EML4905 Senior Design Project

A B.S. THESIS

PREPARED IN PARTIAL FULFILLMENT OF THE

REQUIREMENT FOR THE DEGREE OF

BACHELOR OF SCIENCE

IN

MECHANICAL ENGINEERING

Multi-Purpose Aerial Drone for Bridge Inspection and Fire Extinguishing

Completed Report

Raquel Remington

Ramon Cordero

Larry March

Daniel Villanueva

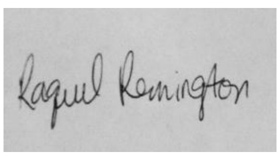
Advisor: Professor Ibrahim Tansel

November 19, 2014

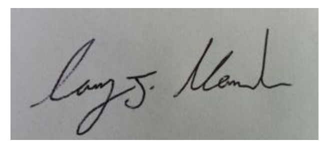
This B.S. thesis is written in partial fulfillment of the requirements in EML 4905. The contents represent the opinion of the authors and not the Department of Mechanical and Materials Engineering.

Ethics Statement and Signatures

The work submitted in this B.S. thesis is solely prepared by a team consisting of Raquel Remington, Ramon Cordero, Daniel Villanueva, and Larry March and it is original. Excerpts from others' work have been clearly identified, their work acknowledged within the text and listed in the list of references. All of the engineering drawings, computer programs, formulations, design work, prototype development and testing reported in this document are also original and prepared by the same team of students.







Raquel Remington	Ramon Cordero	Daniel Villanueva	Larry March
Team Leader	Team Member	Team Member	Team Member

Dr. Ibrahim Tansel

Faculty Advisor

TABLE OF CONTENTS

Chapter **Page**

List of Figures

List of Tables

Abstract

Currently, the majority of drones marketed to civilians are rather simple in that they can only perform one task - typically surveillance or video recording of some sort. The goal of this project is to build a quadcopter that can accomplish a variety of practical tasks like bridge inspection, fire extinguishing, and police surveillance. The market for multipurpose drones has the potential to be expansive once proper FAA regulation is passed. Aerial drones, like quadcopters, have a largely protective effect on the users. This project focuses on the extinguishing of small fires remotely with the use of a quadcopter to help prevent injuries to firefighters and potentially even more people, to help prevent very serious or even fatal accidents incurred by inspectors when proper safety precautions are not taken while inspecting bridges, and to help police and other law enforcement officers maintain a level of safety when certain circumstances warrant a possible need for an aerial drone to provide surveillance of these situations.

1. Introduction

1.1 Problem Statement

There is an overall lack of multi-purpose aerial drones, or unmanned aerial vehicles (UAVs), around the world; and until recently, there was a lack of any feasible purposes for drones outside of military applications. Drone technology has advanced to the point in which portable devices are now economically priced enough for civilians to afford as well as easy enough to use with little to no training; however, the main draw back with drones even today is the lack of flexibility in purposes. Most civilian drones are marketed for surveillance purposes only, making the purchaser the one responsible for the labor and economics of any type of design changes to allow for different or more functions. The problem then evolves itself to how to make an economical UAV that can be used for more than one purpose?

1.2 Motivation

Currently there are many safety issues surrounding the inspection of bridges. In order to inspect a bridge for any signs of deterioration, a person must inspect said bridge directly. This poses a safety hazard due to the drafts under bridges that might result in failures of platforms on which the inspector is located, or even causing the inspector to lose balance and tumble off of the inspection platform. Even overhead power lines can pose risks to workers on platforms inspecting bridges since a knowledge in electrical safety is needed, which can complicate the situation when multiple crews are involved in a seemingly simple inspection. Bodies of water below a bridge can pose significant safety threats. In this case, normal ground platforms used in inspections are no longer of any use, and suspended platforms can be extremely dangerous due to the lack of stability, yet it is still highly important to constantly monitor bridges for potential hazards because failures do occur.

Fire extinguishing can be even more hazardous in some instances. Fires in enclosed spaces cause a decrease in visibility due to smoke production and have a potential to cut off any exit routes either immediately or later on, causing a potential for injuries or fatalities when exit routes are removed. Even so, fires in open spaces can be even more dangerous. Wild fires tend to spread extremely quickly, sometimes at speeds of 16-20 kmph, or 9.9-12.2 mph (Cheney), and rather sporadically since its movement is so heavily dependent on the wind, something mostly unpredictable. Due to the lack of predictability of wildfires, many deaths and injuries have occurred to both firefighters and civilians; thus, it is extremely imperative to find a safe alternative to direct fire extinguishing.

1.3 Literature Survey

Although drones have been around since the 1970s, it was not until recent that they became feasibly useful for more than military purposes (Whittle 1). Drone technology has advanced to the point in which portable devices are now economically priced enough for civilians to afford as well as easy enough to use with little to no training; some models even start around $599 as seen with the Parallax 80000 Quadcopter Kit. The main draw back with drones even today, though, is the lack of flexibility in purposes. One may pay $599 for a Parallax 80000, but will only have the opportunity to use it for surveillance purposes without major design changes, which can be expensive relative to purchase price. This is one of the main motivations to produce a multipurpose aerial drone for bridge inspection and fire extinguishing.

Although bridge inspections may not seem like the most dangerous job in the world, especially to the layman, injuries and fatalities have occurred while people have surveyed bridges. Most recently, Paul Schisler, an engineer for Shiavone Construction, fell to his death while inspecting the Aqueduct Bridge in New York in January 2013 (Heller). It is also not possible to end inspections on bridges to prevent injuries and fatalities of engineers and inspectors since bridges have a tendency to fail after a while, making it necessary to monitor a bridge to assign repairs to older or damaged bridges. According to "The National Bridge Inspection Program and the Highway Bridge Replacement and Rehabilitation Program," the Federal-Aid Highway Act of 1970, a result of the Silver Bridge collapse in 1967 during rush hour, which resulted in 46 deaths and many injuries, makes it mandatory for bridges to be periodically inspected for potential hazards. And in 1987, the Surface Transportation and Uniform Relocation Assistance Act made for additional requirements for underwater inspections of bridges due to a collapse at Schoharie Creek on I-90, which resulted in fatalities as well. The production of a drone that can inspect bridges for possible causes of failure is extremely important to inspectors as well as civilians who travel along the bridge; this drone will help to prevent any unwarranted deaths or injuries as well as any traffic delays due to lane or bridge closures during inspections.

Fires also cause fatalities and deaths every year for both civilians and firefighters. There were twenty-two fire related deaths for on-duty firefighters in 2012 alone ("On-Duty Firefighter Fatalities 1977-2012"), though injuries caused either directly or indirectly by fires have an even higher rate of incidence among firefighters. One of the most notable incidences of fatalities caused by wildfires occurred in Arizona in 2013. Nineteen firefighters died when a wildfire abruptly changed directions and surrounded them; although they all carried protective shelters for this very reason, the shelters proved not to be enough (Hanna). Civilian deaths and injuries are even higher, with 728 fire related fatalities that have occurred between January 1 and March

7, 2014 alone ("Residential Fire Fatalities in the News"), and that number will most definitely grow by the end of this year. This drone has the potential to prevent deaths of firefighters; and in the future, once the technology has been further developed, to prevent deaths of civilians who would typically be waiting for the firefighters to arrive at the scene.

1.4 Discussion

The overall and paramount purpose of multi-purpose aerial drones, or unmanned aerial vehicles (UAVs), is to reduce the risk of injury or loss of life due to fire fighting and bridge inspecting. By implementing a cost effective approach to producing a UAV to extinguishing fires and inspecting bridges, manpower can be minimized, which will in turn increase safety and reduce the risks of injuries and fatalities involved in either tasks.

2. Project Formulation

2.1 Overview

There are many new techniques and methods formulated to make a certain task more feasible than the previous ones. These new methods are accomplished by implementing a new design or updating a preceding design that will ultimately improve the function, efficiency, and cost of the system. This multipurpose drone will be designed in order to integrate and enhance certain robotic, electrical, aeronautical, and mechanical components in a former quadcopter. The major functions that this UAV will perform is to inspect bridges, extinguish small fires, and to be utilized as a testing mechanism for future research projects involving chemical compounds. This will be achieved by mounting a camera to the UAV that will transmit live footage through wireless video glasses, and installing a robotic device that will release fire extinguishing chemical grenades at a desired location. In order to accomplish these functions required, the design must take into account all the knowledge and elements used in the engineering field; particularly those in electrical, aerospace, and mechanical disciplines.

2.2 Project Objectives

Although new innovations are being conducted in the UAV field as seen in today’s generation, the standard UAV purposes are typically for navigation and surveillance from elevated heights without the need of a human pilot. The objective is to augment the functions that a standard UAV performs in today’s society by installing cameras that can transmit video recordings wirelessly to a receiver, and manufacture and design a release mechanism that will be used for testing and fire extinguishing purposes. In the engineering perspective, the intentions of this project are to maximize the UAV's overall efficiency and minimize the cost by taking into account material, mechanical, aerospace, and electrical engineering methods that will improve the UAV's functions. In the environmental perspective, the objective is to make our UAV safe for all living creatures and the planet by using material that can be recycled and reused without polluting the land, water, and air. Lastly, the intentions of this project are to make this UAV on a global production that will be used to aid all people and societies that have bridges, fires, and research purposes in the chemical field. This drone will be able to extinguish fires at places where firefighters cannot reach, make it safer to inspect bridges without putting a person's life in danger by having to inspect them at high altitudes, and be used to advance research on chemical substances.

2.3 Design specifications

The current design is a multipurpose quadcopter, also known as a quad-rotor helicopter. A quadcopter is also qualified as a rotorcraft which is a heavier than an air machine that utilizes lift generate by its wing, which are also called rotor blades that revolve around a mast. Specifically for this design, there will be four rotor blades that will generate lift; hence, the name quadcopter. Quadcopters utilize two sets of identical propellers in fixed locations. Two of the propellers will spin clockwise, and the other two will spin counter-clockwise to negate the torque generated by the opposing rotors.

The quadcopter has obtained quite a reputation as a UAV system in the engineering field mainly because of system's simplicity in terms of function and set up, which makes it a desirable platform to work on. This particular design will perform different tasks; one of which is bridge inspection, where it will utilize an onboard camera system to send feedback to the operator about the conditions of the part of the bridge currently under inspection, as well as an onboard fire extinguishing system to control small scale fires that cannot otherwise be reached by a human.

Figure 1: Example of a Quadcopter Model

The quadcopter is also known for its ability to carry a small payload, an ability which will be utilized to carry a small firefighting agent bomb, which will be dropped onto the targeted fire. The extinguishing agent will be dropped using a small scale dropping mechanism.

Figure 2: Release Mechanism for Chemical Extinguisher

The payload for this quadcopter is also a key factor in this design since the secondary function is to extinguish fires. The payload has to consist of a fire-extinguishing grenade. The grenade is spherical in shape, and has a mass of 1.3 kilograms. It is filled with fire extinguishing chemicals that will automatically activate once in the presence temperatures above 82ºC.

Figure 3: Fire Extinguishing Grenade

2.4 Constraints and Other Considerations

The first apparent constraint to the design is that the chemical extinguisher can only extinguish a fire with a volume of 9.5 m^3. This would be ideal for small or indoor fires (i.e. in a house or tall building), which makes a UAV an ideal platform to enter through windows to drop the fire extinguishing grenades. In the presence of larger fires (i.e. wildfires), the grenade can only be realistically placed on the ground as a preventive measure against the fire. Furthermore, when dropping the grenade onto a larger fire, the quadcopter cannot be above the fire as the pilot runs the risk of losing control of the quadcopter due to severe updrafts associated with these larger fires.

When flying underneath bridges, the quadcopter runs the risk of flying through wind drafts, which can increase the chances of it colliding with the surfaces of the bridge or losing control; therefore, operators must be well trained when in operation of the quadcopter. Also, good calibration of the altitude as well as the proximity sensors will reduce the chance of collisions; therefore enabling more accurate acquisition of measurements and observations in an easier fashion.

2.5 Discussion

Developing a newer generation of this multi-purpose aerial is one of the key objectives to overcome the draw backs of this design. By manipulating the UAV to accommodate for the release of a fire extinguishing grenade at the exact location will be a great asset to achieving one of the functionality goals: to reduce the loss of life and prevent injuries to anyone either directly or indirectly due to fires. Furthermore, the continuing practice of getting familiarized with the maneuvering of the UAV will help provide a greater accuracy of the information obtained while performing inspections on bridges. In the optimization of the UAV, it would be beneficial to introduce a proximity sensor to be able to warn the operator of the proximity of the UAV to the bridge, which will help to reduce the chance of collisions with the quadcopter and bridge.

3. Design Alternative

3.1 Overview of Conceptual Design Alternative

In order to accomplish the necessary functions that the quadcopter will execute, three main designs were chosen. These designs involve the quadcopter's main components that will be optimized, which are the release mechanism and camera. The release mechanism designs were designed in order for the quadcopter to drop a chemical fire extinguishing grenade onto a selected location to extinguish fires or for testing and research motives. Additionally, a camera is to be installed on top of the quadcopter that will be utilized for recording, photographing, and inspecting purposes. The camera will be predominantly used to inspect bridges, buildings, and other structures that engineers evaluate. These two key characteristics of the quadcopter are the focal points to the designs demonstrated in the subsequent sections.

3.2 Design Alternate 1

The first design illustrates a robotic claw. This claw is designed so that it will open and close its arms whenever the user presses the control button on the quadcopter's remote control, which will relay a radio signal to the onboard computer to send an electrical signal to the motor that will be controlling this action. The motor that will be controlling this claw mechanism will acquire its power from the onboard battery supply, because the same power supply is used by the four rotors that keep the quadcopter suspended in air as well as all of the other on board sensors and computer equipment, the motor that will control the movement of the claw mechanism must not require too much power. The mechanical claw will be composed of aluminum because it is lightweight and durable. One of the main disadvantages of this design is the fact that it would only be able to carry one fire extinguishing grenade at a time, which will require the user to self-load a new fire extinguishing grenade after each use.

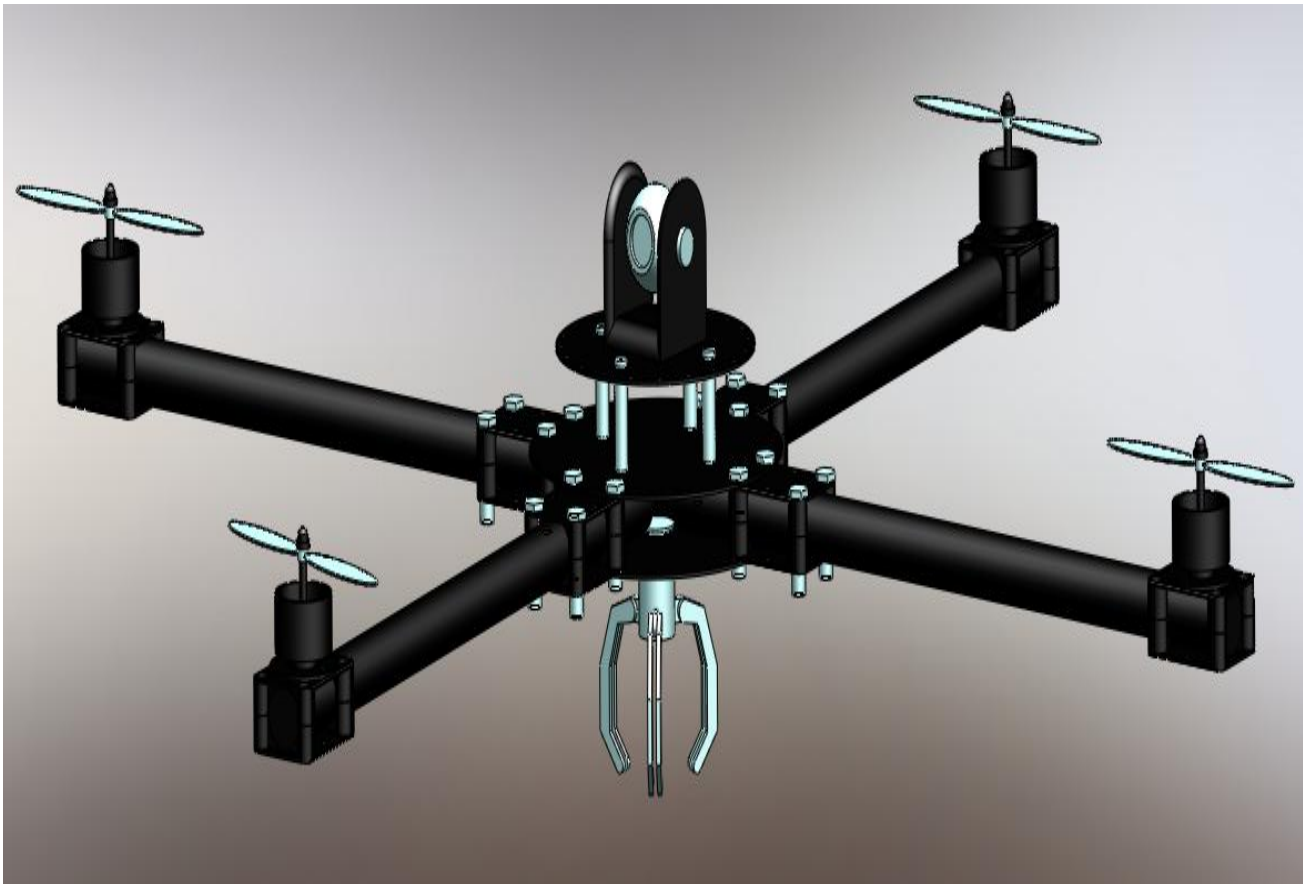


Figure 4: Design Alternative 1 (View 1)

Figure 5: Design Alternative 1 (View 2)

3.3 Design Alternate 2

The second design alternative is to build a cylindrically shaped cage for the extinguishing grenades. The benefit of this structure is that it will be able to carry more than one fire extinguishing ball. This is essential since a larger volume of fire can be extinguished at a faster rate, which is a vital when an emergency fire hazard occurs. The cylindrical release mechanism will be designed in order to hold and release the fire extinguishing grenades by the radio signal emitted by the remote control. This design will include a stepping motor, which will be used to control the arm that will hold and release the fire extinguishing grenades. The stepping motor will rotate at a total angle of 30º counterclockwise to release the first grenade, and then be programmed to rotate 30º clockwise until it reaches its initial position in order to catch and hold the second grenade in place. The same procedure will be used to release the second grenade and any subsequent grenades that the cylindrical cage mechanism can contain. For weight purposes, this release mechanism will only be able to hold two fire extinguishing grenades and will be made out of carbon fiber because of its lightweight and durable properties.

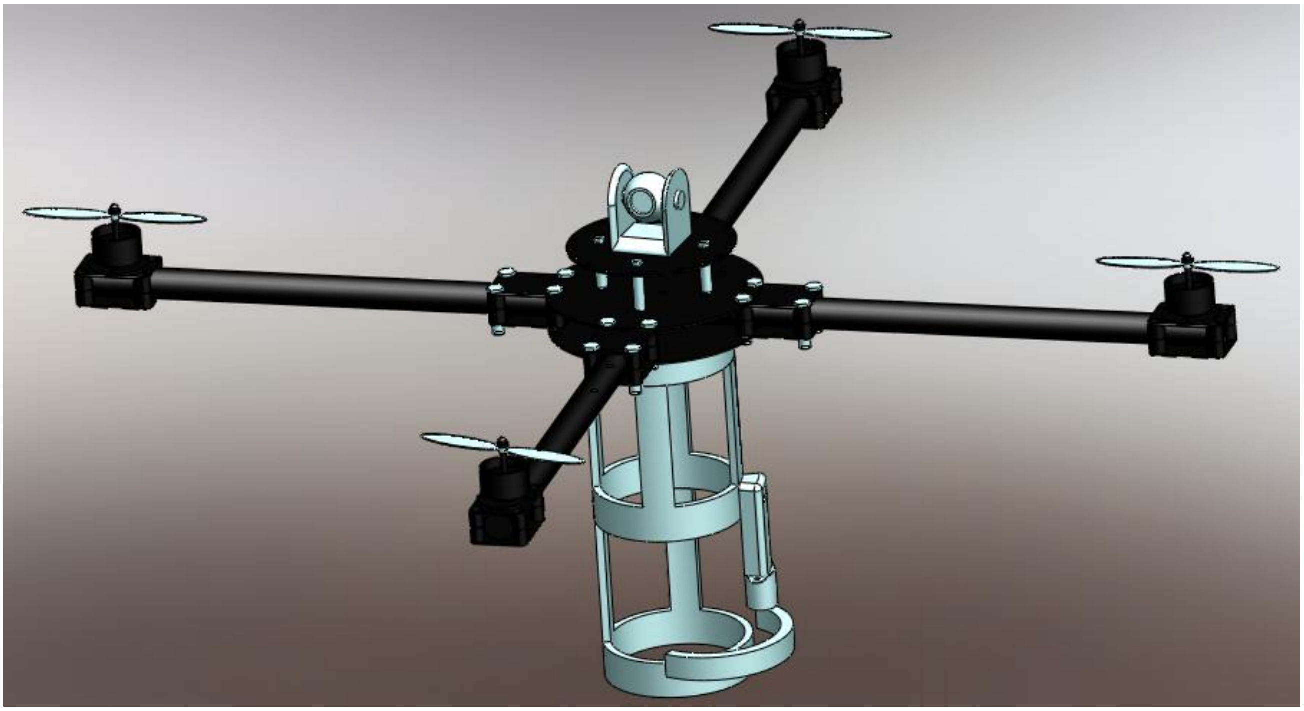


Figure 6: Design Alternative 2 (View 1)

Figure 7: Design Alternative 2 (View 2)

3.4 Feasibility Assessment

Feasibility of design alternatives for any project is one of the most considerations when choosing a design. Because a camera for surveillance or inspection usage can be mounted to a wide variety of locations on the quadcopter, the mechanism for fire extinguishing became the most important item to assess the feasibility of. It was determined early on that although it would be desirable to toss the fire extinguishing grenade, the action of tossing would greatly decrease the accuracy of the placement of the grenade. Since the volume of the fire that can be extinguished per grenade is relatively small, being only 9.5 m^3, small fires are the ideal application for this quadcopter use. Smaller fires do not create as large of updrafts as larger fires (i.e. brush fires, large building fires, etc.), and are easier to combat with a single deployment of a grenade; therefore, it was decided to drop the extinguishing grenade above the fire. The two previously mentioned design alternatives illustrate differing ways that the extinguishing grenades can be carried.

The first design alternative, as illustrated in Figures 4 and 5, illustrates a claw mechanism attached to the bottom of the quadcopter that is capable of holding a single fire extinguishing grenade at a time. This design allows for a highly accurate placement of the grenades since it will be dropped in a centralized fashion purely under the force of gravity.

The second design alternative, as illustrated in Figures 6 and 7, illustrates a tubular containment mechanism that can hold two fire extinguishing grenades at a time. This design, much like the first design alternative, is centered underneath the quadcopter; but differs in that when the grenades are released, they must travel to the side before falling, making the placement of the grenades slightly off-center from the quadcopter itself.

3.5 Proposed Design

The first design alternative, with the claw mechanism as shown in Figure 5, was chosen to be the most feasible due to two largely important factors: weight limitations and precise placement of the fire extinguishing grenade. It was determined that the quadcopter would not be able to fly or be adequately controlled if multiple fire extinguishing grenades were carried above updrafts caused by fires. The claw mechanism was chosen since the prong system gives added grip when carrying the extinguishing grenade and will allow for the grenade to drop once released rather than shifting to one side and then dropping like in the second design alternative as shown in Figure 6. The direct dropping of the extinguishing grenade will provide for a slightly more accurate placement on the fire.

4. Project Management

4.1 Overview

In order to have a successful project, the division of task and responsibilities among the team members is necessary for an orderly and organized work environment in which the developing system at hand can be completed. Making sure that every team member withholds a certain level of dedication and determination, the division of the work load gave way to milestones in which the team members can predict the due date for the project based upon which of these goals have been achieved first. This gives way to an optimized team efficiency. Therefore, with these facts in mind, the expected date for the quadcopter to be fully optimized and completed will be by the beginning of December 2014 according to Table 1. This will give more time to test the quadcopter's abilities and make adjustment to the system in order to make it more efficient in the specific tasks that it must complete. Certain parts may still need to be ordered for the optimization to be made, but as soon as the planning process has been completed the building task will commence.

4.2 Breakdown of Work into Specific Tasks

Table 1 details the main steps that will be taken to complete this project. It will be important to maintain strict time management as processes in the designing, manufacturing, and optimization may involve delays and/or several iterations, which can severely delay the projected completion date.

Table 1: Work Break Down Outline

1	**Initiate Project**
1.1	**Literature Survey**
1.1.1	Define Scope
1.1.2	Define Requirements
1.1.3	Hold Review Meeting
1.1.4	Revise Project
1.1.5	Gain Approvals
1.1.6	Finalize
2	**Plan Project**
2.1	**Project Formulation**
2.1.1	Develop Work Breakdown Structure
2.1.2	Develop Project Staffing Plan
2.1.3	Develop Project Schedule
2.2	**Solidworks Modeling**
2.2.1	Develop a Solidworks model
2.2.2	Finalized Drawing
2.3	**Material Selection**
3	**Execute and Control Project**
3.1	**Design Optimization**
3.1.1	Define stages and activities
3.1.2	Design Content formats
3.2	**Build Prototype**
3.2.1	Write the content
3.2.2	Review content for quality
3.3	**Testing / Analysis**
3.3.1	Test Quadcopter
3.3.2	Test Flying and Maneuvering
3.3.3	Analyze based on feedback
3.4	**Final Optimization**
3.4.1	Test Accuracy of Quadcopter
3.4.2	Final Adjustment
4	**Close the Project**
4.1	Final Report
4.2	Celebrate

As Figure 8 illustrates in a more visual sense, the work break down is set into four main stages: Initiation, Planning, Execution and Optimization, and Closure. Multiple steps will be followed within each of the main stages of the project. The most time consuming aspects of this project will occur in the planning and execution stages. This is mostly due to design, fabrication, and optimization iterations. Ideally, very few iterations will be needed if the design and optimization processes are completed efficiently.

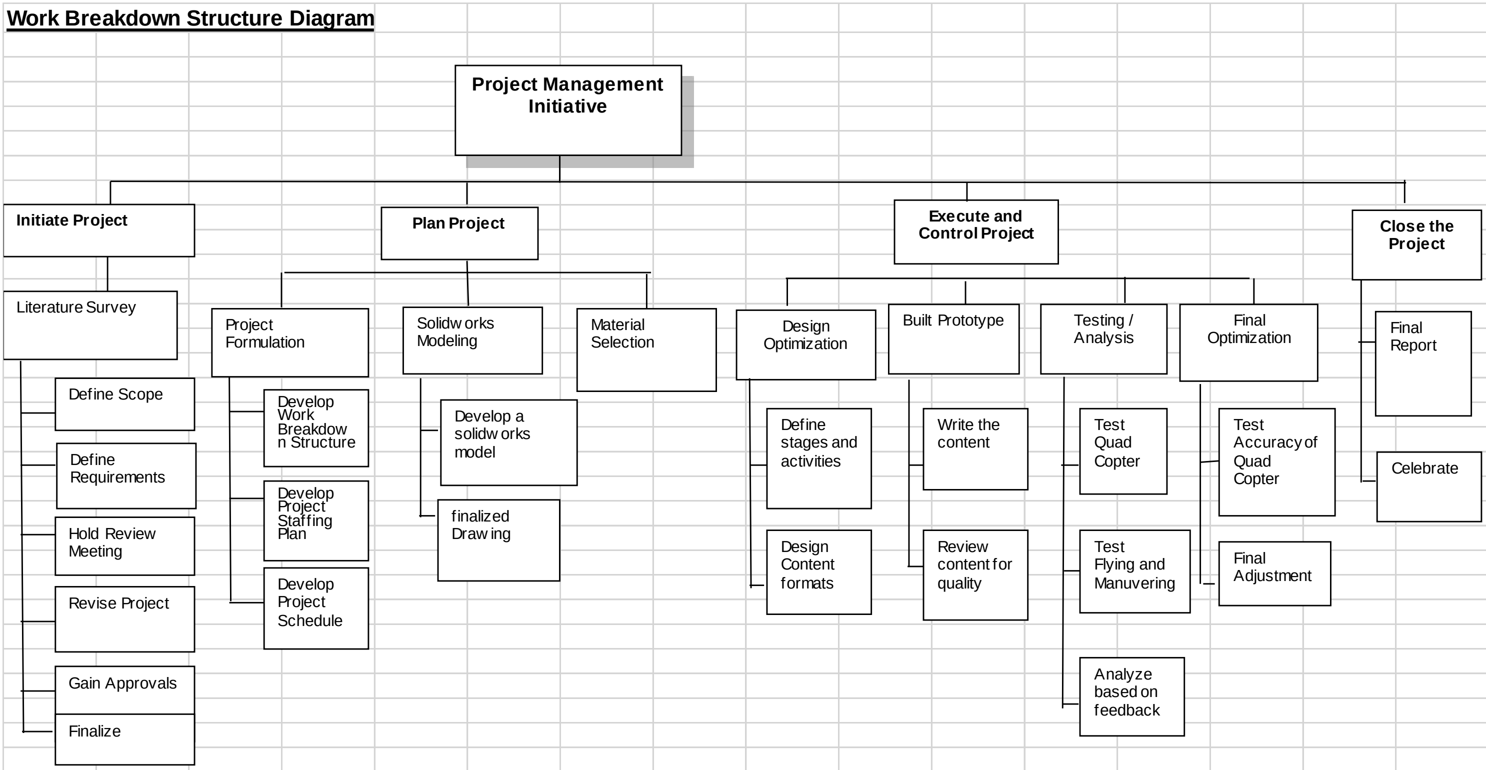


Figure 8: Work Breakdown Structure Diagram

4.3 *Organization of Work and Timeline*

Table 2 illustrates the timeline that will be maintained throughout the project. As mentioned in the previous section, the most time to be spent on this project is expected to occur within the design, fabrication, and optimization processes. Each of these sections is projected to take anywhere between one to three months to fulfill.

Table 2: Timeline

Months	January				February				March				April				May				June				July				August				September				October				November				December			
Weeks	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Literature Survey																																																
Project Formulation																																																
SolidWorks Modeling																																																
Material Selection																																																
Design Optimization																																																
Build Prototype																																																
Testing/Analysis																																																
Final Optimization																																																
Final Report																																																

4.4 *Breakdown of Responsibilities among Team Members*

It is necessary in any project to assign tasks to specific individuals or groups of individuals in order for the total project to be most efficient. The majority of the tasks in this project are going to be group efforts as seen in Table 3. It is necessary in this project to have individual inputs from every group member on the designs, parts, prototype builds, etc. There are a few tasks in which one or two team members may be better apt at completing these tasks; and accordingly, those individual tasks have been distributed based on the ability level of individual team members, although it may be necessary to eventually change the distribution of workloads or have more than one or two people working on specific individual tasks.

Table 3: Tasks

Task	Team Member(s)
CAD Modeling	Ramon C.
Prototype Design	Raquel R., Daniel V. Larry M., Ramon C.
Optimizations of Design	Raquel R., Daniel V. Larry M., Ramon C.
Parts Purchasing	Raquel R., Daniel V. Larry M., Ramon C.
Prototype Assembly	Raquel R., Daniel V. Larry M., Ramon C.
Testing	Raquel R., Daniel V. Larry M., Ramon C.
Analysis of Test Results	Raquel R., Daniel V. Larry M., Ramon C.
Simulations	Daniel V., Larry M.
Cost Analysis	Raquel R.
Second Iteration of Design	Raquel R., Daniel V. Larry M., Ramon C.
Final Assembly	Raquel R., Daniel V. Larry M., Ramon C.

5. Engineering Design and Analysis

5.1 Major Components

- Multi-Rotor Frame - This is the structure that holds all of the components together; not only does it need to be designed with strength in mind, but also to be light weight.

Figure 9: Quadcopter Prototype

- Spektrum DX6i RC Transmitter - A six channel transmitter designed to control a variety of different types of aerial drones. It can store up to ten different profiles for a variety of aerial drones, while being able to produce a wide range of statistical graphs on the LCD screen including throttle curves.

Figure 10: Spektrum DX6i RC Transmitter

- Motors/ Speed Controller – The MultiStar 480 KV motors are brushless DC motors that can provide the necessary thrust to propel the craft. Each rotor needs to be controlled separately by a speed controller.

Figure 11: MultiStar Motor

Figure 12: Motor Accessories

- The quadcopter has to include a motor and flight controller. Both components are in charge of receiving and processing the signal from the remote control. Using this signal, these two components provide stability once the quadcopter is on the air. In case the quadcopter suddenly loses balance, due to things like changes in wind or unexpected gusts, the motor controller (Figure 13) and the flight controller (Figure 14) have the capability of resetting the quadcopter to its initial position by operating the motors independently such that they stabilize the vehicle. Both devices are extremely relevant at the time of releasing the fire extinguishing grenade since they will provide the necessary stability in order for the quadcopter not to crash into the structure in question or the ground.

Figure 13: Flight Controller

Figure 14: Motor Controller

- Power Source - 5100 mAh, 8 cell lithium polymer power pack by 3D Robotics with an XTC60 connector and JST-XH charging connector.

Figure 15: Battery

- Pixhawk Microcontroller, Accessories, and Interfaces – Flight microcontroller manufactured by 3D Robotics as seen in Figure 16. It comes with a variety of accessories, shown in Figure 17, that include sensors like the ST Micro L3GD20 3-axis 16-bit gyroscope, the ST Micro LSM303D 3-axis 14-bit accelerometer/magnetometer, the Invensense MPU 6000 3-axis accelerometer/gyroscope, and the MEAS MS5611 barometer. These sensors work with the Pixhawk flight controller to maintain stability and give relevant feedback to the user on specific conditions. Because of the sensors and ability to program the Pixhawk to do a variety of auxiliary functions and tasks, interfaces, like those detailed in Figure 18, are needed within the Pixhawk. These include five UART ports (one being high-power capable and two with HW flow control), two CAN ports, one Spektrum DX input port (only compatible with Spektrum RC transmitters up to and including DX8s), an Futaba SBUS compatible input and output, a PPM sum signal, an RSSI input, an SPI port, 3.3 volt and 6.6 volt ADC inputs, and an external microUSB port.

Figure 16: Pixhawk Flight Controller

Figure 17: Pixhawk Accessories

Figure 18: Pixhawk Interfaces

- GPS flight control system - 3DR GPS that can transmit location data to or from the quadcopter control board.

- Component Housing - As shown in Figure 19, the component housing is designed to help protect the microcontroller and other electrical components that may be easily susceptible to damage from debris or weather.

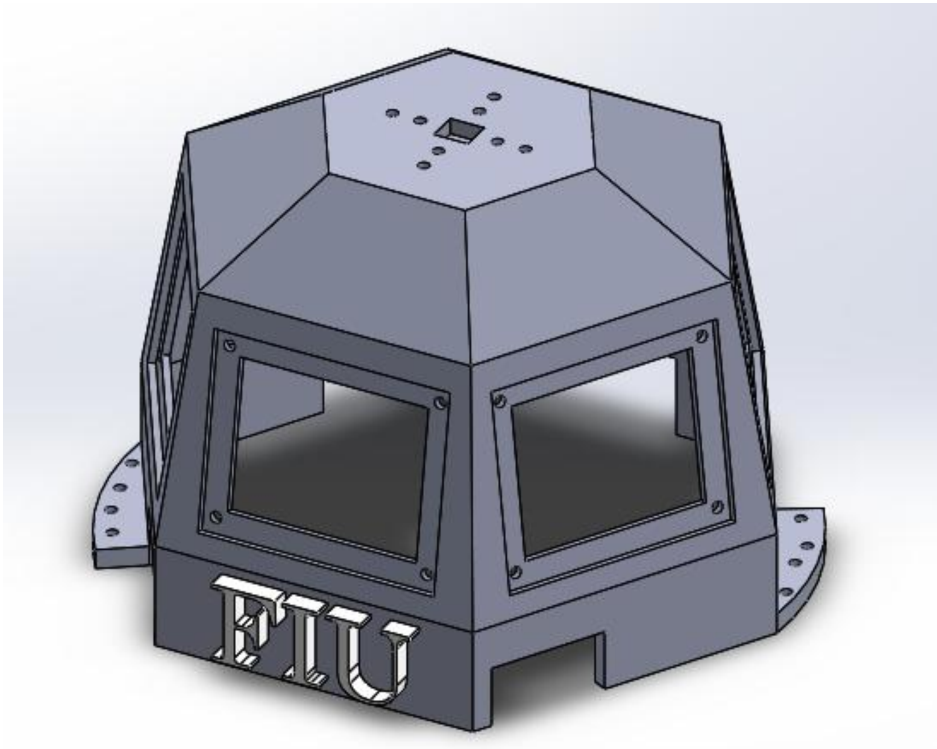


Figure 19: Component Housing

- Elide Fire Ball Extinguish Grenade - As shown in the Figure 20 below, the fire extinguishing grenade is spherical in nature and has a mass of 1.4 kgs and has a radius of 10 cm.

Figure 20: Fire Extinguishing Grenade

5.2 Structural Design

One of the most important structural considerations for this quadcopter is to maintain an even weight distribution when designing the structural framework and placement of major components. As seen in Figure 21, the main control components will be centered about the three central, circular plates to maintain minimal moments about the central axis of the quadcopter. The arms are also evenly placed about the central plate arrangement and made to be even lengths in order to cancel out any moment obtained when the motors are running. To compensate for the torque incurred by the running motors, opposing motors are given the same rotation while adjacent motors are given opposing rotations with corresponding propellers. Doing this will help to cancel out the torque of the running motors and resulting lift of the motors and propellers.

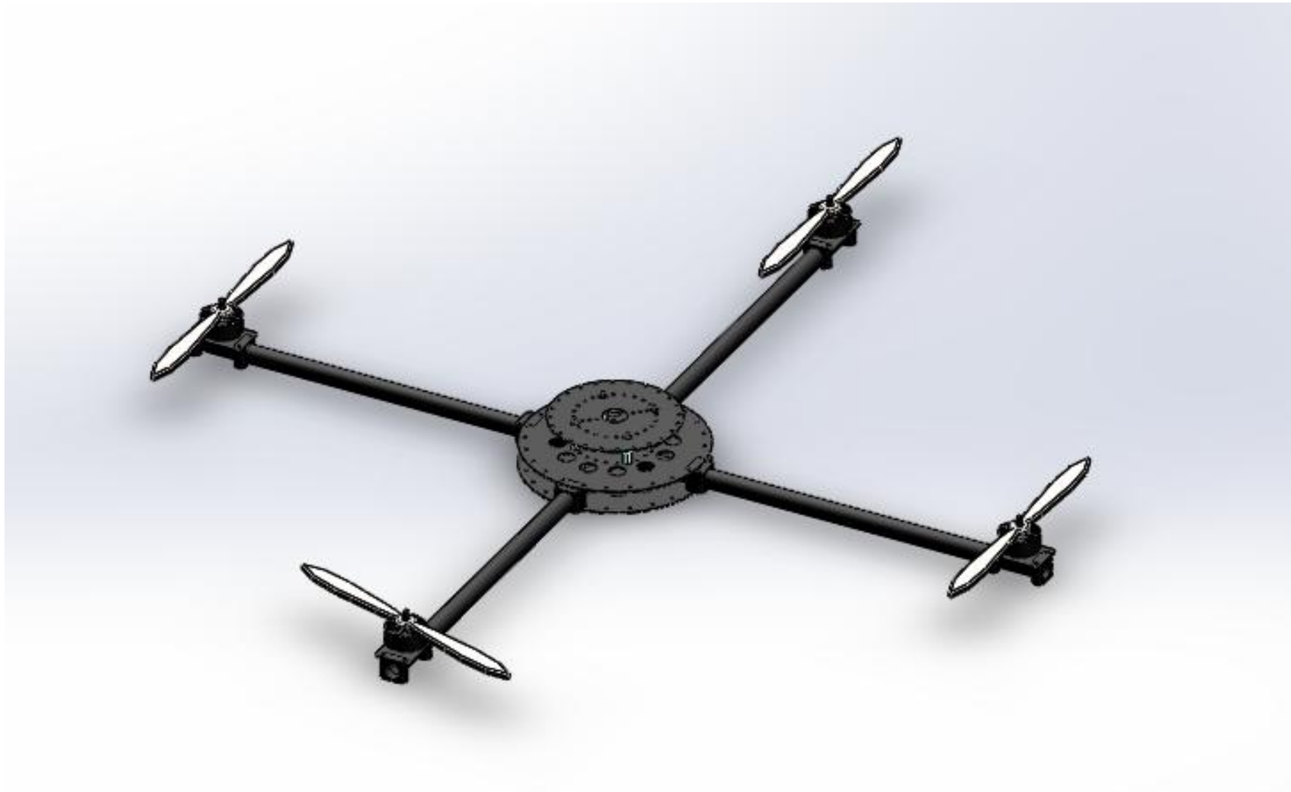


Figure 21: Structural Design of Quadcopter

5.3 *Force Analysis*

The most important aspect of this quadcopter is its ability to fly. In order for it to fly properly, a simple force analysis along the vertical direction is taken in order to determine the minimum radius of a propeller needed to allow the quadcopter to fly.

$$\sum F_y = 4T - W = 0$$

Where T is the thrust supplied by each individual motor and W is the overall weight of the quadcopter. Solving for T yields:

$$T = 0.25W = 0.25 * 48.93 = 12.23N$$

Solving the following equation for R:

$$T^3 = [(\alpha P)^2 * 2\pi R^2 \rho]^{1/3}$$

yields:

$$R = \sqrt{\frac{T^3}{(\alpha P)^2 * 2\pi\rho}}$$

Knowing the required minimum thrust force needed to just begin lifting the quadcopter and substituting it into the above equation, a solution for the minimum radius of propellers needed shows that the propellers must be 0.055m in radius.

To be able to run the static simulations on the claw mechanism of the quadcopter, an understanding of the forces that will be acting upon various parts of the quadcopter must be obtained. Since it was determined that the fire extinguishing grenade was to be dropped from rest by the claw mechanism, the only relatively substantial forces acting upon the mechanism would be the forces used to maintain the fire extinguishing grenade at static equilibrium. In this scenario, the sum of the forces acting within the y-axis direction should be zero at all times:

$$\sum F_y = 4F_g - W = 0$$

In this case, F_g is the force exerted by each individual gripper on the grenade, and W is merely the weight of the fire extinguishing grenade. Solving for F_g, an equation for the force acting upon each of the grippers is obtained:

$$F_g = \frac{W}{4} = \frac{mg}{4}$$

Since the mass of the fire extinguishing grenade is known to be 1.4kg, and gravity is a constant at 9.81 m/s^2, solving for F_g numerically yields a value of 3.43 N.

For thermal stresses to be of major structural concern, the quadcopter must be exposed to temperatures above the thermal limits of the fire extinguishing grenade, which will automatically detonate at temperatures of 82°C. Although the carbon structures within the carbon fibers should maintain integrity at temperatures up to, including, and sometimes greater than 2200°C, the epoxy resin binding the material will begin to soften when exposed to temperatures in excess of 100°C. The PLA components of the claw mechanism will be able to withstand temperatures of 150°C, making the temperature limit of the quadcopter no greater than the detonation temperature of the fire extinguishing grenade. Temperatures of updrafts caused by large scale fires routinely are between 60-100°C, according to Clark, with temperatures lowering as distance increases from the fire. Ideally, when using the quadcopter in the application of fire extinguishing, temperatures surrounding the quadcopter should not reach in excess of 60-70°C to maintain that the fire extinguishing grenade does not detonate before it is necessary to.

5.4 Stress Analysis

The following figure, Figure 22, details the Von Mises stress analysis run through Solidworks when a force of 3.43 N is acting upon each gripper while each gripper is fixed in place.

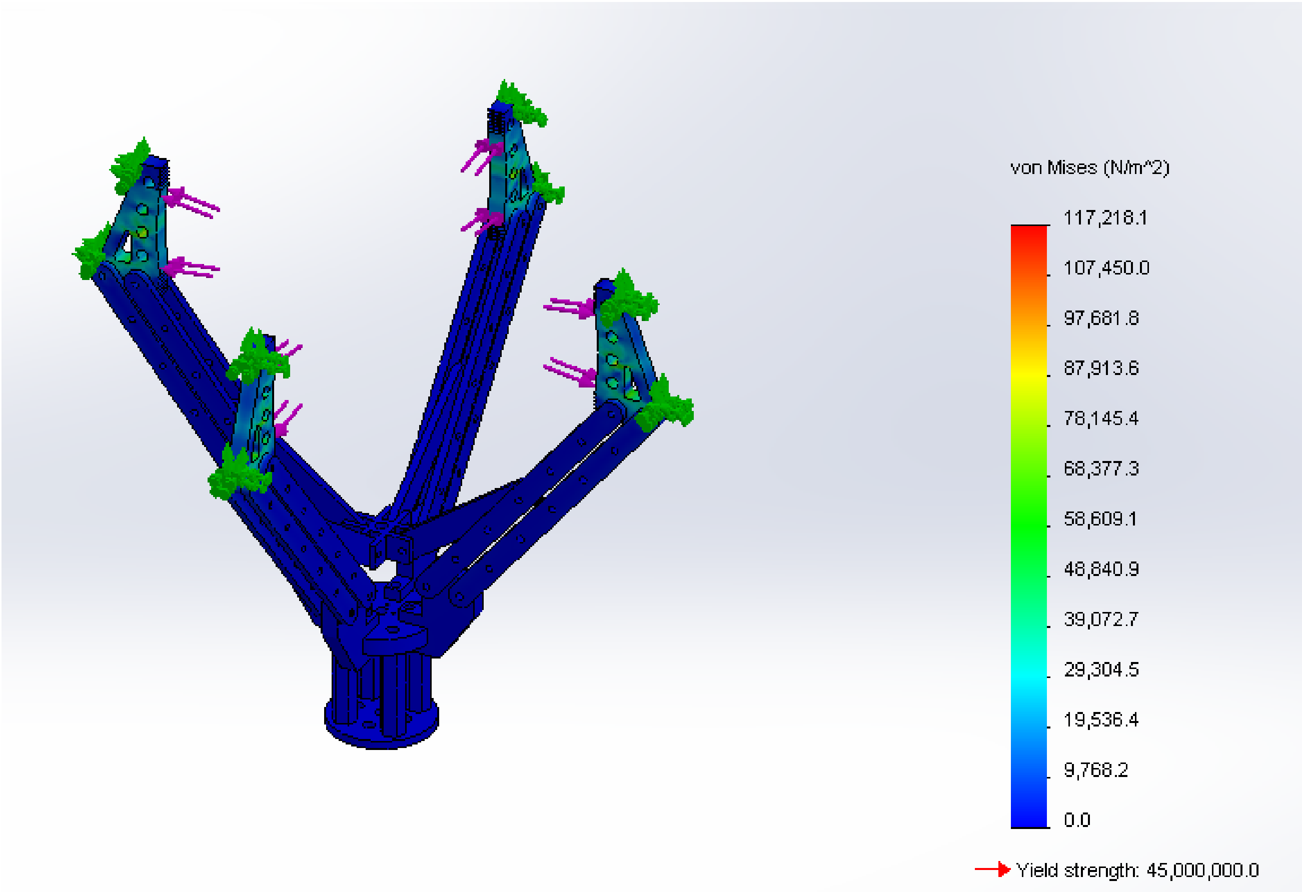


Figure 22: Von Mises Stress Analysis of Claw Mechanism

Table 4: Von Mises Stress Values from Solidworks Simulation

Stress	Stress (kPa)
Maximum	117
Minimum	112
Average	114

As detailed in Table 4, the maximum and minimum stresses are rather close in value, with only a 5 kPa difference, which is negligible compared to the yield strength detailed in Figure 22 of 45 MPa of the material.

5.5 Strain Analysis

The following figure, Figure 23, details the strain analysis run through Solidworks on the claw mechanism while each of the grippers are undergoing a force of 3.43 N. Once again, the strain is localized solely on the gripper areas without any significant effects on the rest of the mechanism.

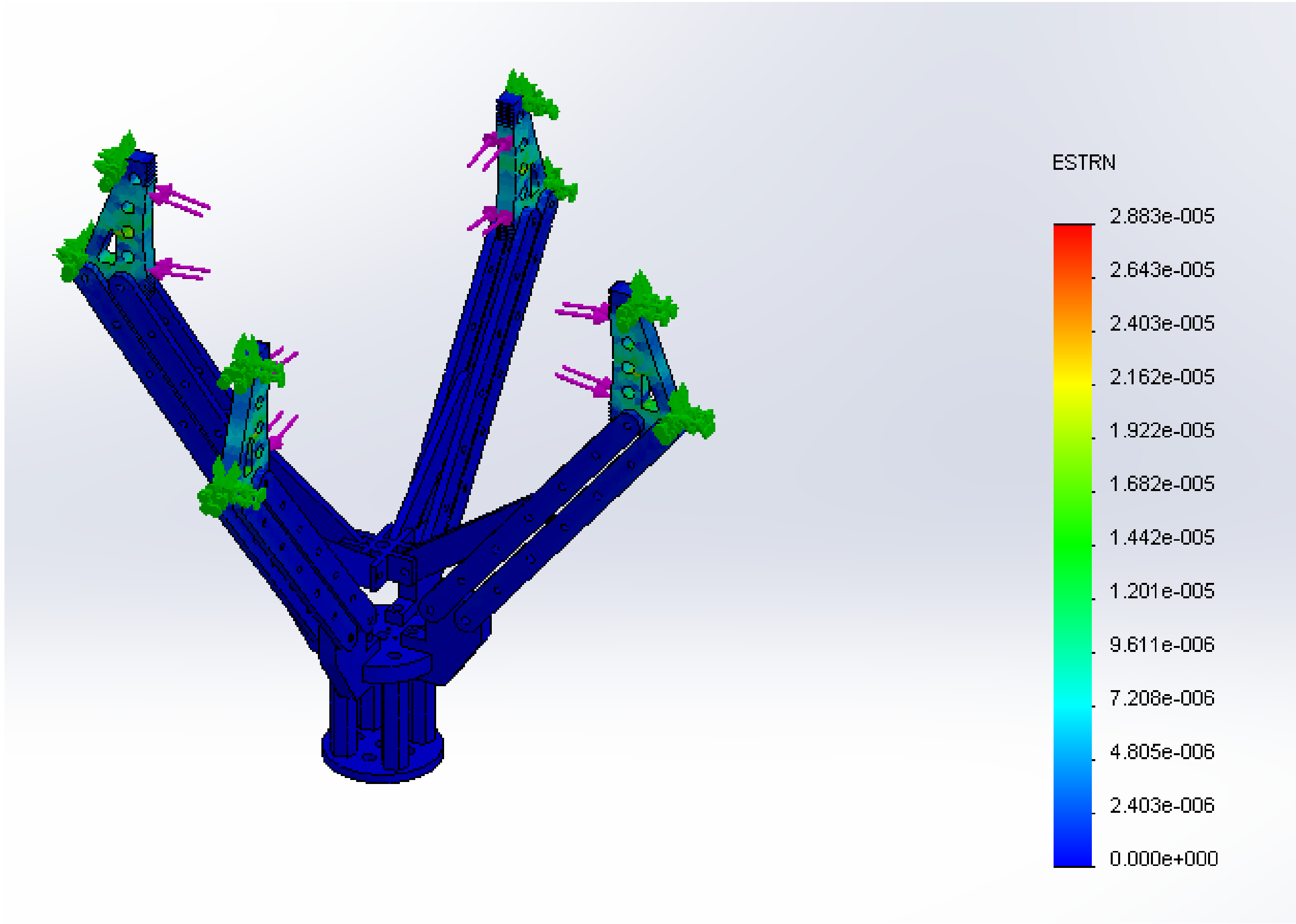


Figure 23: Strain Analysis of Claw Mechanism

Table 5: Strain Values from Solidworks Simulation

Strain	Strain (microstrains)
Maximum	29
Minimum	28
Average	28.5

Likewise, the maximum and minimum strains are rather close as well, with a difference of only one microstrain.

5.6 Safety Factor Analysis

Figure 24 details the calculated safety factors of the claw mechanism as it was simulated through Solidworks. It is noted that the scale in Figure 24 shows a minimum safety factor of 383.90, which dictates that the part is not expected to fail due to mechanical stresses for a long period of time.

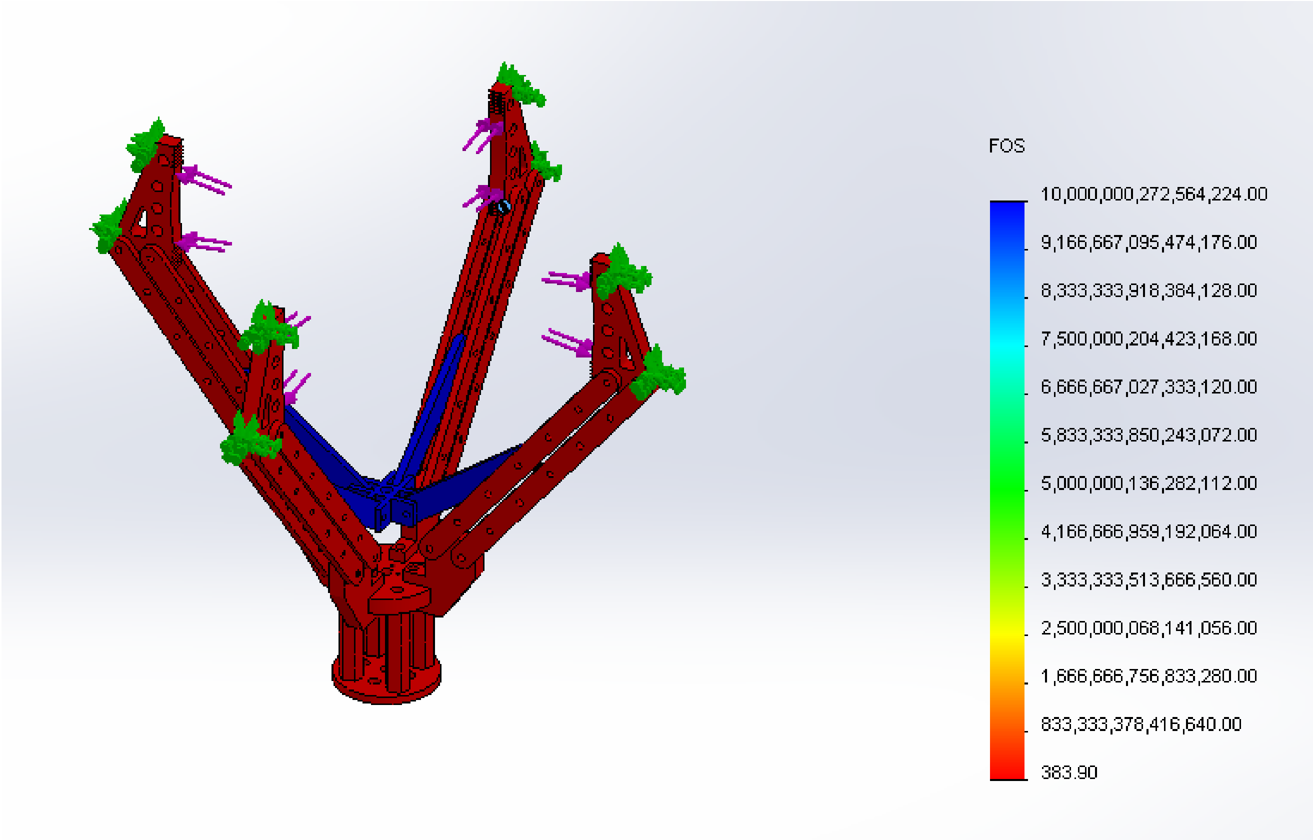


Figure 24: Safety Factor Analysis of Claw Mechanism

5.7 Deformation Analysis

Figure 25 illustrates the expected deformation of the claw mechanism as simulated through Solidworks. Although several members are expected to undergo some sort of deformation, the deformations that will occur are on the scale of micrometers.

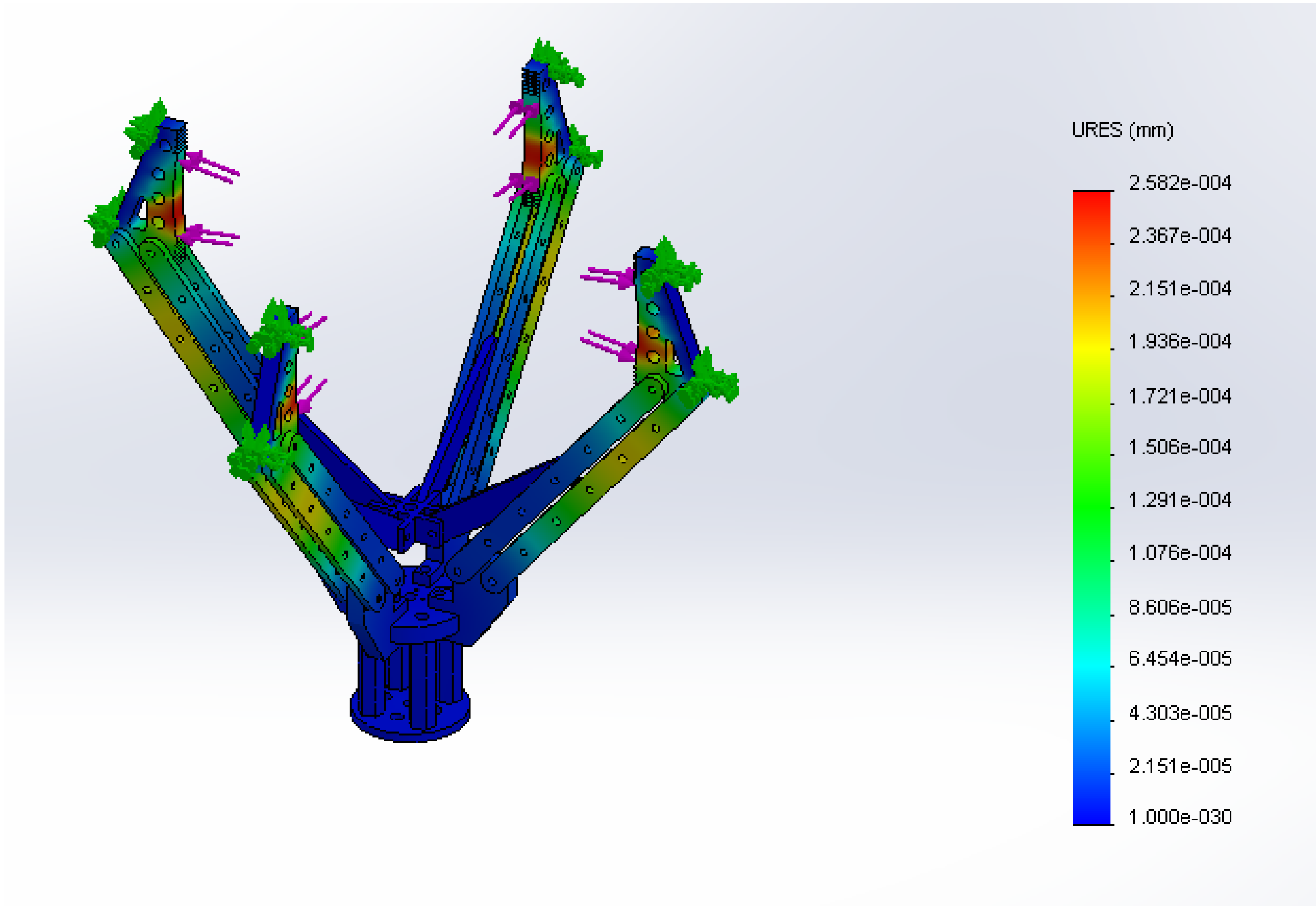


Figure 25: Deformation Analysis of Claw Mechanism

Table 6: Deformation Values from Solidworks Simulation

Deformation	Deformation (micrometers)
Maximum	0.258
Minimum	0.245
Average	0.250

Table 6 details the maximum, minimum, and average values of the expected deformations provided by the Solidworks simulation. It is noted that the deformations are expected to be so minor that none will amount to a full micrometer. Once again, the values of the maximum and minimum deformations are rather close, with only seven nanometers separating the two extreme values.

5.8 Material Selection

The main consideration when discussing material selection for this project is the weight limitation. Because the quadcopter has to carry a relatively significant amount of weight between the onboard control components, camera and battery, the structural framework, the release mechanism, and an Elide fire extinguishing grenade, a light weight, high strength material was chosen for the main structural framework and propellers of the quadcopter: carbon fiber. The light weight properties of carbon fiber will help to minimize the overall weight of it while maintaining enough strength to ensure that the quadcopter will be able to structurally survive and crashes. Because the release mechanism is a compartmentalized component that is solely essential to the fire extinguishing function of the quadcopter, PLA plastic was chosen as the material due to its ease of fabrication, light weight properties, strength for the task at hand, and its thermal resilience under optimal conditions for the deployment of the fire extinguishing grenade. If a crash were to occur where the release mechanism is damaged, spare parts or a completely new release mechanism can be fabricated relatively quickly or be on hand for fast replacement. Apart from the structural framework and release mechanism, the rest of the quadcopter consists of components where material selection does not apply.

5.9 Design Overview

Overall, the final design of the quadcopter consists of a mixture of electronic components for the control system, carbon fiber tubing and plates for the structural skeleton of the quadcopter, and 3D printed parts to fabricate the housing and release mechanism for the fire extinguishing grenade.

Figure 26, as follows, depicts the final CAD drawing of the quadcopter using SolidWorks. As previously stated, the skeletal structure composed of carbon fiber tubing and plates will have a battery mounted in the undercarriage, which will also support the release mechanism. On the center and top carbon fiber plates centrally located on the quadcopter body, an assortment of electronic components will be housed that vary from microcontrollers to sensors. An encasement will be used to house the components on the top plate that either do not need access to the external environment or are especially delicate and can become damaged from collisions, accidents, or weather and environmental conditions. The primary and low resolution camera will be attached on top of the housing and will project the video through a wireless connection in real time so the user can have a better perspective of what is going on in the surroundings of the quadcopter.

Figure 26: Final Design

6. Prototype Construction

6.1 Description of Prototype

The type of UVA prototype selected is known as a quadcopter because of its four rotors powered by brushless DC motors. The quadcopter has an X shape, so that lift force can be equally distributed. Its components are four cylindrical arms, three circular plates, three legs from which only two of the four arms carry one. This prototype is design for the purpose of infrastructure inspections as well as firefighting agent testing; therefore, an analog signal camera for faster video transmission will be mounted on its frame as well as a mechanical claw driven by a lower output brushless motor for carrying the firefighting agent in the form of a heat activated extinguishing grenade filled with the firefighting agent to be tested.

6.2 Prototype Design

The prototype design of the quadcopter can be seen in Figure 27 below. It consists of two carbon fiber plates of the same diameter mounted together by four pins with a third carbon fiber plate of a slightly smaller diameter mounted above it. Four carbon fiber arms of the same length are mounted to the central plate structure and issue out from the main body at 90° positions from one another with a motor is mounted at the end of each of the arms with a corresponding propeller attached to each motor. The release mechanism is mounted on the bottom of the central plate body to maintain even weight distribution and accurate deployment of the extinguisher grenade.

Figure 27: Prototype Design

6.3 Parts List

The skeleton of the quadcopter consists of three circular carbon fiber plates with a thickness of 1.588 mm. Two of the plates are the same diameter of 215.9 mm and the top plate has a diameter of 152.4 mm. These three plates are held together by four hexagonal pins. The arms are composed of four carbon fiber tubing that are 0.508 m long a piece. Each tube has an inner diameter of 20.638 mm and an outer diameter of 22.226 mm.

The onboard electronic components are: one 3DR APM Pixhawk autopilot, one Quadcopter power distribution board, four Electronic speed controllers, four 480 KV brushless DC motors, one 5100 mAh 3S 8C lithium polymer battery , one claw system, and one Vide Video/OSD System kit.

Table 7: Parts List

Item	Description	Quantity
Carbon Fiber Plate	216 mm diameter, 1.6 mm thick	2
Carbon Fiber Plate	152.4 mm diameter, 1.6 mm thick	1
Carbon Fiber Pipe	0.508 m long, 22.2 mm diameter	4
3DR APM Pixhawk		1
3DR Video/OSD System Kit		1
480 KV Motor	brushless	4
8 Cell Lithium Ion Batter	5100 mAh	1
3DR GPS		1
ESC 20 AMP with SimonK		1
Quadcopter Power Board		1
3DR Radio Set		1
PPM Encoder		1
APC Propellers		1
Propellers		2

6.4 Construction

The design limitations of a quadcopter are such that the design structures do not change much from its original form; therefore, many third party companies sell parts and even kits for the assembly of such a system. The frame and some electrical components were provided by the previous working group which assembled the quadcopter for their senior design project from such design we derived our quadcopter. This was done by re-selecting some electrical components in order to reduce weight as well as shock hazard and/or damage by static electricity to each of the components. The construction process is very mechanical, assuring everything fits in the right places and the system circuits do not have any open loops, broken wires, or shorts.

Following the provided diagrams from the companies from which the parts are arriving from. Required tools are a soldering kit, set of screw drivers, hex key wrenches, and pliers.

6.5 Programming

In order to successfully program the microcontroller to fully operate the propellers the autopilot board in this case the Pixhawk from 3D Robotics was programmed using the firmware provided by the software known as Mission Planner. First the mission planner asks what type of setup is to be run with this autopilot, the mission planner has a list of different setups ranging from rover, helicopter, airplane, and a variety of other copters. The copters range from tricopters to hexcopters as well as other set ups depending on how the motors are positioned within the specific frame; in this case, the set up is in an X pattern and a total of four motors are used. Based on the fact that four motors are used, a number of calibrations are run on the GPS, compass, and radio controller system onboard the quadcopter. Using the same software multiple setups can be run in order to make the flight of the quadcopter autonomous when paired with a telemetry kit. The telemetry is programmed similarly using the provided software; one can make a remote connection between the ground station, which in this case could be ether a computer with the required software, an android phone, or table.

6.6 Prototype Cost Analysis

The prototype is composed of different components. Aside from its structural framework, it also has highly sensitive electronic components make up the largest part of the expenses since these are prefabricated parts that must be acquired from third party companies and assembled after the fact. Table 8, as seen below, details the itemized cost and quantity of each unit needed in order to fabricate the quadcopter. The total cost for this particular quadcopter set up is $1,149.26, which does not take into account the reoccurring cost of the fire extinguishing chemical grenade, manufacturing time, and programming time required to get the quadcopter running.

Table 8: Cost Analysis

Item	Cost per Each ($)	Quantity	Total Cost (S)
3DR Video Kit	189.99	1	189.99
XT60 Male Connector	1.25	1	1.25
850 KV Motor	18.00	4	72.00
3DR Pixhawk	199.99	1	199.99
3DR GPS	79.99	1	79.99
Deans Male Connector	1.00	4	4.00
ESC 20 AMP with SimonK	25.99	4	103.96
IRIS + Battery Pack	39.99	1	39.99
Quadcopter Power Board	15.00	1	15.00
3DR Radio Set	100.00	1	100.00
PPM Encoder	24.90	1	24.90
APC Propellers	8.00	1	8.00
Carbon Fiber Tubing (24")	41.25	3	123.75
Propellers	2.8	2	5.60
Carbon Fiber Disk	41.95	2	83.90
Carbon Fiber Disk	31.95	1	31.95
3D Printing	40	1	40.00
Motor for Claw	24.99	1	24.99
Total Cost ($)			1149.26

6.6 Discussion

During the analysis of the prototype build, the complexity of the project can be systematically separated in order to organize the work flow. From the prototype description mention in section 6.1, the project was analyzed and certain milestones were set in place. Section 6.2 puts into perspective the draft sketch of the prototype to be built. Section 6.3, discussed the parts needed for this build and described each of the components required to build the prototype from the structural framework to the onboard electronic components. In section 6.4 the construction process is discussed as well as information regarding the tools required for the build. In section 6.5, a cost analysis based on research estimates is drawn for each of the components required for the build to derive and come up with a total price for this prototype build.

7. Testing and Evaluation

7.1 Overview

Conducting experiments and tests are significant when it comes to analyzing any mechanical system and its functions. Premeditated experiments were planned and performed in order to determine the capability, efficiency, and safety of the quadcopter and its release mechanism. Evaluations of the experiments were made from the test results and data, which then contributed in improving the entire design of both the quadcopter and release mechanism to enhance the entire system's effectiveness and cost. The aspects of how the experiments were established, their results, analysis and development will be shown in the following sections.

7.2 Release Mechanism Experiment

The initial experiment of the release mechanism was conducted without the mounting of the quadcopter's structure. This experiment consisted of programming the robotic claw to both open and close toward a Styrofoam ball with the same weight, size, and shape of the Elide fire extinguishing grenade. The gearbox on the robotic claw was programmed to function on its maximum speed capacity of 600 revolutions per minute. This would demonstrate if the stepping motor on the robotic claw is sufficiently powerful to hold the fire extinguishing grenade. Once the robotic claw was to interconnect with the Styrofoam ball, the last step was to physically lift up the robotic claw with the Styrofoam ball. Different trials would be made with the change of lift force and speed to confirm if the robotic claw can still grasp the Styrofoam ball efficiently enough with these changes in parameters.

7.3 Test Results and Data

The first experiment done to test the release mechanism is demonstrated in Figure 28 below. This figure shows the process taken when the robotic claw was to open and close onto the styrofoam ball. As the robotic claw interconnects with the styrofoam ball, a lift force was applied to the robotic claw end, which would ideally be fixed to the quadcopter in order to validate if it would grab and hold onto the styrofoam ball. This experiment revealed that the robotic claw design, in terms of the gripper component, would not be able to both connect and hold onto the ball when a lift force is applied. The gripper component has a lack of surface area and slip resistance property in order to keep the ball in place. The robotic claw would easily slide off displaying low compressive and shear force towards the ball.

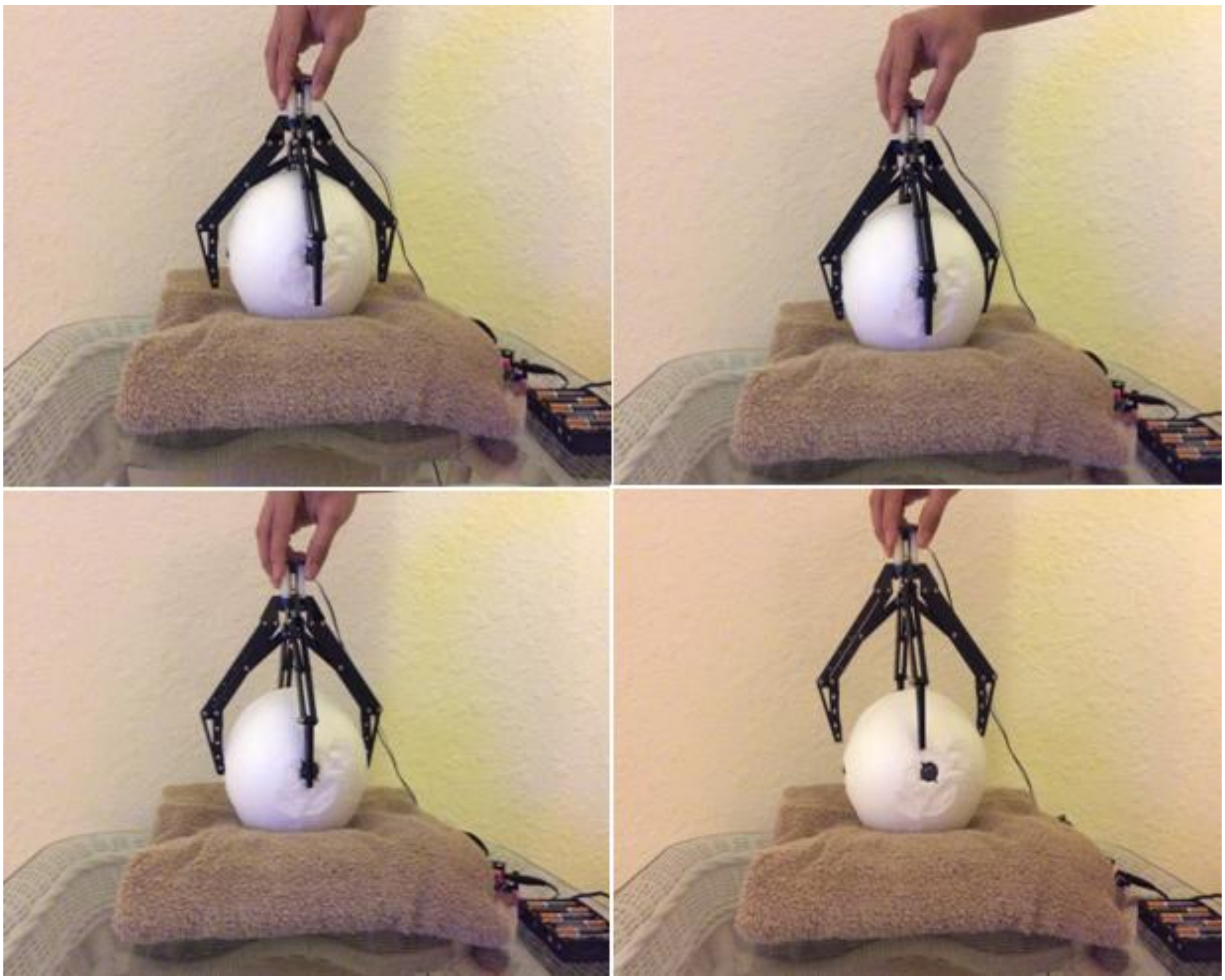


Figure 28: Testing of Claw Mechanism

The second experiment done was to determine if the improved claw mechanism design was functioning properly. Since the motor held fast in the previous experiment, the only items changed were the long links in the arms and the grippers at the ends of the arms. The grippers were widened and the arms were lengthened to increase the gripping effect of the release mechanism on the fire extinguishing grenade. The previous experiment was merely repeated with the new design iteration. The following figures, 29 through 31 illustrate the success of the release mechanism testing. This time around, the grippers effectively held on to the simulated fire extinguishing grenade constructed of lead weights and a styrofoam ball without the ball slipping and falling like in the previous experiment.

Figure 29: Second Experiment - Initial Image

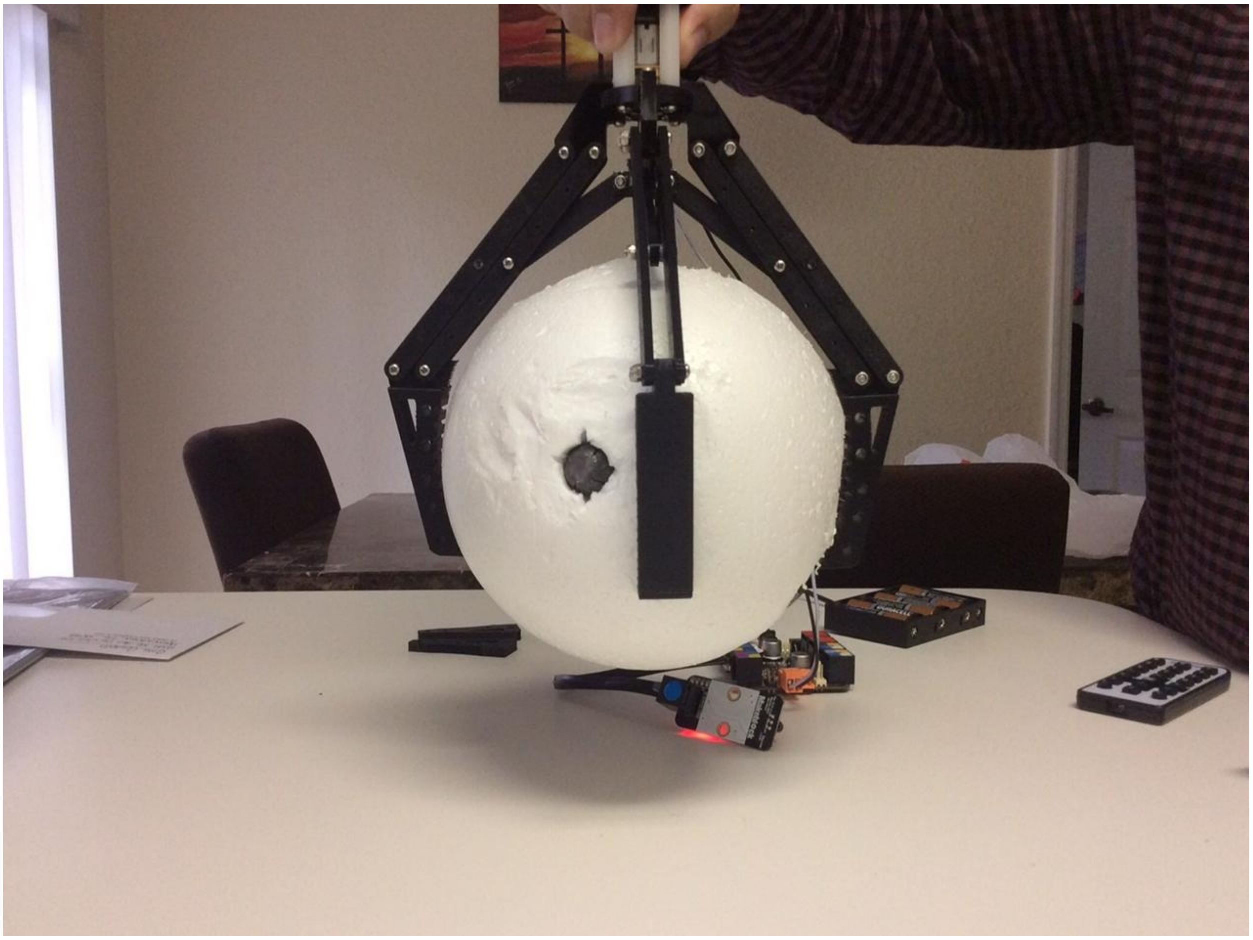


Figure 30: Second Experiment - Intermediate Image

Figure 31: Second Experiment - Final Image

7.4 Evaluation of Experimental Results

The assessments made from the results of the first release mechanism experiment were both positive and negative. One of the features that were to be evaluated was to confirm if the robotic claw's shape structure would interconnect with the fire extinguishing ball. This meant that the claw would both have to open and close towards the ball without any restrictions of collision from other components of the robotic claw. Although the experiment illustrated that the robotic claw was able to interconnect with the ball, the gripper component of the claw design was not adequate to hold the ball and lift it up. This was caused by a lack of surface area interaction, friction, and strength of the gripper component. The results show that the gripper component slid off to easily from the ball; this meant that the gripper's surface friction in contact with the ball was too small from keeping the ball from sliding. The experiment demonstrated that all the links were strong enough to withstand the weight of the ball without any elongation on the links or ductile failure. This was a constructive outcome since the sixteen links that connect with the gripper component of the robotic claw experiences the most stress of the entire release mechanism for its small thickness and long length that causes bending mainly on the middle of the links. Another component that was observed from the robotic claw that was important for the grasping of the Elide ball was its stepping motor. This experiment demonstrated that the motor will be able to provide enough torque to grab and hold onto the Elide ball, but an increase in torque would make the robotic claw more efficient in holding onto the ball. The overall experiment confirmed that the only two components that would require a change would be the gripper of the robotic claw and the stepping motor. Through modifying the shape, size, strength, surface friction and area of the gripper component, the robotic claw should be able to grab and hold onto the Elide ball without really changing the stepping motor.

7.5 Improvement of the Design

One of the major improvements made to the release mechanism would be the gripper component. The gripper had to be modified in terms of size, shape, surface area, and strength. The shape of the gripper was changed considerably into a shape that is rounder on the surface that would mesh with the Elide ball. This would ensure that the entire surface of the gripper will come into contact with the surface, which is better than the first design that left some surface area untouched. The gripper was also thickened three times as much to cover more surface area of the ball for better clench. The surface texture was also changed in order to add more friction and slip resistant to the surface of the gripper. This was done by adding more lofted cuts with both circular and rectangular shapes in different sizes and depths. Friction tape was added to parts of the surface of the improved gripper for providing an increase in slip resistance. The length of the gripper was enlarged in order for the gripper to connect with the bottom surface of the ball, which would decrease the shear force and the effect of gravity that allows the ball to slip from the robotic claw.

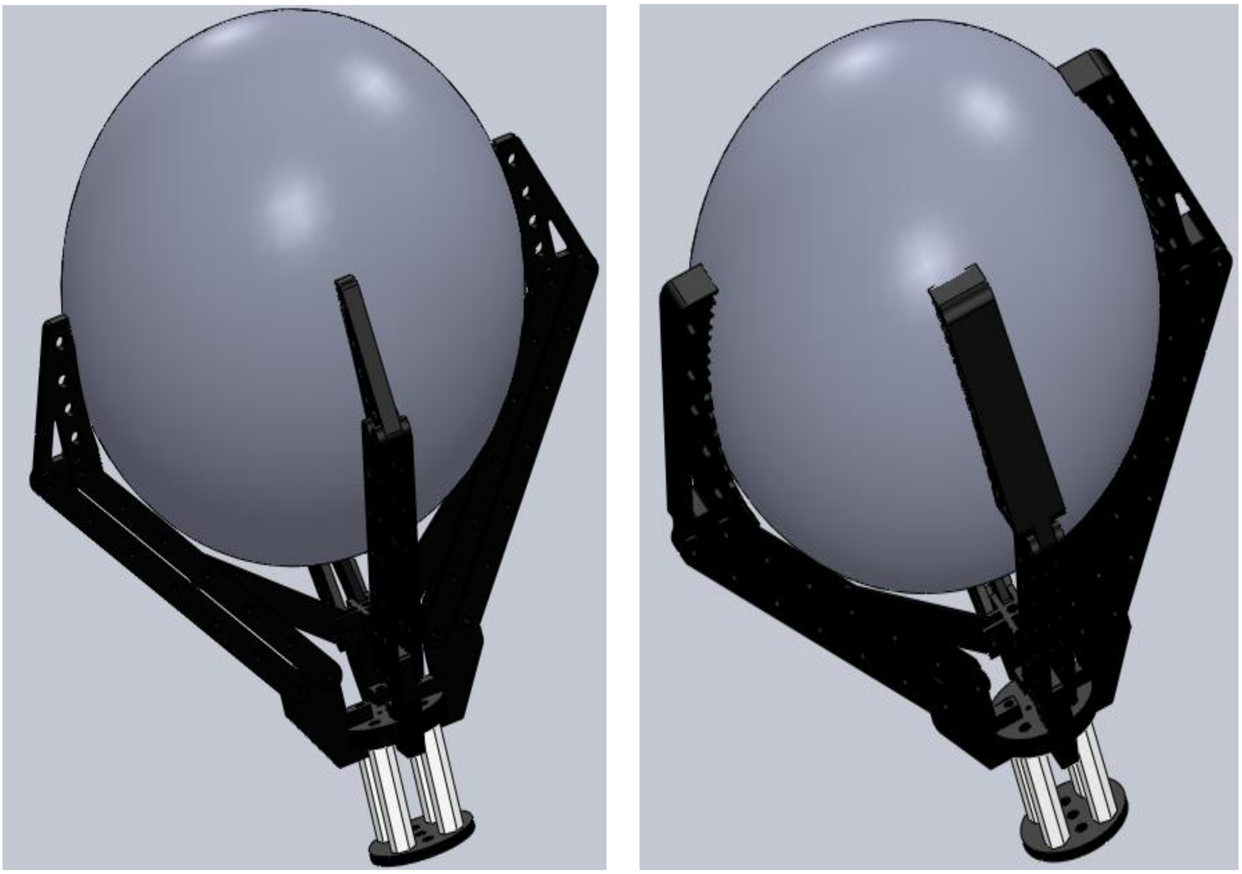


Figure 32: Solidworks Modeling of Claw Mechanism 1

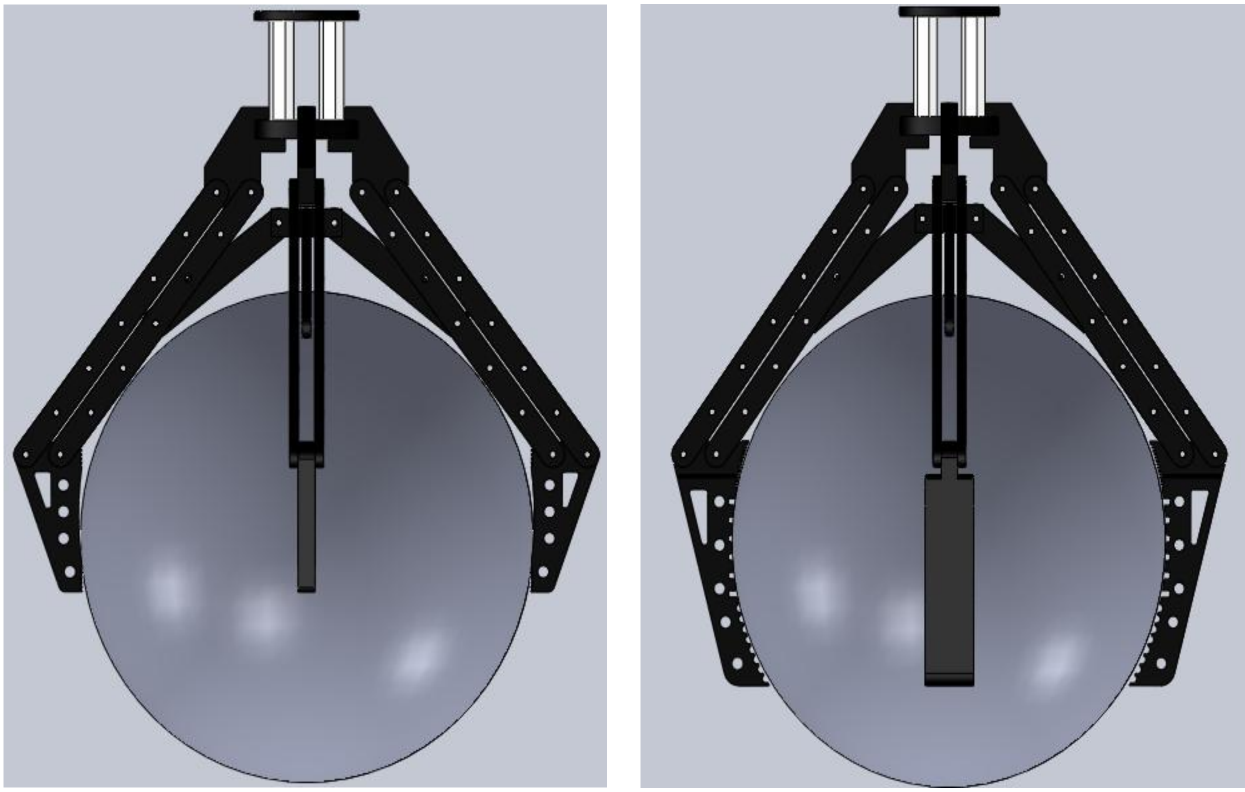


Figure 33: Solidworks Modeling of Claw Mechanism 2

Illustrated, in Figures 32 and 33, is the assembly of the first robotic claw compared to the enhanced one. Both designs are the same apart from their gripper component. The figure clearly display the change in size and shape of the gripper and how it would only improve the interconnection it will have with the ball.

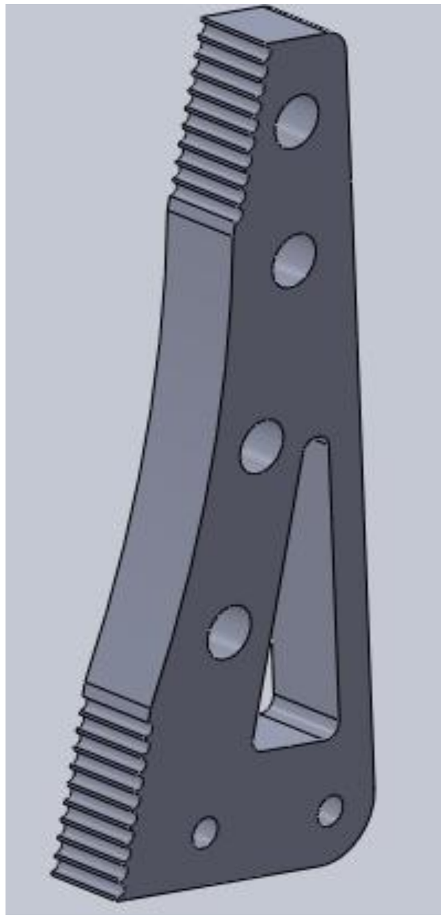


Figure 34: Original Gripper Design

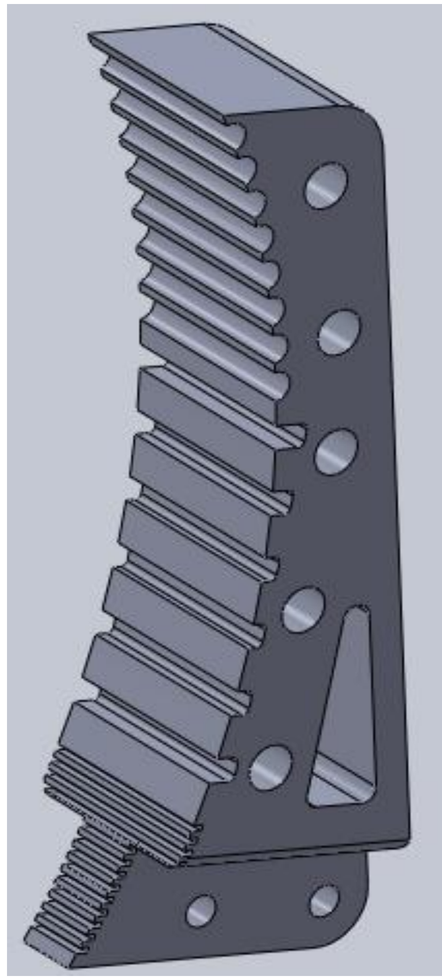


Figure 35: Gripper Design Iteration 1

Figure 36: Complete Finalized Design

8. Design Considerations

8.1 Assembly and Disassembly

The quadcopter's assembly and disassembly will mostly consist of structural assemblies. It is not recommended to constantly remove and assemble the control components as a lot of the wiring and components are minute and thus fragile. In order to store the quadcopter in a more space conserving way or to ship the quadcopter in a more efficient manor, the arms of the quadcopter may be easily detached through removal of a few bolts and screws, as well as the propellers attached to the motors. If further space needs to be conserved, the release mechanism for the fire extinguishing grenade can also be easily detached by removing a few screws.

8.2 Maintenance of the System

The quadcopter system is relatively easy to maintain with the majority of the maintenance centered about ensuring the components are in working order, which is done automatically through the arming function of the Pixhawk. Apart from component maintenance, structural maintenance can be done by visual check for any visible signs of wear or stresses. The compartmentalized design of the quadcopter's release mechanism allows for easy removal and replacement should the PLA plastic deform intense heat during extinguishing, although operating the quadcopter where the PLA plastic would be exposed to temperatures above the average temperature of an updraft of a fire, 60-80°C, is not recommended. The carbon fiber arms, disks, and propellers are also easily exchanged with the removal of a few screws and bolts, as well as the motors should they ever reach their life expectancy. Due to the fragile nature of the wiring of the onboard electrical components, it is also not recommended to operate the quadcopter in wet environments as water can cause a short along the circuitry.

8.3 Environmental Impact

The quadcopter is environmentally friendly for the most part. The largest components of the quadcopter, being the carbon fiber structural framework, the release mechanism, and the battery can all be recycled or repurposed. Carbon fiber is a difficult material to recycle, though it can be done. One of the main concerns with recycling carbon fiber is that the new product is not as strong as it originally once was, which leads to the term downcycling. Recycled carbon fiber can be repurposed to less important or critical functions that will undergo less stresses or potential wearing. In terms of repurposing, the carbon fiber arms can be repurposed to supports stands for the quadcopter should the arms become damaged during a flight accident before being finally recycled to obtain the most usage for each of the parts.

The lithium ion battery can be 100% recycled at any recycling plant that takes batteries, though the only issue with recycling of lithium ion batteries if the cost to do so. The cost to recycle lithium so drives the price of lithium upwards of five times the cost of the raw material, making it financially irresponsible for a company to use recycled lithium batteries currently. Environmentally, disposal of the lithium batteries when no longer functioning is the proper thing to do and should not impact the initial purchase cost of the product.

PLA plastics, unlike carbon fiber, which can only be downcycled if not repurposed, has the potential to be completely cradle-to-cradle recycled. With the advent of 3D printing, a move to finding a way to recycle PLA plastics has been in motion. PLA plastics can be recycled chemically and purified to remanufacture PLA filament without impacting the original properties of the material.

8.4 Standards

Several different types of standards were used throughout this project, both implicitly and explicitly. Implicit standards, like those seen through tried and true methods of calculations when pertaining to the solving of design problems were implemented. In this project, implicit standards regarding thrust forces, static loadings, thermal stresses, and Von Misses Stress Criterion were used to aid in the material, component, design, and mechanism selection process Explicit standards, like those set by governing bodies, can be seen in material selection, some of the component selection, the design of some of the component selections, and environmental and safety impacts. Examples of these include the ASME code of ethics when pertaining to the environmental impacts and safe use of the quadcopter, the SI System of Units when conducting calculations, AGMA standards for gear selection within the stepping motors utilized, and FAA UAS Standards.

9. Conclusion

9.1 Conclusion and Discussion

Overall, this project boasted multiple aspects of engineering knowledge to complete. Basic design considerations were used when designing the structural framework of the quadcopter to ensure no net moments, torques, or forces aside from the thrust force were to be felt on the quadcopter. Keeping this in mind, a very balanced and symmetrical design came into focus with the majority of the components for the quadcopter located in a centralized position among the plates of the quadcopter with the motors and propellers attached to the end of each evenly spaced arm. It was also noted in aviation knowledge, that residual torques incurred from the motors and propellers would need to be dealt with, so opposing rotational patterns were designed to be placed adjacent to one another.

A series of calculations were performed to aid in the choosing process for the correct size of propellers. Knowing the weight of the quadcopter, a minimum thrust force can be determined which will then aid in selecting a specific size of propeller depending on the motors used.

The majority of the complex design process came into play during the design of the release mechanism for the fire extinguishing grenade. It was decided that a four prong claw mechanism would be the most effective and stable design for the release mechanism and that this release mechanism would be placed in a central location along the underside of the quadcopter's central plates. The force exerted along each of the release mechanism's prong was calculated and then used in a SolidWorks simulation to determine stresses, strains, deformations, and safety factors within the PLA plastic. It was concluded that the material is far more resilient than needed, but due to ease of manufacturing and low cost, PLA plastic was chosen as the final material of manufacture.

9.2 Commercialization Prospects of the Product

UAVs will become extremely popular in the near future once the FAA sets regulations and laws into place for use of UAVs in commercial aspects. This quadcopter will have commercialization prospects in several industries with the ease at which the user can switch out main cameras for data collection. Doing this alone allows for the quadcopter to be used for large stress and fatigue points within bridges and other large structures to help prevent accidents associated with improper use of or complete lack of safety equipment. This quadcopter can also be fitted with cameras that can help to determine the repair state of electric wiring for power companies, which currently use expensive and bulky vehicles. Removal of the release mechanism can also allow for a larger, more powerful camera to be mounted to the quadcopter for more in depth imaging to be performed.

Pertaining to the release mechanism, the quadcopter is not prepared for extinguishing large fires due to the instability a large updraft would create. It would, however, be suitable for testing of fire extinguishing chemicals along with any other sort of testing in which distance from the test site would be ideal for safety amongst other reasons.

9.3 Future Work

Future work into UAV technology, especially with this quadcopter could advance the technology of fire extinguishing, surveillance, and construction purposes. The main issue that the quadcopter currently has is its instability in large updrafts, which would result in the quadcopter crashing. Further development of stability controls would be increasingly beneficial since large fires especially pose a safety hazard for civilians as well as fire fighters. Increasing the size of the quadcopter would also be beneficial since larger propellers and therefore lift and thrust forces can be increased for larger payload, which could include better cameras or larger amounts of chemical extinguishers.

10. References

Cheney P, Sullivan A. "Fire Speed - Faster Than a Speeding Bullet?" CSIRO. 14 October 2011. Web. 17 March 2014

Clark, Terry, Janice Coen, Mary Ann Jenkins, David Packham. "Modeling the Links Between Fire and Wind." UCAR.

Hanna J, McLaughlin E, Yan H. "Loss of 19 Firefighters in Arizona Blaze 'Unbearable,' Governor Says." CNN. 2 July 2013. Web. 17 March 2014.

Heller, Aimee. "Engineer Falls to Death during Aqueduct Bridge Inspection." The Perecman Firm. 23 January 2013. Web. 9 March 2014.

"The National Bridge Inspection Program and the Highway Bridge Replacement and Rehabilitation Program." The Federal Highway Administration. DOT. 4 April 2011. Web. 9 March 2014.

"On-Duty Firefighter Fatalities 1977-2012." U.S. Fire Administration. FEMA. 27 January 2014. Web. 9 March 2014.

"Parallax 80000 Quadcopter Kit." Mouser Electronics. Web. 9 March 2014.

"Residential Fire Fatalities in the News." U.S. Fire Administration. FEMA. 7 March 2014. Web. 9 March, 2014.

Whittle, Richard. "The Man Who Invented the Predator." Air & Space Magazine. April 2013. Web. 9 March 2014.