed</td>
<td>Benefits from heated bed</td>
</tr>
<tr>
<td>Works reasonably well without cooling</td>
<td>Benefits greatly from cooling while printing</td>
</tr>
<tr>
<td>Adheres best to polyimide tape</td>
<td>Adheres well to a variety of surfaces</td>
</tr>
<tr>
<td>Filament tolerances are usually tighter</td>
<td>Finer feature detail possible on a well calibrated machine</td>
</tr>
<tr>
<td>Prone to cracking, delamination, and warping</td>
<td>Prone to curling of corners and overhangs</td>
</tr>
<tr>
<td>More flexible</td>
<td>More brittle</td>
</tr>
<tr>
<td>Can be bonded using adhesives or solvents (Acetone or MEK)</td>
<td>Can be bonded using adhesives</td>
</tr>
<tr>
<td>Fumes are unpleasant in enclosed areas</td>
<td>More pleasant smell when extruded</td>
</tr>
<tr>
<td>Oil Based</td>
<td>Plant Based</td>
</tr>
</tbody>
</table>

6.3 Printing Geometry

There is also a significant difference between using a line pattern and honeycomb pattern printing geometry for ABS and PLA 3-D printed plastics. In “Fabrication of FDM 3-D objects with ABS and PLA and Determination of their Mechanical Properties,” Enno Ebbel and Thorsten Sinemmann created a dog bone tensile test for determining the material properties of 3-D-Printed ABS and PLA with both line and honeycomb patterns. The tests were for various common 3-D-Printers such as Felix 1.0e, CB-printer, and uPrint Plus. The dog bone dimensions are shown in Figure 6.1. Diagrams for Stress-Strain, Young’s Modulus, Yield Strength, and Specific Strength are shown below in Figures 6.2, 6.3, 6.4, and 6.5, respectively.

Figure 2: Test sample 1A according to DIN EN ISO 527-1, all values in mm [6]

Figure 3: Filling method, left: Line pattern (lines turned by ± 45° around the horizontal axis), right: Honeycomb pattern

Figure 6.1. ABS and PLA Tensile Test Dog bone Dimensions

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Figure 6.2 ABS and PLA Tensile Test Stress vs. Strain

Figure 6.3 ABS and PLA Tensile Test Young’s Modulus
Figure 6.4 ABS and PLA Tensile Test Yield Strength

<table>
<thead>
<tr>
<th></th>
<th>ABS</th>
<th>PLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honeycomb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB</td>
<td>CB</td>
<td>CB</td>
</tr>
<tr>
<td>Felix</td>
<td>Felix</td>
<td>Felix</td>
</tr>
<tr>
<td>uPrint</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Yield strength $\sigma_y$ in MPa

Figure 6.5 ABS and PLA Tensile Test Specific Strength

<table>
<thead>
<tr>
<th></th>
<th>ABS</th>
<th>PLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honeycomb</td>
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<tr>
<td>CB</td>
<td>CB</td>
<td>CB</td>
</tr>
<tr>
<td>Felix</td>
<td>Felix</td>
<td>Felix</td>
</tr>
</tbody>
</table>

Specific strength in Nm/g
Based on the data in the foregoing diagrams, PLA Lines from the Felix Printer has the highest Young’s modulus, yield strength and specific strength. PLA Lines has a high yield strength, but is more brittle than other thermoplastics. Therefore, PLA components in the design will fracture very close to the yielding value, which will influence the design decisions made in the stress analysis.

Another alternative option for 3-D printable plastics is the less-used Acrylic, specifically the VisiJet line of acrylic based plastics. VisiJet plastics are known for strength, part accuracy and high-definition, toughness, high temperature resistance, durability, stability, water tightness, biocompatibility, and machinability. A chart of the material properties for the VisiJet line of plastic materials is shown in Table 6.2. A full comparison of the three main options can be seen in Appendix B. It should be noted that the VisiJet M3-X black thermoplastic (available at Calvin College) has a slightly lower tensile strength (35.2 MPa) than PLA lines (40 MPa – Figure 6.2).

Table 6.2. VisiJet Material Properties

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>Composition</td>
<td></td>
<td>UV Curable Plastic</td>
<td>Wax Support Material</td>
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<td></td>
<td></td>
</tr>
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<td>Color</td>
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<td>Natural</td>
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<td>Blue</td>
<td>Gray</td>
<td>Dark Blue</td>
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<tr>
<td>Density @ 80°C (liquid)</td>
<td>ASTM D4164</td>
<td>1.04 g/cm³</td>
<td>1.02 g/cm³</td>
<td>1.02 g/cm³</td>
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<td>Tensile Strength</td>
<td>ASTM D633</td>
<td>49 MPa</td>
<td>35.2 MPa</td>
<td>42.4 MPa</td>
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<td>ASTM D638</td>
<td>2168 MPa</td>
<td>1504 MPa</td>
<td>1463 MPa</td>
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<td>735 MPa</td>
<td>866 MPa</td>
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<td>Elongation at Break</td>
<td>ASTM D638</td>
<td>8.3%</td>
<td>19.7%</td>
<td>6.83%</td>
<td>8.97%</td>
<td>8%</td>
<td>6.1%</td>
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<td>Flexural Strength</td>
<td>ASTM D790</td>
<td>65 MPa</td>
<td>44.5 MPa</td>
<td>49 MPa</td>
<td>26.6 MPa</td>
<td>28.1 MPa</td>
<td>28.1 MPa</td>
<td>45 MPa</td>
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<tr>
<td>Heat Distortion Temperature</td>
<td>ASTM D648</td>
<td>88°C</td>
<td>57°C</td>
<td>56°C</td>
<td>46°C</td>
<td>46°C</td>
<td>46°C</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Ash Content</td>
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<td>N/A</td>
<td>0.01%</td>
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<td>0.01%</td>
<td>0.01%</td>
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<td>N/A</td>
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<td>USP Class VI Certified</td>
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<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Projet Compatibility</td>
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<td>SD, HD</td>
<td>SD, HD</td>
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<td>SD, HD</td>
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<td></td>
</tr>
<tr>
<td>Description</td>
<td>ABS+Be Plastic</td>
<td>High strength &amp; flexibility plastic</td>
<td>Tough Plastic, Translucent</td>
<td>Plastic, Natural</td>
<td>Plastic, Beige, Plastic, Gray</td>
<td>Castable Plastic</td>
<td>Non-toxic wax material for hands-free meltaway supports</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The team also 3-D printed dog bone samples for each of the 3-D printable plastic options: the acrylic from the ProJet printer, and the ABS and PLA from the MakerBot Replicator 2X printer. Tensile tests were taken in order to determine the strength of the plastics in comparison to the Ebbel and Sinemmann data as well as while using the available printers. The tensile test data is shown in Figure 6.6. From the graph, it was determined that plastics that are 100% filled (lines) are the strongest. PLA 15% filled was the next strongest, followed by ABS 15% filled and acrylic. Based on this tensile test, the yield strengths for all 3-D printed plastics were significantly lower than the results found from the Ebbel and Sinemmann data. This could be a result of different printing methods, printer settings, and ultimately printer selection. However, the relative strengths of the plastics in comparison to each other gained similar results.

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6.4 3-D Printer Capabilities/Options

In order to produce 3-D printed plastic parts, the team needs to utilize the best 3-D Printer available. There are three 3-D printers that are accessible to the team: Calvin College’s ProJet 3500, and GR Makers Cube and MakerBot Printers. Each 3-D printer has advantages and disadvantages regarding plastic material use, printing methods, printing time, cost, platform size, and part resolution.
Calvin College currently owns a ProJet 3500 in the Engineering Building shown in Figure 6.7. The ProJet 3500 only uses its own VisiJet line of plastic materials as previously mentioned. According to Calvin College Engineering Department Metal and Wood Shop Supervisor, Phil Jasperse, the printing method of the ProJet involves multi-jet printing (MJP) in which the printer head prints layers of UV curable liquid plastic onto the platform, which has wax support material jetted into fill voids of the part structure. Afterwards, the UV lamp flashes to solidify material creating a fully cured plastic part. The support wax is then melted away leaving the finished printed part. As a result of the need of support wax, there has to be two holes within the part material design in order to drain the wax and have an air hole. These holes could possibly be stress risk areas for the plastic part design. The ProJet Printer costs $170 per pound of VisiJet plastic material and takes seven hours per inch in the vertical axis to complete. In summary, the ProJet is very expensive and time-consuming. The platform size for the ProJet 3500 is 11.75 x 7.3 x 8 inches which is relatively small, but this is a constraint the team will have to work within when producing certain 3-D printed plastic parts. For part accuracy, the ProJet 3500 is recognized for producing very precise and high-resolution parts with a resolution of 375 x 375 x 790 DPI; 32 micro layers.
The next option of available 3-D Printers is GR Makers’ MakerBot Replicator 2X, as shown in Figure 6.8. The MakerBot Replicator 2X is capable of printing PLA and ABS thermoplastics. The printing method involves Fused Deposition Modeling (FDM) which produces parts by extruding beads of material through a nozzle which hardens immediately to form layers. The printing time would be significantly less than the ProJet. Through GR Makers, the cost of printing would only be dependent on a $30 per person per month membership fee and is independent of material use. The platform size of the MakerBot Replicator 2X is 9.7 x 6.0 x 6.1 inches, which is somewhat smaller than the ProJet 5300. Although the part accuracy is excellent, based on the printing method and printing time, the part layers are not fused together as well as the ProJet 3-D Printer and only has a layer resolution of 100 microns (about 3 times the resolution of the ProJet 3-D).

![Figure 6.8 MakerBot Replicator 2X 3-D Printer](image)

The final option for 3-D Printers is GR Makers’ Cube Printer shown in Figure 6.9. The Cube 3-D Printer has the same material capabilities, FDM printing method, printing time, and printing cost as the MakerBot Replicator 2X. The platform size for the Cube 3-D Printer is 6 x 6 x 6 inches, which is significantly smaller than the other alternatives. The part resolution is similar to the MakerBot Replicator 2X.

---

6.5 Selected 3-D Printer and Plastic Material

The 3-D printer and material selection were determined by all these factors, particularly on the applicable material to be used, platform size constraint, print quality, and cost. Each individual design component of the UAV will have varying uses of plastic based on these same constraints relative to the application.

The chosen 3-D printer was the MakerBot Replicator 2X. It has the options of printing either ABS or PLA plastics which were tested to be stronger than acrylic. In addition, the MakerBot Replicator 2X also has advantages in being less costly, having a relatively large platform size, having a shorter printing time, and producing parts that adequately accurate for our application of the drone. The next step was determining which plastic to use for implementation in the drone. Although PLA was determined to be the stronger 3-D printable plastic of the two choices, the team ultimately chose to use ABS plastic after testing the printer. The determining factor for using ABS over PLA was the printability of the ABS compared to PLA. Although the MakerBot Replicator 2X can print both ABS and PLA, the recommended plastic to print on the printer was ABS as it was functionally made towards printing ABS. The PLA plastic had difficulties in sticking to the printer bed and extruding smoothly from the printer nozzle. Ultimately, the ABS 3-D printed plastic parts were higher quality and more repeatable to print than the PLA parts. Although the yield strength was lower for ABS than PLA, its strength was sufficient for our design purposes. In addition, some other advantages to using ABS over PLA are its recyclability and much higher heat distortion temperature.

6.6 3-D Printer Settings and Practices

Once the MakerBot Replicator 2X was chosen, the next step was to fine-tune the 3-D print in order to achieve the most successful printed parts. The first step was determining the correct printing extruder temperature and printer bed temperature for ABS. The recommended temperature settings for ABS on the MakerBot Replicator 2X was a print extruder temperature of 230 °C and a heated bed of 100 °C. In addition, another important factor in creating a quality print was the printing speed. It was determined that the best speed combination was to have the plastic extrusion speed from the nozzle be the same as the nozzle along the printer bed. This results in an even distribution and correct amount of plastic extruded onto the printing bed. The most efficient extrusion speed which took into account print quality and printing time was 70-90 mm/s with a traveling speed (speed of extruder while not extruding plastic) of 130-150 mm/s.

The next printer setting factors are based on layer strength and printer time. The setting of layer height was determined to be 200 microns resolution which is the standard layer thickness which provides the benefits of both a relatively strong inter-layer bonds and a faster print. Another strengthening component was the number of perimeter shells or outside layers to the piece. For our pieces, we determined the proper amount of outside layers to be 4 which provides additional external strength to the parts for applications of localized loads. Within the outer layers, the setting of infill percentage is important. Having 3-D parts completely solid, or 100% infill, would obviously provide the most strength; however, this causes an extremely long printing time. Therefore, the determined infill percentage was 15% with an infill pattern of honeycomb. The honeycomb pattern provides a strong internal pattern to attain parts with high structural integrity while using the least possible amount of material when printing. The internal honeycomb pattern for a 3-D printed part is shown in Figure 6.10.

![Honeycomb Infill Pattern](image)

Figure 6.10 Honeycomb Infill Pattern

Another important aspect for producing optimal 3-D printed parts is the printing orientation and part printability. The first goal is to make sure the component can fit onto the printer platform. An STL (StereoLithography) file is created from a CAD file and imported into the MakerBot Desktop program shown in Figure 6.11. The part shown in Figure 6.11 is an example of a part that does not fit within the platform size in the z direction of the MakerBot Replicator 2X printer. Thus, the print will either need to be oriented differently or modified in order to fit within the constrictions of the platform size constraints. Next, it is essential that the 3-D printer can easily print the component. The parts are the strongest in the X and Y axes, while the Z axis generally tends to be the weakest due to inter-layer bonding strength. Therefore, components were designed in order to be printed mainly on the X and Y plane and less in the Z direction (less height). Moreover, the parts were designed in order to achieve smooth transitions between delicate features. Thus, fillets, chamfers, and blends were used extensively and significant overhangs (over 45 degrees) were avoided either by changing the print orientation or by redesign. If there were necessary overhang features in the part due to functionality, support material was printed to ensure the gap between the two sections could be met.

![Figure 6.11. MakerBot Desktop Print Orientation](image)

The final major printer settings and practice was preventing part warping. The main step was heating the build plate and applying an adhesive to the printer bed to ensure the first layer of the part stuck to the build plate. This usually entailed applying a thin layer of glue from a glue stick onto the build plate. An additional measure was taken at times to prevent part warping by enabling the raft option to provide the print with a broader first layer. An important factor in limiting warping as well was to limit the print time since the longer the print stayed on the printer bed, the longer it had the opportunity to warp away from the bed.
7 Propeller Thrust & Motor Selection

7.1 Design Criteria

In order for the drone to achieve flight, it needs to have enough thrust to lift off of the ground, hover, and maneuver in the air. For multi-rotor aerial vehicles, the rotor disk is generally oriented such that the force is called lift instead of thrust. As shown in the Figure 7.1 below, the source of thrust is from the propeller propulsion system. The thrust is caused by a change of pressure across the propeller disk, which can be rewritten in terms of a velocity change using Bernoulli’s equation. The general correlation is that the larger the propeller disk area, also called the propeller sweep area, the larger the lift/thrust force.

![Figure 7.1 Propeller Thrust](image)

Equation 7.1 shows the general thrust force equation used for the system. The velocity portion of the equation is just the change in velocity across the propeller disk. The exit velocity can be approximated to be the pitch speed of the propeller.

\[
F_{\text{lift}} = \frac{1}{2} \rho \frac{\pi d^2}{4} (V_e^2 - V_0^2)
\] (7.1)

In order for the drone to have enough thrust to hover, the total force weight of the drone has to equal the thrust force. However, the drone needs to also have enough thrust force to lift off and maneuver; thus, the thrust force equaling the drone system weight will not be sufficient. The general consensus is that to have enough throttle space for lift and maneuverability, the throttle force needs to be around twice the all-up weight (weight including electronics) of the drone and attached package.

---

The design criteria for propeller thrust is to select a propeller diameter and motor in order to have enough thrust force to lift the drone and package with reasonable maneuverability. In addition, the motor needs to be working towards the highest efficiency possible at maximum power usage and also at hover. Next, the linear throttle needs to be less than 80 percent in order to have enough space for maneuverability, which involves tilting therefore decreasing the thrust force of the drone. Preferably, the throttle will be around 50 percent at hover without the package and less than 80 percent with the attached package.

Another main portion of the design criteria of the propeller motor configuration is to have 10 minutes of flight time when the drone is carrying the package. This designed time will be enough time to attach, carry, and release packages to desired locations within a range of one mile, which can be considered the size of a college campus. Other design considerations are to choose a configuration that has a maximum power that does not exceed the limit of the motor and the critical temperature for overheating. The design of the motor mounts, which will be printed using 3-D printable thermo-plastics, must also account for the risk of plastic distortion during high power maneuvers.

In addition, there are also design criteria for the propeller size and number of motors/arms in terms of the frame and material selection. The larger the propeller size, the longer the arms that hold the motors need to be away from the main body of the drone since there needs to be clearance between adjacent propeller blades. For a larger amount of motors/arms, there also needs to be longer arms, as there is less space between adjacent arms. As a result, there are design obstacles for the length of possible plastic arms needed. The length of arm is constrained by the 3-D Printer platform size and the maximum stresses and impact forces due to external forces. There also is an additional cost for more motors, propellers and arm material if an eight-arm multi-copter is to be built. Therefore, if the desired criteria are for lifting the additional package with a low cost, then an additional design goal would be to limit the size of the propellers and number of motors/propellers.

### 7.2 Design Alternatives

#### 7.2.1 Approach

The process for finding the proper motor and propeller configuration first involves the determination the amount of power needed by each arm motor in order to lift the entire all-up weight of the UAV. The all up weight is the total weight of the drone, including the extra weight of the package. Based on methods by Professor of Aeronautical Engineering, Dr. Barnes W. McCormick[^14], and the equations shown below by helicopter flight emulator production company, Heli-Chair[^15], the theoretical thrust generated by a propeller or rotor can be calculated.

Equation 7.2 shows the lift per individual motor by assuming the maximum lift needs to be twice the weight of the drone with variable N equaling the number of arms.

\[ \text{Lift}_{\text{motor}} = \frac{2W}{N} \quad (7.2) \]

The next step is to determine a parameter called power loading in units of horsepower per square foot. The power loading is defined as the mechanical power delivered to the propeller per unit area of propeller. Power loading is calculated using Equation 7.3.

\[ P_{\text{Loading}} = \frac{P}{A} \quad (7.3) \]

After finding the power loading parameter, McCormick’s empirically defined formula is used to calculate thrust loading, which is in units of pound-force per horsepower, and is a function of power loading. Thrust loading is calculated using Equation 7.4.

\[ T_{\text{Loading}} = 8.6859 \times P_{\text{Loading}}^{-0.3107} \quad (7.4) \]

The next equation involves finding the thrust loading and lift per individual motor and relating it to the power needed for each motor while including an estimate for the efficiency, \( \eta \), of the motor. The electrical power needed for each motor is calculated in Equation 7.5.

\[ P = \frac{\text{Lift}_{\text{motor}}}{T_{\text{Loading}} \eta} \quad (7.5) \]

These equations were then solved in EES with varying all-up weights of the UAV, number of arms from four to eight arms, and propeller sizes in a range of eight to sixteen inch diameters to determine the power needed per motor. The EES calculations are in Appendix C.

The following graph, Figure 7.2, shows the total lift force produced per watt of electrical power delivered to each motor. The total lift is produced from four equal power motors of 85% efficiency. This curve was used to determine a suitable power per motor requirement when evaluating a motor’s peak power rating (20% greater than the continuous power rating). The estimated weight of the drone with a 3 lb. package and four motors was determined to be 11 lbs. The markers on the graph are used to indicate the necessary power required to produce double the weight in thrust.
7.2.2 Thrust Calculations Synthesis Method

The different combinations of estimated weight, number of rotors, propeller diameter, and motor power needed were entered into the Multicopter Calculator “eCalc” to determine the best possible outcome based on the propeller thrust and motor configuration desired criteria.\textsuperscript{16} The results provided by eCalc were confirmed by the team’s own calculations. The results are also shown in Appendix C.

Within the eCalc multi-rotor calculator, there were general trends determined for alternative solutions: 1.) Increasing the diameter of propellers causes an increase in motor power. 2.) Increasing the number of arms with propeller diameter constant, will result in less power draw from motors. 3.) An increase in propeller diameter will increase the flight time. 4.) The flight time is also dependent on the motor power and will be the highest at a certain range of optimal efficiencies.

With a higher kV motor selection, the larger the current and smaller the voltage, usually causing a larger power outcome. With too high of a power, the maximum power used by the motor can be over the limit of the motor. If too small a power, there will not be enough available power sufficient to hover.

7.3 Selected Design

Based on the calculations for motor thrust, the determined optimal design selection to carry the three-pound package was determined to be a quad-copter with a propeller size of 14 inches and pitch of 4.7 inches shown in Figure 7.3. The pitch is described as the distance a propeller would move in one revolution if it were moving through a soft solid, like a screw through wood. A higher pitch reaches a higher maximum speed, but at a slower acceleration. The selected motor was a Tarot 4114/320 kV shown in Figure 7.4. In addition, a chart for the Tarot motor with a 15-inch propeller blade was provided in Table 7.1. The chart shows various performance data for the 15-inch propellers. Knowing that the RPM will increase for a smaller propeller diameter, the team determined an average performance value of around 7000 rpm for the selected 14-inch propeller when doing the calculations, which therefore correlated nicely with the eCalc values. The optimal battery was a LiPo 4000mAh -20/30c 7S-2P battery shown in Figure 7.5. The full specifications and theoretical outcomes are shown in Figure 7.6, and a graph of the motor property data is shown in Figure 7.7.

Figure 7.3. Selected 14 Inch Diameter and 4.7 Inch Pitch Propellers

---

Table 7.1. Performance for a Tarot 4114/320kV Motor with 15 Inch Propellers

<table>
<thead>
<tr>
<th>Floating Current</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>RPM</th>
<th>g/W</th>
<th>W/Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.4</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22.2</td>
<td>0.5</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.2</td>
<td>0.6</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**THRUST TEST**

<table>
<thead>
<tr>
<th>Propeller: DJI—15x5</th>
<th>Thrust (kg)</th>
<th>Voltage (V): Current (A)</th>
<th>RPM</th>
<th>g/W</th>
<th>W/Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>25</td>
<td>5.2</td>
<td>4370</td>
<td>7.69</td>
<td>130.00</td>
</tr>
<tr>
<td>1.5</td>
<td>25</td>
<td>7.4</td>
<td>5045</td>
<td>8.11</td>
<td>123.33</td>
</tr>
<tr>
<td>2.0</td>
<td>25</td>
<td>11.1</td>
<td>5755</td>
<td>7.21</td>
<td>138.75</td>
</tr>
<tr>
<td>2.5</td>
<td>25</td>
<td>15.1</td>
<td>6311</td>
<td>6.62</td>
<td>151.00</td>
</tr>
</tbody>
</table>

**MAX THRUST TEST**

<table>
<thead>
<tr>
<th>Propeller: DJI—15x5</th>
<th>Thrust (kg)</th>
<th>Voltage (V): Current (A)</th>
<th>RPM</th>
<th>g/W</th>
<th>W/Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.15</td>
<td>22.2</td>
<td>14.5</td>
<td>5979</td>
<td>6.68</td>
<td>149.72</td>
</tr>
<tr>
<td>2.65</td>
<td>25.2</td>
<td>16.8</td>
<td>6655</td>
<td>6.26</td>
<td>159.76</td>
</tr>
</tbody>
</table>

---

Figure 7.5 Selected LiPo 4000mAh -20/30c 7S battery

![Image]

Figure 7.6 eCalc Final Configuration Model Data

<table>
<thead>
<tr>
<th>General</th>
<th>Motor Cooling: medium ▼</th>
<th># of Rotors: 4</th>
<th>Model Weight: 27.22 g</th>
<th>without Drive ▼</th>
<th>Field Elevation: 800 ft</th>
<th>Air Temperature: 25 °C</th>
<th>Pressure (QNH): 1013 mBar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Cell</td>
<td>Type (Cont. / max. C - charge state): LiPo 4000mAh - 20/30C ▼</td>
<td>Configuration: 7</td>
<td>Cell Capacity: 4000 mAh</td>
<td>Total Capacity: 16000 mAh</td>
<td>Resistance: 0.007 Ω</td>
<td>Voltage: 5.7 V</td>
<td>Weight: 105 g</td>
</tr>
<tr>
<td>Controller</td>
<td>Type: max 30A ▼</td>
<td>cont. Current: 60 A</td>
<td>max. Current: 60 A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor</td>
<td>Manufacturer - Type (kV): Tarot ▼</td>
<td>KV (kV/torque): 4114/2200KV/230 V ▼</td>
<td>No-load Current: 0.5 A ▼</td>
<td>Limit (up to 15A): 500 W ▼</td>
<td>Resistance: 0.125 Ω</td>
<td>Case Length: 92 mm</td>
<td>Weight: 145 g</td>
</tr>
<tr>
<td>Propeller</td>
<td>Type - yoke thickness: custom ▼</td>
<td>Diameter: 14 inch</td>
<td>Pitch: 4.7 inch</td>
<td># Blades: 2</td>
<td>R: 1.3</td>
<td>Gear Ratio: 1:1</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7.6 eCalc Final Configuration Model Data

---


The selected setup of a quad-copter with 14-inch propeller blades provides a configuration that meets the design criteria previously mentioned. The quad-copter is a very efficient system with an average efficiency of around 85%, which is the maximum realistic efficiency for a motor. In addition, the configuration has a mixed flight time of about 9.4 minutes, which is very close to the goal of around 10 minutes of flight time. Next, the hover throttle with the 3-pound package is at 67%, which is a good value since it meets the requirement of being less than 80% throttle for minimum maneuverability. Finally, the quad-copter has a maximum speed of 23.6 mile per hour, which is a respectable speed in order to deliver packages in a timely manner.

The eCalc tabulated results for the drone without the package is shown in Appendix D. The results show an extended flight time of 13.1 minutes and a higher maximum flying velocity of 35.4 miles per hour for the drone without the carrying load of the three-pound package. In addition, the hover throttle will be 46% without the package, which is very close to the design criteria of being around 50% hover throttle for a drone during normal flight without an additional load.
The selected drone design would have the ability to convert to a different configuration of 8 motors to carry different weighted packages, but would have a different optimal efficiency for doing so. The octo-copter would still have the same setup as the quad-copter including the same battery, controller, and motors, but just having 4 additional motors. Important thrust and flight results for the octo-copter are shown in the eCalc results table in A-5 involving specific additional loading cases: no-carrying load, a 3 pounds, a 6 pounds (twice the load of the quad-copter), 8 pounds (minimum maneuverability), and 14 pounds (max throttle necessary just for lift). A summary of important results to meet design criteria of flight time, throttle, and maximum speed for the octo-copter as well as the quad-copter is provided in Table 7.2 below. As shown in Table 7.2, both configurations provide the necessary setup in order to meet the design criteria and prove the feasibility of the efficient flight and carrying a load.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Loading [lbf]</th>
<th>Flight Time [min]</th>
<th>Hover Throttle [%]</th>
<th>Maximum Speed [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>No load</td>
<td>13.1</td>
<td>46</td>
<td>35.4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>9.4</td>
<td>67</td>
<td>23.6</td>
</tr>
<tr>
<td>8</td>
<td>No load</td>
<td>10.7</td>
<td>31</td>
<td>38.5</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>6.9</td>
<td>53</td>
<td>30.4</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>4.4</td>
<td>79</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>3.1</td>
<td>99</td>
<td>?</td>
</tr>
</tbody>
</table>

In conclusion, the selected quad-copter configuration involving the selected propellers and motors meets all of the design criteria previously mentioned in order to efficiently fly and carry a 3 lb. package. A possible disadvantage of this configuration would be the estimated temperature of 140° F at maximum motor use. This temperature would be higher than the distortion temperature of PLA. Another disadvantage to this configuration is the large dimensions of the arms. By having 14 inch propeller blades, the drone arms carrying the motors will need to be long enough so that the propeller’s sweep areas do not cross. Therefore, this will be a factor involving the frame design and using a 3-D printer with a set platform size.

8 Electronic Interface
8.1 Design Criteria
The on-board IMU must be fully calibrated before being installed into the drone and distributed to the customer. The micro-controller must incorporate a fail-safe mechanism to ensure the drone does not crash when transmitter connection is lost during flight. The electrical wiring and components must be well insulated and protected from the outside environment, and magnetic fields generated from the motors. Last, the auxiliary channel used for toggling the electromagnet on/off must be reliable.

8.2 Roll, Pitch, and Yaw
A quad-copter uses two pairs of counter rotating propellers to maneuver. For a quad-copter in an “X” orientation shown in Figure 8.1, each pair of motors lie on a different axis. In order to yaw, which is rotating about the z-axis (perpendicular to the ground), one pair of motors increases speed and the other pair of motors decreases speed. The increase in torque from the pair of motors causes the frame to rotate. In order to pitch or roll, one pair of motors decreases speed while the opposite pair increases speed. This causes the quad-copter to tilt and move forward in the direction of the tilt.

Figure 8.1 UAV Pitch, Roll, and Yaw

8.3 Micro-Controller

The single most important electrical component of a drone is the micro-controller. The purpose of a micro-controller is to stabilize the drone during flight by using a continuous feedback control system. There are two types of micro-controller boards used for aviation: inertial measurement unit (IMU) integrated, and non-integrated IMU controller boards. The most common interface for programming micro-controllers is through the Arduino IDE (integrated development environment). Some micro-controller interfaces include software that allows for the user to easily configure a micro-controller for a specific flight pattern. Other micro-controllers simply supply source code that the user must adjust via the Arduino IDE. The group researched many different controller boards; Table 8.1 shows the best types of available controller boards. The group evaluated the performance of each configuration against the different design criteria.

### Table 8.1 Controller Board Functionalities and Cost

<table>
<thead>
<tr>
<th>Controller Board</th>
<th>Integrated IMU</th>
<th>Programming Interface</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>OpenPilot Revo</td>
<td>Yes</td>
<td>OpenPilot GUI</td>
<td>$40</td>
</tr>
<tr>
<td>ArduPilot APM 2.6</td>
<td>Yes</td>
<td>Mission Planner GUI</td>
<td>$180</td>
</tr>
<tr>
<td>Hobby King MultiWii/MegaPirate AIO</td>
<td>Yes</td>
<td>Ardupilot Mission Planner GUI / MultiWii Configuration GUI</td>
<td>$50</td>
</tr>
<tr>
<td>Arduino Mega</td>
<td>No</td>
<td>Arduino IDE</td>
<td>$30</td>
</tr>
<tr>
<td>RCTimer Crius V2</td>
<td>Yes</td>
<td>Ardupilot Mission Planner GUI / MultiWii Configuration GUI</td>
<td>$50</td>
</tr>
</tbody>
</table>

The best controller board that meets the design criteria, and has the lowest relative cost, is the Hobby King MultiWii AIO controller board. This board features the 16 MHz Atmel ATMEGA250 micro-controller, which is also used on the Ardupilot 2.6 controller board, but is $100 less. The board features a 10-degree of freedom integrated IMU, which allows for very accurate attitude positioning and proportion-integral-derivative (PID) tuning. Furthermore, the board is cross platform compatible with the MultiWii interface and the Ardupilot Mission Planner interface. The IMU can be configured and calibrated using either programming interface.

#### 8.4 Electronic Speed Control

The design requirements for the electronic speed control (ESC) are that it has a maximum current rating of +20% of the maximum current draw from the motor. It should be noted that each motor requires an individual ESC due to the high power draw from the 25V 8000 maH power source.

#### 8.5 Electromagnet

The design of the PAM incorporates four electromagnets. Each electromagnet is rated for a 25V power source. The power calculations revealed that each electromagnet draws 2% of battery power, which is 160 maH. With four electromagnets, the power requirement quadruples to 8% of battery power.

#### 8.6 Relay Switch
A relay switch was used to turn on/off the electromagnets. The relay switch used was rated for a 10A/25VDC power draw, which was more than sufficient for the power draw from the four electromagnets.

### 8.6.1 Code Modifications

The relay switch is turned on/off from a digital (5V/0V) signal. The open source code was modified to produce a 5V digital signal from one of the outputs on the microcontroller when one of the PPM auxiliary inputs reads greater than 1400 microseconds. A single if-else statement was added to the microcontroller loop function to achieve this functionality. A function called “readRawRCvalue” was used to read the PPM signal from the receiver channel to the microcontroller and return the value in microseconds.

### 8.6.2 Relay Switch Schematic

The following figure shows the relay switch interface with the microcontroller and the 25V 8000 maH power source.

![Relay Switch Schematic](image)

### 8.7 Materials

The electronic interface will consist of the following components:

- Lithium Polymer battery – 4000 maH 7S 2P
- Controller board with integrated IMU – Hobby King MultiWii/MegaPirate AIO
- Transmitter and Receiver – Spektrum 2.4 GHz
- ESC(s) – Turnigy 30A
- Brushless DC motors – Tarot 4114 320 (kV)
- 25 lb rated Electromagnets – APW EPM100-24
- 10A/25VDC Relay Switch
The following schematic, Figure 8.2, shows the layout of the electronic interface. The schematic is for a quad-copter configuration. The microcontroller can support up to 8 motors, plus 2 more servo outputs. It also features an I2C communication port for an additional sensor.

8.8 Design Alternatives

There are two open source platforms that the team found are most popular for aviation control: MultiWii and Ardupilot. Both of these control programs are developed for Arduino Mega based flight control boards. The MultiWii platform has less sophisticated control algorithms than the Ardupilot control program, but offers a wide range of supported controller boards, including the Arduino Uno. The Ardupilot platform has limited controller board options due to its support of only Arduino Mega based flight controllers, but it has a more successful control algorithm, which has won it awards in the 2012 and 2014 UAV Outback Challenge. The Ardupilot platform is supported by the DIYDrones online community, and like MultiWii, is also built and compiled using the Arduino IDE.

8.9 Selected Design

The final electronic interface will incorporate a Hobby King MultiWii/MegaPirate AIO controller board. The controller board will be configured using the MultiWii open source platform. The integrated IMU will be calibrated using the MultiWii configuration program.

Two 4000 maH 7S (25V) batteries will be used to power the motors and the electromagnets. These batteries will be connected in parallel. Each motor will be connected to an ESC, which will be connected to the PWM output pin on the controller board. The channel wires from the receiver will connect to the PPM input pins on the controller board. The power from one ESC will be used to power the controller board.

9 Frame Design
9.1 Design Criteria
The frame of the UAV is configurable to two different flight setups: quad and octo-copter. The user is able to switch between these with a reasonable effort as none of the parts are permanently affixed to another part and are removable with readily available tools.

The frame contains of a ports to which the arms can be attached, a unit to house the batteries and a mount for the PAM magnets.

The natural frequency of the frame was engineered to be higher than the frequency of the blades during maximum rotational velocity in order to eliminate resonant stresses. The arms are able to lift the body of the UAV, along with its payload, with limited deflection, as deflection in the arms can cause the UAV to be unstable.

9.2 Design Alternatives
One option for a UAV frame is to simply purchase one that is available on the market. There are many companies and people who make and sell these frames at a variety of price points, and they are readily available to purchase. These frames are made specifically for a fixed number of motors, so a new frame would need to be purchased if a different number of motors is required. Many of these frames are injection molded into a single part so if part of the frame fails, the whole frame needs to be replaced.

A second option is to make the frame out of aluminum. Aluminum is readily available in extruded tubes of varying sizes and shapes, is relatively inexpensive and has a good strength to weight ratio. An aluminum frame would be made by welding the extruded tubes together, or by connecting them with fasteners. Welding aluminum is difficult to do and requires specific equipment that is not readily accessible to the general customer. Also, connecting parts of the frame with fasteners make for more areas for stress risers. Fasteners are also more likely to fail in the presence of vibrations.

9.3 Selected Design
To help visualize the required dimensions of the frame, a wooden model of the UAV was created as shown in Figure 9.1. This also allowed the team to easily adjust the dimensions based on the thrust calculations and translate the dimensions into a CAD model.
The design that was selected uses 3-D printed parts with carbon fiber arms.

The motor mounts, center body, battery holder and magnet holder are made from 3-D printed ABS plastic and are shown in Figures 9.2, 9.3, 9.5, and 13.3, respectively (material properties can be found in Appendix B). The geometries were designed in Solid Works and/or Autodesk Inventor and were printed on a MakerBot Replicator 2X at GR Makers.
Figure 9.2 Motor Mount

Figure 9.3 UAV Main Body
The arm shafts are made from 25 millimeter diameter carbon fiber tubes with a 1 millimeter wall thickness shown in Figure 9.4. Carbon fiber works well because it is very stiff, so it is not affected as much by vibrations from the motor and propellers. It also has a high strength to weight ratio. Carbon fiber was also selected because the length required for the arms exceeds the printer platform size of the MakerBot Replicator 2X.

![Image of carbon fiber tube with motor assembly](image)

Figure 9.4 Carbon Fiber Tube with motor assembly (carbon fiber plate not pictured).

Each arm consists of two parts assembled together. The first part of the arm is the carbon fiber shaft. This is the portion that connects the body to the motors. The length of these arms is 400 mm. The second part of the arm is the motor mount. This includes a 2 in. diameter flat portion for the motor to sit. There are 3 holes at the bottom of the mount for attaching the motors. A carbon fiber plate I placed between the motor mount and the motor to give the motor a stiff base to sit on. It was discovered that connecting the motor directly to the motor mount caused the motor to slightly deform making the motor run rough. The stiffer carbon fiber plate resolved this completely. The carbon fiber tube is inserted into the motor mount and the four bolts tighten the top and bottom piece leading to a friction fit.

The main UAV body also incorporates two pieces. The other end of the carbon fiber tubes are inserted into the UAV main body which acts as an “arm hub” for the drone. An array of evenly distributed bolts tighten the top and bottom piece leading to a friction fit around the carbon fiber tube arms. The body pieces were designed in order to fit within the constraints of the MakerBot Replicator 2X printer bed. They were also designed for the drone to have the ability to configure into the quadcopter and octocopter. In addition, there are wiring outlets from the carbon fiber tube openings into the center of the piece where ESC wires can be routed through to the flight control board and power distribution board.
A 3-D printed part was also designed in order to store the batteries directly underneath the main body of the UAV. The batteries center of gravity was designed to be in the center of the drone and underneath the main body frame of the arm hub in order to maintain consistent and user-friendly flight. Having the batteries weight above the center of drone would cause the drone to be top-heavy and result in less desirable flight controls. The battery holder part is shown in Figure 9.5. The battery holder was designed in order to property fit within the platform size constraints of the MakerBot Replicator 2x printer. It incorporates smooth transitions and no support is necessary providing for an optimal 3-D print. It is designed in order to ensure a tight enclosure for the two batteries. There is a backing to stop the batteries from sliding out the front and velcro straps in the back to securely fasten the batteries, while still allowing the user to easily remove them for charging purposes. In addition, the battery holder has evenly-spaced fastener holes to disperse the forces of the magnet and package weight evenly across the entire piece. Finally, the battery holder incorporates fastener holes for attaching the magnet holder part and an opening to the flight control board (center hole) for the magnet wires.

The body is designed to allow for four or eight arms to attach to it. The quadcopter design is shown in Figure 9.6, and the octocopter is shown in Figure 9.7. The length of the arms of the drone were designed to allow clearance between the 14 inch propellers for the octocopter configuration.
Since the motors and propellers are not perfectly balanced, they create vibrations. These vibrations are especially hard on areas at which two components join. Since many of the connections rely on a friction fit, it was important to take efforts to help these joints. The tolerance between the carbon fiber tubes and the connecting points are very tight so the tubes are always being compressed. The carbon fiber tubes were also sanded to increase the coefficient of friction. Also, carbon fiber tubes were selected because of their stiffness. This stiffness makes the resonant frequency of the arm higher than the forced vibration of the motors so the arms never reach resonance.
The final quadcopter prototype frame is shown in Figure 9.8. The quadcopter prototype frame clearly represents the vision of the CAD designed quadcopter of Figure 9.6 and has the same capability of transforming into the octocopter shown in the CAD design in Figure 9.7.

![UAV Quad-copter Prototype](image-url)

**Figure 9.8. UAV Quad-copter Prototype**

10 Landing Legs Design

10.1 Design Criteria

The landing legs must be able to safely absorb impact energy from vertical drops of up to 3 feet. The landing legs must also be lightweight due to the very sensitive weight requirements of the scope of this project.

10.2 Design Changes

Initially, the group was decided on printing curved rectangular cross section beams for landing gear. However, the design was not able to be printed using standard FDM printing technology. Therefore, the design was simplified to a straight rectangular design.
Another design change was made that incorporated two reinforcing carbon fiber rods into the design. The carbon fiber rod was used to attach two adjacent landing gears together, as shown in Figure 9.7. The benefit of this change was that the force at impact on one landing gear, which previously caused torsion in the landing leg, would be distributed to two landing gear. The friction force between the carbon fiber rod and the plastic would theoretically double as a result of this design change, which warranted the design change.

10.3 Impact Force Calculations

The group used the data collected from the impact force testing to use as a basis for theoretical impact force calculations. Theoretical impact force calculations are located in Appendix E. The theoretical model for the landing leg was a spring-mass first order system. The landing leg plus the foam was modeled as a spring with a mass of one-quarter the weight of the drone because the weight of the drone is distributed equally to each landing leg.

First the stiffness properties of the foam and landing gear were determined. For the foam, a simple load-deflection experiment was performed to determine a stiffness; a force of 5 lbf produced a deflection of 10 mm. This translates to a stiffness of about 2200 N/m. Next, the stiffness of the landing gear was determined by using the modulus of elasticity and geometric dimensions of the part. The modulus of elasticity was obtained from the tensile test data and was equal to 20 MPa. The stiffness of the landing gear was calculated to be 250,000 N/m. Using the following equation for two springs in series

\[ \frac{1}{k} = \frac{1}{k_{\text{landing gear}}} + \frac{1}{k_{\text{foam}}} \]

The stiffness was calculated to be 2200 N/m. It should be noted that the stiffness of the foam dominates the overall stiffness of the system.

Next, the period for compression was determined using the following equation for the period of spring oscillation.

\[ T = 2\pi \sqrt{\frac{m}{k}} \]

Where \( m \) is the mass of the spring and \( k \) is the equivalent stiffness of the foam and landing leg in series. The time of compression is equal to half the period because the spring collapses and expands in one oscillation.

Third the final velocity from a drop of height \( h \) was determined using the following equation of motion.

\[ v_f^2 = v_0^2 + 2gh \]

Where \( v_0 \) is equal to zero and \( g \) is the acceleration due to gravity.

Finally, the impact force was determined using Newton’s second law.

\[ F = m \frac{v_f - 0 \, m/s}{t} \]

Where \( t \) is the time of compression (\( T/2 \)) and \( v_f \) is the velocity right before impact. It should be noted that the actual velocity is less than the calculated value because of wind resistance. However, this calculation gives a conservative estimate, which is ideal for engineering purposes.

10.4 Results of Theoretical Calculations
The calculations showed that with the current setup, the generated impact force at a height of 2 feet is about 13 lbf, which is 5 lbf greater than the breaking force determined in testing. In order to reduce the impact force to meet the required goal of 3 feet, the group would have to obtain a material with a stiffness of about 500 N/m. Due to the limitations in being able to procure such a material, the group has determined that the drone is suitable for only impact heights of up to 18 inches.

10.5 Materials

Four 3-D printed materials were researched for building the landing legs. These include: PLA honeycomb, PLA lines, ABS honeycomb, and ABS lines. It should be noted that the honeycomb distinction means that the printer saves material when printing solid cross sections by printing a honeycomb pattern. See Appendix B for yield strength, specific strength, and Young’s Modulus values for these materials printed using common printers. The material used to print the landing gears was ABS plastic because it produces the highest quality prints on the MakerBot Replicator 2X.

10.6 Selected Design

The final design will be a straight landing gear leg, as shown in Figures 10.1 and 10.2, that is constructed using 15% fill ABS plastic. The cross-sectional area of the landing leg will be 0.25 x 0.75 inch with a length of 3 in. The four landing legs will be attached to the frame of the drone by using screws fasteners. The landing legs will be reinforced by two carbon fiber cross beams which will connect into adjacent landing legs. In addition to the plastic legs, whiffle balls filled with foam were attached to the bottom of the leg. The foam absorbs impact energy and greatly reduces the impact force, as shown in the calculations in Appendix E.
Figure 10.2 Final Landing gear design. (Foam is inserted inside a wiffle bar attached to the bottom of the landing gear. Adjacent landing gears are connected by a carbon fiber rod.)

11 Vibrations Analysis

11.1 Theoretical Analysis

A vibrational analysis was performed on the carbon fiber arms to assess the risk of reaching resonant frequency during flight. These calculations are located in Appendix G. First, the resonant frequency of the carbon fiber rods had to be theoretically determined by assuming the arms resemble a rigidly fixed cantilever arm. The following equation is the stiffness of a cantilever beam.

$$k = \frac{3EI}{l^3}$$

(12.1)

The Modulus of Elasticity (E), second moment of area (I), and the length (l) where given based on the dimensions of the arm and the material properties of carbon fiber, which were obtained from the built-in Inventor material libraries. Then, using the following theoretical equation for natural (resonant) frequency, the natural frequency was determined.

$$\omega_n = \sqrt{\frac{k}{m}}$$

(12.2)

Finally, the maximum frequency of oscillation had to be determined. The maximum frequency of oscillation was determined using the following generic equation.

$$\omega_{\text{max}} = 2\pi n_{\text{max}}B$$

(12.3)
Where $n_{\text{max}}$ is the maximum rpm of the motor, and $B$ is the number of blades per propeller.

### 11.2 Theoretical Results

The dimensions of each carbon fiber rod are: length (9in – 228.6mm), diameter (25mm), and thickness (1mm). Based on these dimensions, the natural frequency of each arm was determined to be 2562 radians per second. The maximum frequency of oscillation, based on max revolutions per minute of 7000 and two blades per propeller, was determined to be 1466 radians per second. This yielded a safety factor of about 1.7 against resonant frequency. Calculations for vibration analysis are located in Appendix G.

### 11.3 Flight Results

There were no significant vibration issues during flight-testing.

### 12 Package Attachment Mechanism

#### 12.1 Design Criteria

The Package Attachment Mechanism or PAM will be used to center the drone over the package and attach the package to the body. The package should be aligned with and connected to the drone using only electrical controls (without it being manually manipulated). The PAM design will be low weight to keep the weight of the drone low and keep the flight time high. The package will be securely attached to the PAM to prevent it from being released while in flight and potentially injure someone or damage personal property. The PAM will hold the package in such a way that it does not make the drone difficult and dangerous to pilot.

#### 12.2 Design Alternatives

One design alternative is to have the PAM fixed to the drone and have a person manually place and remove the payload to/from the drone. This procedure is how the DHL package delivery drone is designed. The issue with this is that a person has to manually load and unload the payload.

A second design alternative is to connect the package to the drone manually and have the PAM release the package from the UAV. This is how the Google and Amazon UAVs work. The issue with this is that the drone cannot pick up the package without the use of an auxiliary mechanism.

A third design alternative is to have a mechanism that can pick up any shaped box. This would be flexible enough to accommodate many different sizes and shapes and would carry the package is such a way that keeps the package intact and the cargo inside safe. This design would increase the weight and power consumption, which would make the design not worth pursuing.
A fourth design alternative is to have a mechanism that connects to the outside of a fixed dimension box. The mechanism would grab the box by its outside edge by coming from a larger footprint and moving the lifting arms towards the center until the package is secure. An issue with this mechanism is aligning the mechanism with the top of the box. Either the drone needs to be perfectly aligned with the package when picking it up or the lifting arms need to extend well past the outside parameter of the package. This would require an unrealistically stable UAV or a large and heavy mechanism.

A fifth design option is to have a package with pole extending out of its top with a ball at the end of it. This ball will enter the bottom of the PAM where it will be secured. The ball will be secured with two clamping levers with a reduced diameter hole that will prevent the larger ball from sliding through. The clamping levers will be held closed by an extension spring and will be opened with a small high-torque servo, which will be controlled from the flight control transmitter. This was the initial design decision; however, after extensive research and collaboration, it was determined that this design alternative would be too costly, heavy, and complicated for the purpose of picking up and dropping off the package.

The next major alternative considered was to implement a single electromagnet in achieving the pick-up and drop off of a ferrous material covered package. The electromagnet would be attached to a relay switch, which could then allow a user to turn on/off the electromagnet via the controller. The electromagnet would be a 24V electromagnet with a holding force of 19-25 lbs. This PAM design alternative was tested during flight in holding the package. While it could hold the 3 lb. package, the electromagnet would sometimes drop the package expectantly due to the moment arm of the package while flying at various angles.

12.3 Selected PAM Design
The chosen PAM design was four 24V electromagnets with 25 lbs. holding force each arranged in a rectangular pattern underneath the batteries of the drone. This selected design was determined based on previous testing knowledge of the single electromagnet. In order to reduce the moment arm of the package, three additional electromagnets were added that would cause additional electromagnet surface contact area at various areas of the top package surface. Having all four electromagnets engaged with the package would reduce the moment arm and increase the overall holding strength. The electromagnets would also be connected to a relay switch that could control the current provided to the magnets via the controller. The user could fly the drone above the package, land on top of the package in order for the four electromagnets to contact the ferrous material on the top the package, turn on the magnets via a toggle switch on the controller, fly with the package, and then drop off the package by turning off the electromagnets via the toggle switch. The 3-D printed component where the magnets will be held is shown in Figure 13.3. The electromagnets would only consume around 8 percent of the battery life, which would not significantly decrease the flight time of the drone while carrying the package.
13 Cost

The cost for the project is over $1400. This cost can be broken down into two major components, the cost of the propulsion system and the cost of the frame.

The cost of the propulsion system includes the electronics and motors required to fly the UAV. The main costs come from the batteries and motors. Expensive batteries and motors are required due to the requirement to lift the 3-pound payload.

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<td>Contingency (20%)</td>
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</table>
The cost of the frame is dependent on where and how the parts are 3-D printed. It was decided that the frame parts will be printed at GR Makers using their MakerBot Replicator 2X printer. The materials for this printer are free, as they are donated to GR Makers, but the use of the printer requires a membership to their club. This membership costs $30 a month for students. The total cost of the membership was $360. This gave Jeff and Kemal access from January through May, and Ross access from February through May.

The frame cost $480 to produce, which includes the GR Makers membership. Without membership costs, the expected cost to another user to build the frame is $120; this cost includes the propellers, carbon fiber tubes, and plastic filament costs.

## 14 Testing

### 14.1 Moment Arm Testing

The goal of this test was to see what kind of load the motor mount–arm–frame assembly can handle. A single motor mount and arm assembly was connected to the frame. Carbon fiber tube scraps were placed in the other holes to keep the spacing even. The frame was then clamped into a vice up-side-down and a bucket was placed on the motor mount where the motor would be attached. Figure 14.1 shows the testing setup. Weight (scrap steel) was added to the bucket in increments of about 1 lb. At each increment, the assembly was inspected. The goal was for the assembly to handle 7.5 lbs. as this would allow for a 1.5 safety factor. Weight was added until the total weight was 8.25 lbs. At this point, the frame made a cracking sound so the test was stopped. This test showed that the assembly has a 1.65 safety factor, which is greater than what was expected.

![Figure 14.1. Moment arm testing set up.](image)
14.2 Tethered Testing
Once the UAV was assembled, it was placed into a wooded tethering fixture. The UAV was connected at two ends by cables and those cables were then tensioned, allowing it to rotate around one axis. The drone was then powered on and started up. The throttle was increased until the thrust of the motors was holding it up. The transmitter was then used to rotate the UAV about the axis. A long stick was then used to push the arms up to see how they respond.

The first axis that was tested was the roll axis. The UAV responded quickly and with precision to the transmitter controls. The UAV responded quickly and with precision to the stick agitation as well. This indicated that the PID values were sufficient to control the roll axis without the tether.

The second axis that was tested was the pitch axis. The UAV responded quickly and with precision to the transmitter controls. The UAV responded quickly and with precision to the stick agitation as well. This indicated that the PID values were sufficient to control the pitch axis without the tether.

14.3 Initial Flight Testing
After the tethered testing was successful, the UAV was brought to the Calvin College Tennis Center for some controlled environment flight-testing. The UAV was powered on and put through a few tests to see how it handled.

First, the thrust was tested. The thrust was increased until the UAV left the ground. This happened at about 60% throttle, which was expected. The thrust was then adjusted until the UAV was hovering, this happened at about 45% throttle, which was close to what was calculated in the thrust model.

Next, the yaw was tested. The UAV was turned left and right. They UAV responded well to the controls, which indicated that the YAW PID settings were optimal.

Next, pitch and roll was tested. The UAV was driven forward and backwards, and left and right. The UAV responded well to the controls, through it was found that the UAV was very sensitive to the controls. This was expected since the UAV was being flown without its payload weight making it over-powered for the weight at which it was flying.

Next, the package was added to the UAV and it was free-flown with the package. It was found that the UAV handled with much more control with the additional weight of the package.

The biggest lesson learned from flight-testing was that the landing gear had to be changed. When the UAV would land, the landing gear would be twisted from the torque of hitting the ground at an angle. This led the team to changing the landing gear to its current design.

14.4 Flight Time Testing
To test the flight time, the UAV was flown around in an open field away from people. The drone was flown back and forth on the field until the power in the batteries was too low for flight to be sustained. The drone was flown without the package. A second teammate was present to time the flight and to ensure people did not enter the flight area. The drone flew a total of 18 minutes. This was 3 minutes longer than what was predicted by the calculations.

### 14.5 Flight Distance Testing

To test the flight distance, the UAV was taken to the baseball diamond at Calvin College. The distance between home plate and the end of the practice soccer field is .16 mile (figure 14.2.).

![Figure 14.2. Flight path for flight distance test. (Using www.mapmyrun.com)](image)

The drone was flown a total of 6 lengths of the flight path making the total distance around 1 mile. One teammate was at home plate. Another teammate was at the end of the soccer field. They were there to help communicate to the pilot when the drone was directly overhead so the pilot knew the complete length was achieved. The pilot was in the middle of the flight path and flew the drone from there. The first 3 lengths (.5 mile) were flown with the package and the final 3 lengths were flown without the package. The drone successfully flew the entire mile.

### 14.6 PAM Safety Testing

A PAM safety test was planned but had to be canceled after the drone crashed and the magnets of the PAM were destroyed. The team did not have the time or the money to buy new magnets to repair the prototype. The excerpt below is the test that was planned for the PAM from the PPFS.
“The PAM will be attached to the center of a 2 x 2 foot piece of 1 inch plywood. An I-bolt will be connected at each corner. A 4-foot long piece of cable will be connected to each I-bolt and the other side will be attached to an anchor above it. The PAM package will then be loaded with its maximum carrying weight of 3 pounds and attached to the PAM. The whole assembly will be lifted to the anchor point of the rope and will be dropped. The PAM will pass the test if the package is still securely attached.”

While the team did not have a chance to do a controlled test, they did have a chance to fly it with the package attached to the drone using the PAM. The best example of this was during the flight distance test. For this test the package was attached to the drone for half a mile and the PAM worked properly. While this does not show that the PAM would work under extreme conditions, it does show that the PAM could be successfully used in normal flight conditions safely.

15 Safety

15.1 Public Safety

While the use of UAVs by the general public is becoming much more commonplace than even 2 years ago, it is important to remember that these machines are not toys and can cause harm with those who come in contact with them. The rotors spin at high rotational velocity. If they come in contact with a person, the rotors can lacerate the skin.

The UAV also poses a risk to people, as it will be heavy, and has the potential to injure people. The whole setup will be over 8 pounds and will be able to travel at a high velocity. This means that the UAV has a lot of kinetic energy at a high speed and can cause harm to anyone it runs into. Furthermore, the propeller blades are extremely sharp and can easily pierce through skin and bone.

15.2 FAA

The FAA is the governmental body tasked with the US airspace. They ensure that air traffic is run in a safe manner. The FAA has not yet introduced regulation for the inclusion of UAVs in US airspace. They have a blanket ban on UAV use for commercial purposes but do allow UAV use for non-commercial purposes. They classify these as model aircraft.

Model aircraft can be used, but must be used within certain guidelines. First, a UAV may not be flown at any altitude within 2 miles from an airport. Second, a UAV may not fly higher than 400 feet from the ground. Third, a UAV must be tested to ensure it can fly safely before it can be flown near spectators. Fourth, a UAV may only be flown in an area “a sufficient distance” from populated areas. Last, the UAV must always be flown within “line-of-sight” of its operator.

15.3 Safety Precautions
To prevent accidents that harm people or damage property, a series of precautions were taken during the course of this project. Before flying in public areas, the UAV was tested to ensure it flew in a safe and predictable manner. Before each flight, the UAV is visually inspected to make sure all the parts are in good working order. After any crash or hard landing, the UAV is inspected to ensure it is not damaged. If the UAV is inspected and found not to be in good working order, the issues is corrected before it is flown again. Before each flight, the weather conditions are assessed and the UAV is flown in conditions in which it can be predictably controlled.

15.4 Additional Recommended Precautions

The team did not have time to implement the following safety precautions but recommends that people building a similar drone take them. First, since the PAM is reliant on magnet to carry the payload, it would be good to implement a secondary mechanical latching system. This redundant system would ensure the package stays attached to the UAV and is not accidentally released. Second, the team recommends adding propeller guards. This will help protect people from the propellers if the drone is accidently flown into them. This also will protect the propellers from trees or poles, which could damage the propellers, making it difficult to control.

16 Conclusion

The completed 3-D printed drone along with the successful package delivery tests indicates the project was a success. A majority of the initial goals of this project were achieved due to the time doing up-front calculations, the prototypes that were tested and built, and the lessons learned from the iterative design process.

The key lessons the team is walking away from this project with are to double check critical equipment, to communicate important information to the rest of the team, and to build in contingency to both the budget and schedule. These items would have saved the team some difficulties towards the end of the project when the drone experienced a large crash.

If this project were to continue, there are a few things the team would like to see happen. The first is to build safety features into the drones design. This would include adding propeller guards, adding a return to home function when communication between the transmitter and the drone is lost, and adding a backup mechanical attachment mechanism to the PAM.
17 Acknowledgements
The team would like to acknowledge the assistance provided by the Senior Design Professors, with special regard to our team advisor, Professor Nielsen, who gave the team guidance throughout the duration of the course and design process. In addition, the team expresses appreciation to other engineering faculty members for their help. Professor Kim was extremely generous and helpful to the team. He provided materials, gave engineering advice, and was a great support throughout the year. Professor Emeritus DeJong was very helpful in providing insight to the vibration section of our design. Professor Tubergen, our industrial consultant, was also a great source for engineering insight. Phil Jaspers provided assistance and knowledge pertaining to 3-D printing, materials, and metal shop. Chuck Holwerda was very helpful in providing electrical equipment and guidance. The team would also like to thank Bob DeKraker for his assistance with the 3-D printed parts tensile test and helping the team acquire essential materials. Finally, the team would like to thank Mark Van Holstyn of Mutually Human for providing our membership at GR Makers.
18 References/Bibliography


### 19 Appendices

#### Appendix: Table of Contents

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<th>Page</th>
</tr>
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<td>62</td>
</tr>
</tbody>
</table>
Appendix A. Microsoft Project Schedule
# Appendix B. 3-D Printable Plastic Material Comparison

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>ABS Lines</th>
<th>ABS Honeycomb</th>
<th>PLA Lines</th>
<th>PLA Honeycomb</th>
<th>VisiJet Black (Acrylic-base)</th>
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</thead>
<tbody>
<tr>
<td><strong>Yield Strength</strong></td>
<td>20 MPa (u printer)</td>
<td>15 MPa (cb printer)</td>
<td>40 MPa (felix)</td>
<td>17 MPa (felix)</td>
<td>35.2 MPa</td>
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<tr>
<td><strong>Young’s Modulus</strong></td>
<td>1300 MPa</td>
<td>1000 MPa</td>
<td>2500 MPa</td>
<td>1200 MPa</td>
<td>1594 MPa</td>
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<tr>
<td><strong>Specific Strength</strong></td>
<td>22.5 Nm/g</td>
<td>22 Nm/g</td>
<td>39 Nm/g</td>
<td>31.5 Nm/g</td>
<td>34.5 Nm/g</td>
</tr>
<tr>
<td><strong>General Characteristics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Part Accuracy</td>
<td>some part warping</td>
<td>same as ABS Lines</td>
<td>liquefies, sharper details, stronger layer binding</td>
<td>same as PLA lines</td>
<td>sharp and high-resolution details</td>
</tr>
<tr>
<td>Flexibility</td>
<td>mild flexibility</td>
<td>same as ABS Lines</td>
<td>more rigid</td>
<td>same as PLA lines</td>
<td>some flexibility</td>
</tr>
<tr>
<td>Modifications</td>
<td>easily sanded, machined</td>
<td>same as ABS Lines</td>
<td>with more work, sanded and machined</td>
<td>same as PLA lines</td>
<td>easily sanded, machined</td>
</tr>
<tr>
<td>Recyclability</td>
<td>very high</td>
<td>same as ABS Lines</td>
<td>medium</td>
<td>same as PLA lines</td>
<td>low</td>
</tr>
<tr>
<td>Earth-friendly</td>
<td>petroleum-based</td>
<td>same as ABS Lines</td>
<td>plant-products</td>
<td>same as PLA lines</td>
<td>organic material</td>
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<tr>
<td>Heat Distortion Temperature @ 0.46 MPa</td>
<td>208.4 degrees F</td>
<td>same as ABS Lines</td>
<td>110 degrees F</td>
<td>same as PLA lines</td>
<td>134 degrees F</td>
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<tr>
<td>Aesthetics</td>
<td>soft milky beige</td>
<td>same as ABS Lines</td>
<td>translucent/glossy</td>
<td>same as PLA lines</td>
<td>black/glossy</td>
</tr>
</tbody>
</table>
Appendix C. Power-Thrust Calculations

"Power-Thrust Calculations"

"SETUP"
W = 11.38908[lb_f]  "All-up weight of UAV"
N_motor = 4  "Number of motors/propellers"
n = 0.85  "Average efficiency of motors"
RPM = 7000  "Estimated setup RPM"

"BATTERY"
V = 25  "Selected motor voltage in volts"
N_Batt = 2  "Number of batteries in parallel"
C = 4000  "Battery cell capacity in mAh"

"PROPELLER"
D = 14 [in]  "Propeller diameter in inches"
Pitch = 4.7 [in]  "Propeller pitch in inches"
A = 0.25*pi*D^2  "Propeller sweep area in square inches"
A_ft = A*convert(in^2, ft^2)  "Propeller sweep area in square feet"

"FULL THROTTLE"
PL = (P_in*n)/A_ft  "Power loading equation"
TL = 8.6859*PL^(-0.3107)*1[lbf/hp]  "Thrust loading equation"
Lift = TL*(P_in*n)  "Lift per Motor"
Lift_Total = Lift*N_motor  "Total lift of the UAV"
P_inWatt = P_in*convert(hp,W)  "Power input to motor in Watts"
Lift_Total = 2*W  "Common Thrust-to-Weight Ratio to generate needed lift"

I_tot = I_motor*N_motor  "Total UAV current  
I_motor = P_inWatt/V  "Current of motor"
P_inWatt = P_outWatt/n  "Power relation involving motor efficiency"
KV_req = RPM/V  "Required KV of motor"
NomKV_req = KV_req/n  "Nominal KV (labeled) of motor which accounts for efficiency"
ESC_req = I_motor*1.2  "Required ESC current for motor"

"HOVER"
PL_H = (P_Hin*n)/A_ft  "Power loading equation for hover"
TL_H = 8.6859*PL_H^(-0.3107)*1[lbf/hp]  "Thrust loading equation for hover"
Lift_H = TL_H*(P_Hin*n)  "Lift per motor at hover"
Lift_HTotal = Lift_H*N_motor  "Total lift of the UAV at hover"
P_HinWatt = P_Hin*convert(hp,W)  "Power input to motor at hover in Watts"
Lift_HTotal = 1*W  "Total hover UAV current  
I_Htot = I_Hmotor*N_motor
I_Hmotor = P_HinWatt/V
P_HinWatt = P_HoutWatt/n

"Current of motor at hover"
"Power relation involving motor efficiency"

"ENDURANCE"
t_hover = (60*(C/1000)* N_Batt)/I_Htot

t_fullthrottle = (60*(C/1000)* N_Batt)/I_tot

t_average = (t_hover+t_fullthrottle)/2

"Hover endurance time based on the battery capacity and motor current"
"Full throttle endurance time based on the battery capacity and motor current"
"Average endurance time"

Unit Settings: Eng F psia mass deg

A = 153.9 [in²]
D = 14 [in]
I_Htot = 27.01 [A]
KV_req = 280 [rpm/V]
Lift = 5.695 [lbf]
NomKV_req = 329.4 [rpm/V]
Pitch = 4.7 [in]
P_Hin = 0.2264 [hp]
P_Htot = 27.01 [A]
RPM = 7000 [rpm]
t_average = 12.14 [min]
V = 25 [V]

A_R = 1.069 [ft²]
ESC_req = 22.15 [A]
I_motor = 16.46 [A]
Lift_Total = 22.78 [lbf]
NomKV = 2 [rpm/V]
FL = 0.492 [hp/ft²]
P_L = 0.18 [hp/ft²]
RPM = 7000 [rpm]
TL = 10.83 [lbft/hp]
W = 11.39 [lbf]

C = 4000 [mAh]
I_Hmotor = 6.752 [A]
I_tot = 73.82 [A]
Lift_H = 2.847 [lbf]
n = 0.85
N_motor = 4

Table C-1. Various Combinations to Produce 22 lbf Lift

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<thead>
<tr>
<th>Number of Motors</th>
<th>Propeller Diameter [in]</th>
<th>Power to Motor [W]</th>
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<td>4</td>
<td>8</td>
<td>764.1</td>
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<td>4</td>
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<td>4</td>
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<td>10</td>
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</tr>
<tr>
<td>4</td>
<td>10.5</td>
<td>598</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>573.5</td>
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<tr>
<td>4</td>
<td>11.5</td>
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<tr>
<td>4</td>
<td>12</td>
<td>530.2</td>
</tr>
<tr>
<td>4</td>
<td>12.5</td>
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<td>4</td>
<td>13</td>
<td>493.3</td>
</tr>
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<td>4</td>
<td>13.5</td>
<td>476.8</td>
</tr>
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<td>----</td>
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</tr>
<tr>
<td>4</td>
<td>14</td>
<td>461.4</td>
</tr>
<tr>
<td>4</td>
<td>14.5</td>
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<td>4</td>
<td>15</td>
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<td>15.5</td>
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<td>163.5</td>
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<td>8</td>
<td>16.5</td>
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Figure C-1. Various Combinations to Produce 22 lbf Lift
### Appendix D. eCalc UAV Configurations with Varying Loads

#### Figure D-1. Quad-Copter with No Additional Load

<table>
<thead>
<tr>
<th>Battery Cell</th>
<th>Type (Cont./max. C) - charge state:</th>
<th>Voltage</th>
<th>Rated Voltage</th>
<th>Flight Time</th>
<th>Mixed Flight Time</th>
<th>Hover Flight Time</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller</td>
<td>Type: max 3C ▼</td>
<td>Current</td>
<td>max 3C</td>
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<td></td>
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</tr>
<tr>
<td>Motor</td>
<td>Manufacturer - Type (Kv):</td>
<td>Kv (rpm/kV)</td>
<td>no-load Current</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propeller</td>
<td>Type: yoke tail ▼</td>
<td>Diameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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#### Figure D-2. Octo-Copter with No Additional Load

<table>
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<th>Battery Cell</th>
<th>Type (Cont./max. C) - charge state:</th>
<th>Voltage</th>
<th>Rated Voltage</th>
<th>Flight Time</th>
<th>Mixed Flight Time</th>
<th>Hover Flight Time</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller</td>
<td>Type: max 3C ▼</td>
<td>Current</td>
<td>max 3C</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Motor</td>
<td>Manufacturer - Type (Kv):</td>
<td>Kv (rpm/kV)</td>
<td>no-load Current</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Propeller</td>
<td>Type: yoke tail ▼</td>
<td>Diameter</td>
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**Figure D-3. Octo-Copter with 3 Pound Load**

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<tr>
<td><strong>Motor Cooling</strong></td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
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<td>medium</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
</tr>
<tr>
<td><strong># of Rotors</strong></td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
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<tr>
<td><strong>Model Weight</strong></td>
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<td>3157 g</td>
<td>3157 g</td>
<td>3157 g</td>
</tr>
<tr>
<td><strong>Battery Cell</strong></td>
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<td><strong>Cell Capacity</strong></td>
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</tr>
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<td><strong>Total Capacity</strong></td>
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</tr>
<tr>
<td><strong>Resistance</strong></td>
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<td>0.005 Ω</td>
<td>0.005 Ω</td>
<td>0.005 Ω</td>
<td>0.005 Ω</td>
<td>0.005 Ω</td>
<td>0.005 Ω</td>
<td>0.005 Ω</td>
<td>0.005 Ω</td>
<td>0.005 Ω</td>
<td>0.005 Ω</td>
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</tr>
<tr>
<td><strong>Controller</strong></td>
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<td>max. Curr.</td>
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<td>custom</td>
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</tr>
<tr>
<td><strong>Motor</strong></td>
<td>Manufacturer - Type (Kv)</td>
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</tr>
<tr>
<td><strong>Propeller</strong></td>
<td>Type - (paddle twist)</td>
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<td>custom</td>
</tr>
</tbody>
</table>

**Remarks:**
- **Battery**
  - **Load:** 17.79 C
  - **Voltage:** 23.11 V
  - **Rated Voltage:** 25.90 V
  - **Flight Time:** 3.4 min
  - **Mixed Flight Time:** 8.6 min
  - **Hover Flight Time:** 10.8 min
  - **Weight:** 1470 g

**Motor @ Optimum Efficiency**
- **Current:** 5.96 A
- **Voltage:** 24.36 V
- **Revolutions:** 7141 rpm
- **Efficiency:** 93.5 %

**Motor @ Maximum**
- **Current:** 17.79 A
- **Voltage:** 22.97 V
- **Revolutions:** 6434 rpm
- **Efficiency:** 89.9 %

**Motor @ Hover**
- **Current:** 4.73 A
- **Voltage:** 25.12 V
- **Throttle (set):** 42 %
- **Efficiency:** 93.3 %

**Multicopter**
- **Drive Weight:** 3271 g
- **All-up Weight:** 115.4 oz
- **Add. Payload:** 4050 g
- **Max. Tilt:** 55°
- **Max. Speed:** 35.4 mph

---

**Figure D-4. Octo-Copter with 6 Pound Load**

<table>
<thead>
<tr>
<th>General</th>
<th></th>
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<td><strong>Motor Cooling</strong></td>
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<td>medium</td>
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<td>medium</td>
</tr>
<tr>
<td><strong># of Rotors</strong></td>
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</tr>
<tr>
<td><strong>Model Weight</strong></td>
<td>3157 g</td>
<td>3157 g</td>
<td>3157 g</td>
<td>3157 g</td>
<td>3157 g</td>
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<td>3157 g</td>
<td>3157 g</td>
<td>3157 g</td>
</tr>
<tr>
<td><strong>Battery Cell</strong></td>
<td>Type (Conc. / max. C)</td>
<td>charge state</td>
<td>normal</td>
<td>normal</td>
<td>normal</td>
<td>normal</td>
<td>normal</td>
<td>normal</td>
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<td>normal</td>
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</tr>
<tr>
<td><strong>Configuration</strong></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Cell Capacity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td><strong>Total Capacity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Resistance</strong></td>
<td>0.005 Ω</td>
<td>0.005 Ω</td>
<td>0.005 Ω</td>
<td>0.005 Ω</td>
<td>0.005 Ω</td>
<td>0.005 Ω</td>
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<td>0.005 Ω</td>
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<tr>
<td><strong>Controller</strong></td>
<td>Type</td>
<td>cont. Curr.</td>
<td>max. Curr.</td>
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<td>50 A</td>
<td>50 A</td>
<td>50 A</td>
<td>50 A</td>
<td>50 A</td>
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<td>50 A</td>
<td>50 A</td>
<td>50 A</td>
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<tr>
<td><strong>Motor</strong></td>
<td>Manufacturer - Type (Kv)</td>
<td>custom</td>
<td>custom</td>
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<td>custom</td>
<td>custom</td>
<td>custom</td>
<td>custom</td>
</tr>
<tr>
<td><strong>Propeller</strong></td>
<td>Type - (paddle twist)</td>
<td>custom</td>
<td>custom</td>
<td>custom</td>
<td>custom</td>
<td>custom</td>
<td>custom</td>
<td>custom</td>
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<td>custom</td>
<td>custom</td>
<td>custom</td>
<td>custom</td>
<td>custom</td>
</tr>
</tbody>
</table>

**Remarks:**
- **Battery**
  - **Load:** 17.79 C
  - **Voltage:** 23.11 V
  - **Rated Voltage:** 25.90 V
  - **Flight Time:** 3.4 min
  - **Mixed Flight Time:** 8.6 min
  - **Hover Flight Time:** 10.8 min
  - **Weight:** 1470 g

**Motor @ Optimum Efficiency**
- **Current:** 5.96 A
- **Voltage:** 24.36 V
- **Revolutions:** 7141 rpm
- **Efficiency:** 93.5 %

**Motor @ Maximum**
- **Current:** 17.79 A
- **Voltage:** 22.97 V
- **Revolutions:** 6434 rpm
- **Efficiency:** 89.9 %

**Motor @ Hover**
- **Current:** 4.73 A
- **Voltage:** 25.12 V
- **Throttle (set):** 42 %
- **Efficiency:** 93.3 %

**Multicopter**
- **Drive Weight:** 3271 g
- **All-up Weight:** 115.4 oz
- **Add. Payload:** 4050 g
- **Max. Tilt:** 55°
- **Max. Speed:** 35.4 mph
### Figure D-5. Octo-Copter with 8 Pound Load (Minimum Maneuverability)

<table>
<thead>
<tr>
<th>General</th>
<th>Motor Cooling: medium</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># of Rotors:</td>
</tr>
<tr>
<td></td>
<td>Model Weight: 7 lbs</td>
</tr>
<tr>
<td>Battery Cell</td>
<td>Type (Cont./max. C) - charge state: custom</td>
</tr>
<tr>
<td>Config:</td>
<td>Cell Capacity: 4000 mAh</td>
</tr>
<tr>
<td>Voltage:</td>
<td>Total Capacity: 8000 mAh</td>
</tr>
<tr>
<td>Rated Voltage:</td>
<td>Resistance: 3.7 V</td>
</tr>
<tr>
<td>PV:</td>
<td>C-Rate: 0.16 A</td>
</tr>
<tr>
<td>Flight Time:</td>
<td>Weight: 1470 g</td>
</tr>
<tr>
<td>Motor</td>
<td>Type: custom</td>
</tr>
<tr>
<td>Voltage:</td>
<td>Efficiency: 69.9%</td>
</tr>
<tr>
<td>Rated Voltage:</td>
<td>Temperature: 61°C</td>
</tr>
<tr>
<td>Motor</td>
<td>Height: 14.7 inch</td>
</tr>
</tbody>
</table>

### Figure D-6 Octo-Copter with 14 Pound Load (Maximum Throttle Necessary just for Lift)

<table>
<thead>
<tr>
<th>General</th>
<th>Motor Cooling: medium</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># of Rotors:</td>
</tr>
<tr>
<td></td>
<td>Model Weight: 7 lbs</td>
</tr>
<tr>
<td>Battery Cell</td>
<td>Type (Cont./max. C) - charge state: custom</td>
</tr>
<tr>
<td>Config:</td>
<td>Cell Capacity: 4000 mAh</td>
</tr>
<tr>
<td>Voltage:</td>
<td>Total Capacity: 8000 mAh</td>
</tr>
<tr>
<td>Rated Voltage:</td>
<td>Resistance: 3.7 V</td>
</tr>
<tr>
<td>PV:</td>
<td>C-Rate: 0.16 A</td>
</tr>
<tr>
<td>Flight Time:</td>
<td>Weight: 1470 g</td>
</tr>
<tr>
<td>Motor</td>
<td>Type: custom</td>
</tr>
<tr>
<td>Voltage:</td>
<td>Efficiency: 69.9%</td>
</tr>
<tr>
<td>Rated Voltage:</td>
<td>Temperature: 61°C</td>
</tr>
<tr>
<td>Motor</td>
<td>Height: 14.7 inch</td>
</tr>
</tbody>
</table>

**Remarks:**
- For minimal maneuverability you need Throttle of less than 50%
Appendix E. Impact Force Analysis

"Impact Force Calculations"
"Failing Moment"
"Note: the body didn't break during testing, but it did make a breaking noise inside the part."

\[ M_{\text{fail}} = 8.25 \text{ [lbf]} \times 16 \text{ [in]} \times \text{convert(lbf-in, N-m)} \]

"Landing gear distance to hub"
\[ d = 10 \text{ [in]} \times \text{convert(in,m)} \]

"Drone"
\[ \text{mass} = (9.5 \text{ [lbm]/4}) \times \text{convert(lbm, kg)} \]

"ABS 15% Fill - Material Properties"
\[ E = 20e6 \text{ [Pa]} \]

"Simple Geometry of Landing Gear"
\[ \text{length} = 40e-3 \text{ [m]} \]
\[ \text{width} = 20e-3 \text{ [m]} \]
\[ \text{height} = 82e-3 \text{ [m]} \]
\[ A_x = \text{length} \times \text{width} \]

"Stiffness of landing gear"
\[ k = \frac{E \times A_x}{\text{height}} \]

"Foam Spring Properties"
"Note: Stiffness calculated experimentally"
\[ k_{\text{foam}} = \frac{5 \text{ [lbf]}}{0.005 \text{ [m]}} \times \text{convert(lbf/m, N/m)} \]
\[ \left( \frac{1}{k_{\text{eq}}} \right) = \left( \frac{1}{k} \right) + \left( \frac{1}{k_{\text{foam}}} \right) \]

"Spring-Mass First Order System"
\[ T = 2\pi \sqrt{\text{mass/}k_{\text{eq}}} \]
\[ \text{DELTA}_T = \frac{T}{2} \]
\[ v_0 = 0 \text{ [m/s]} \]
\[ h = 6 \text{ [in]} \times \text{convert(in,m)} \]
\[ v_f^2 = v_0^2 + 2 \times 9.91 \text{ [m/s^2]} \times h \]

"Impact Force"
\[ F_i = \text{mass} \times (v_f - v_0)/\text{DELTA}_T \]
\[ F_i_{\text{lbf}} = F_i \times \text{convert(N,lbf)} \]

"Safety Factor"
\[ N = M_{\text{fail}}/(F_i \times d) \]

Results

<table>
<thead>
<tr>
<th>Impact Force [lbf]</th>
<th>8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety Factor</td>
<td>1.5</td>
</tr>
<tr>
<td>Height of Drop [in]</td>
<td>6</td>
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</tbody>
</table>
Appendix F: PAM Calculations

"Electromagnet Calcs"

Battery_Cap = 8.0 [A*hr]  "batery capacity"
Voltage = 25 [V]  "battery voltage"

Electromag_idraw = 0.160 [A]  "current draw per magnet"
N = 4  "number of electromagnets"

Motor_hover_current = 7.5 [A]  "hover current"

electromag_powerpercentage = 100 * (N*Electromag_idraw/(Electromag_idraw + Motor_hover_current))

Results

<table>
<thead>
<tr>
<th>Power Percentage [%]</th>
<th>8.4</th>
</tr>
</thead>
</table>
Appendix G: Vibration Analysis

"Vibration Calculations"

"material properties from www.performance-composites.com"

density = 1550 [kg/m^3]  "Density"
E = 150*10^9  "Modulus of Elasticity of Carbon"
t = 0.002 [m]  "thickness of rod"
l = 0.410 [m]  "outer diameter of rod"
D_o = 0.025 [m]  "Density"
D_i = D_o - 2*t  "mass of carbon fiber arm"

l = (pi/64)*(D_o^4 - D_i^4)  "moment of inertia"
k = 41121 [N/m]  "FEA calculated stiffness"
m = 0.25*pi*(D_o^2 - D_i^2)*t*density  "mass of carbon fiber arm"

omega_n = sqrt(k/m)  "Natural Frequency"

n_max = 6500 [1/min] * convert(1/min, 1/s)  "maximum frequency of blade rotation"
n_min = 3000 [1/min] * convert(1/min, 1/s)  "minimum frequency of blade rotation"
n_blade = 2  "number of blades"
omega_propeller_min = n_blade * 2 * pi * n_min  "minimum angular velocity"
omega_propeller_max = n_blade * 2 * pi * n_max  "maximum angular velocity"

Results

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>669.1</td>
<td>628.3</td>
<td>1361.0</td>
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</tbody>
</table>
Appendix H: Arm Stress Analysis

"Density of Carbon Fiber"
density = 1550 [kg/m^3]
E = 150*10^9  "Modulus of Elasticity"
t = 0.001 [m]  "thickness of rod"
length = 0.406 [m]
body_depth = 0.040 [m]  "length from end of carbon fiber arm to motor"
"depth of carbon fiber arm contact with body"

density = 1550 [kg/m^3]
E = 150*10^9  "Modulus of Elasticity"
t = 0.001 [m]  "thickness of rod"
length = 0.406 [m]
body_depth = 0.040 [m]  "length from end of carbon fiber arm to motor"
"depth of carbon fiber arm contact with body"

"Sum of Moments"
F*length = F_b*body_depth
"Sum of vertical forces"
F_b - F_v - F = 0
"Maximum Moment"
M_max = F_v*body_depth

"Maximum stress"
sigma_max = (M_max * (D_o/2))/I
D_o = 0.025 [m]  "outer diameter of rod"
D_i = D_o - 2*t  "inner diameter of rod"

"Moment of Inertia"
l = (pi/64)*(D_o^4 - D_i^4)

"mass of arm"
m = 0.25*pi*(D_o^2 - D_i^2)*length*density

"mass of drone"
m_drone = 4.124 [kg]

"weight of drone"
weight_drone = m_drone*9.8 [m/s^2]

"Thrust Force"
F = weight_drone/2
F_en = F*convert(N,lbf)

"Yield Stress"
sigma_y = 500E6 [Pa]  "www.performance-composites.com"

"Safety factor against yielding"
N_y = sigma_y/sigma_max

Results

<p>| | |</p>
<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Stress [MPa]</td>
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<tr>
<td>Safety Factor against Yielding</td>
<td>29.4</td>
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