EML 4905 Senior Design Project

A B.S. THESIS
PREPARED IN PARTIAL FULFILLMENT OF THE
REQUIREMENT FOR THE DEGREE OF
BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

# UNMANNED AERIAL VEHICLE WITH FIRE EXTINGUISHING GRENADE RELEASE AND INSPECTION SYSTEM
# 25% Report

Cesar Beltran
Miriam Carolina Freitas
Alex Moribe

Advisor: Professor Igor Tsukanov

April 10, 2013

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 Miriam Carolina Freitas, Cesar Beltran and Alex Moribe 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.

| Miriam Carolina Freitas | Cesar Beltran | Alex Moribe |
|---|---|---|
| Team Leader | Team Member | Team Member |

Professor Igor Tsukanov
Faculty Advisor

# Table of Contents

# List of Figures

# List of Tables

# Abstract

The ignition of certain materials that combust to create a fire is something that most of the times occurs without being wanted. The damages that a fire causes are proportional to the size of the fire. Sometimes, nothing happens to property and living beings, but other times, the emotional and economic losses are too great to afford to keep having fires that are difficult to control, and eventually extinguish.

For that reason, the intention of this design project is to improve the ways in which fires are prevented and extinguished. UAVs are apparatuses that have become popular in recent years thanks to not only their many capabilities to program, but also that a human being does not need to be on board in order to control it. Hence, this team decided to use them in an innovative and inventive manner to create a mechanism to release a fire extinguishing grenade in the desired location that will prevent fires or directly extinguish them.

# 1. Introduction

## *1.1 Problem Statement*

Currently, there is a lack of unmanned aerial vehicles that are being used with the purpose of extinguish a fire or help prevent one. An unmanned aerial vehicle (UAV) is an aircraft without a human pilot on board. Its flight can be controlled autonomously by computers in the vehicle, or by remote control under the direct command of a human. In the United States and the rest of the world, most of the UAVs in existence are being used for defense purposes.

Fires that occur in homes and nonresidential buildings as well as fires in wild lands cause plenty of health issues; including death to humans and animals, in addition to great economic losses in structures, equipment and vegetation. Furthermore, the first response teams, such as firefighters, are exposing their lives to great risks in order to extinguish a fire.

In addition to those huge problems, there is another one that does not cause so many struggles, but it does have a negative effect when a fire occurs. One of the most popular ways to extinguish fires is to spray water in the area affected by the flames. The water can be delivered via hose using a pressurized fire hydrant, fire sprinkler system, pumped from water sources, such as lakes, rivers or tanker trucks, or dropped from aircrafts in the case of wild land fires. These techniques result effective in extinguishing the fire; however, the damages that they cause to large structures and its contents once the fire is extinguished, generally, are great. The main disadvantage of spraying water in the area of the fire is that water can damage the interior of the building. Especially in office buildings, where electronic equipment and important documents exist in abundance, the contents of the building are in great danger even if the fire is suppressed in a proper manner.

Also, the prevention of wildfires entails creating conscience among the population living near forests and large spaces of vegetation. Letting the residents know that they are the ones that can have the greatest impact in regards to starting a fire; therefore, they are the ones in charge of preventing them. If awareness is not raised successfully, there are still chances that fires can occur. Here is where our team plays a great role by generating new ways of preventing wildfires.

In order to help those that risk their life when a fire takes place, the living beings that can be potentially harmed and their surroundings, such as edifications and forests, to preserve the goods inside a building once a fire occurs, and to help avoid fires in open spaces, this team decided to focus this senior design project in the development of an UAV that is going to prevent fires and also assist in extinguishing them.

## *1.2 Motivation*

The main reason why this team decided to build an UAV and integrate a fire extinguishing ball release mechanism is because of all the advantages that UAVs provide. Starting with the fact that UAVs do not need a pilot on board, they also can get access to places in which life can be in danger if entered. Another reason to use an UAV for this particular project is that it can be programmed to perform any mission desired, without having human error on board. Of course, it has to be taken into account that if any of the systems fail, the UAV will be in great risk of crashing, but those probabilities are too small in comparison to the probabilities of having a successful mission.

On the other hand, according to the U.S. Fire Administration National Fire Incident Reporting, in the year 2011, there were 364,500 residential building fires. A residential building is defined as a structure in which people live. Those fires caused 2,450 deaths, 13,900 injuries and more than $6.6 billion in losses. On the side of nonresidential buildings, they are defined as public or private enclosed structures in which businesses, educational facilities, underground buildings, hospitals and subway terminals are included. In the year 2011, there were 85,400 fires in nonresidential buildings in the U.S., causing 80 deaths, 1,100 injuries and more than $2.4 billion in losses.

A wildfire is defined as the ignition and burning of large extensions of vegetation in a wilderness area. Wildfires take place when the components of a fire triangle come together in a vulnerable and sometimes predisposed area. These components cause a fire when an ignition source is brought into contact with a combustible material, such as trees and dry leaves, that are exposed to enough heat and has a satisfactory supply of oxygen from the ambient air. A wildfire can be caused by natural events, such as spontaneous combustion, lightning, sparks from rock falls and volcanic eruptions; and can also be caused by human activities, such as, discarded cigarettes, discarded glass and plastic (magnifying the rays and heat of the sun), sparks from equipment, and power line arcs [3].

By the same token, in 2012, wildfires were responsible for burning more than 9.3 million acres in the United States, causing more than $450 million in property damages, putting at risk around $136 billion in properties and generated more than $270 million in fire suppression costs.

Regarding the ways in which fires are extinguished, lately two new techniques were introduced to the market. The first one uses a fire extinguishing ball that needs to be thrown in the location of the fire and once it is in contact with the fire, it self-activates within 3 seconds and releases fire extinguishing chemicals that work effectively in a room with a volume of approximately 9 $m^3$. The second technique consists of a similar method. It is called DSPA-5. It requires throwing the device with fire extinguishing agents inside the room, and someone has to pull a trigger to activate it. Presently, both devices are put in the location of the fire by a human. This puts the person in charge of this task in huge danger, since the person has to be very close to the fire.

Another important thing to keep in mind is that by the year 2030, Unmanned Aerial Systems will be allowed by the Federal Aviation Administration (FAA) to operate in the National Airspace system and provide a wide range of services.

As seen by all the facts described before, fires are causing plenty of human and monetary losses in this country; therefore, this team decided to change the application of the regular UAVs being constructed for military purposes, and build and design an UAV that can help a great amount of people being affected by flames and smoke, that most of the times cannot be prevented or well controlled in an effective and timely manner.

## *1.3 Literature Survey*

### 1.3.1 Review History of Remote Control Vehicles

The beginning of the development of remote controlled devices started with the invention of the radio, back in the 1880's, when Nikola Tesla invented the induction coil, a necessary device to send and receive radio waves. At first, these radio signals were intended for communications purposes, but during World War I the Germans started using remote control stations for manipulating tanks loaded with explosives. Between 1914 and 1918, the development of various radio controlled unmanned aircraft were intended to be used for military purposes; however none of the prototypes was fully functional to be used during the war. This also marked the beginning of the use of radio waves for commanding machines and computers, such as power plants and satellites.

After the increasing development in computer technologies in the 1940's, the use of UAVs had opened new frontiers, mostly military purposes for reconnaissance missions and also pilot trainings, but their civilian applications were moving slowly along with research. One clear example is the incorporation of GPS technologies. Since World War II, the preliminary research into general relativity led to the base for our actual GPS technologies, this was called ground-based radio-navigation systems. Although, it was not until the 1990's that the US began incorporating this technology into the UAVs of that period.

### 1.3.2 Sensors and Software in UAVs

With the culmination of the programmable digital computer in the 1940's, the idea of having a totally independent machine has been the subject of multiple studies. While a fully independent machine was not developed, the components of such devices could work independently according to the input signals they compute from the surrounding areas, this signals vary from changes in:

- Altitude (altimeters)
- Acceleration (accelerometers)
- Temperature (thermocouples)
- Light (photo resistors)

Multiple lines of code can be used to control the most desired outcome after reading the sensor; this is done through computer software that uploads the necessary instructions for the UAV to follow.

The reason why sensors are important is because they are the main source of input information for a machine to have its decisions based on. GPS, ultrasonic, thermal sensors, cameras, are just a few of the different types of sensors that can be incorporated into an UAV; speed for this input is important, but what matters most is the code used in order to manipulate this information.

Technological advances in the performance of sensors were seen between the 1950 and 1990, improving the response for their tasks, which were mainly surveillance, bombing, and pilot training. It was not until the introduction of the GPS in the 1990's that UAVs took a major role in not only military but also civilian objective.

In these last years, the U.S. is spending more than $50 billion annually in UAV development and testing. This covers from drones to weather balloons, but advances in UAVs for firefighting technology has not been put together yet.

### 1.3.3 Firefighting Systems

The different types of firefighting systems that are currently used in the market are:

- Fire sprinkler systems: This system consists of a series of devices attached to the roof of each floor of a building or home, and water is connected to them. When the fire sprinkler detects smoke, it activates and releases water.

- Wet and dry chemical agents: This method to fight fires works by minimizing, isolating, or reducing the fuel or heat. Reducing or isolating the oxygen or inhibiting the chain reaction of the components. This method causes less damage than water but some agents can be harmful after long term exposure.
- Gaseous agents: Leaving the wet chemical agents aside for practical reasons like saving electronic devices in the affected area, dry chemical agents are the best solution to firefighting. They are similar to the gaseous systems but in most cases had been proved faster than other methods.

Extinguishing a fire is a dangerous task, especially if the place is not equipped with any firefighting system and in most cases a firefighter needs to enter a building if there are people inside. To avoid putting at risks more human lives, an aerial firefighting gadget can be send inside the building that is in fire to place a gaseous firefighting agent tool; for this purpose a quad copter works best because of its stability capabilities. Few companies in the US already sell generators of gaseous firefighting systems. They are small in size, portable, easily deployed and can cover a substantial damaged area. By adapting a generator to an UAV equipped with a front camera, one can easily enter a building in fire without risks, and the placing of the generator will be more accurate.

### 1.3.4 Regulations

Similar to what has happened with incorporating new technologies into our lives, UAVs are part of ethics discussions and companies that hold the technologies to create such flying devices, and their components, are waiting to start profiting from the results.

So far, the use of UAVs in the civilian sector is mainly for surveillance purposes, which is one of the functions of drones, for military purposes, but there are no limits for what they can be useful in research and governmental purposes. To name a few, Vertical Profiles of Shortwave Atmospheric Heating Rates, Imaging Spectroscopy, Topographic Mapping; and non-research, Coastal Patrol, Forest Fire

Damage Assessment, Forest Fire Mapping, Invasive Plant Assessment. Most of these applications are in early developments and there is lack of regulations and specifications for starting with new projects. These regulations concern the following:

- Lack of airspace regulation that covers all types of UAV systems (encompassing 'sense and avoid')
- Affordability - price and customization issues
- Efforts to establish joint customer requirements
- Liability for civil operation

The lack of precise regulations has not stopped the enthusiasm of individuals and known universities, to create or modify existing UAVs into what could possibly be helpful in the future. The Swiss Federal Institute of Technology Zurich has a department focused only in the development of intelligent aircraft. In there, competitions are held often and individuals can share open source code for their UAVs.

The development of UAVs must be accompanied by a high ethical sense and preservation of privacy of everyone. This does not mean that research should be stopped or restricted, just the opposite, it should be open to everyone to get more contributions and increase the capabilities of any application. Until now, the computing and programming part of the UAVs had been moving along side, which means that the faster and more accurate technology becomes, better, more interesting and helpful ideas for UAVs can be designed.

## *1.4 Discussion*

The eradication of fires in a manner that no lives are lost, and that the cost of extinguishing the flames is reduced to a minimum comes from prevention and having a well educated population. Nonetheless, there are certain situations in which fires occur in unexpected and fast ways; therefore, there have to be competent and cost efficient methods in order to approach the extinguishing of the flames and smoke without the losses that usually fires cause.

# 2. Project Formulation

## 2.1 Overview

Fires spread around the U.S. in an unpredictable way. Because of this, most of the times it is hard for firefighting departments across the country to control them, as well as eradicate the flames and smoke of the affected area in an inexpensive and timely manner.

Knowing these facts, this team will design and build an UAV that will have three purposes: fire prevention, firefighting and inspection. Fire prevention and firefighting will be achieved through the ejection of a fire extinguishing ball or grenade in the area in which the fire is taking place. Inspection will be accomplished by installing cameras in the UAV.

## 2.2 Project Objectives

The purpose of this project is to build an UAV and attach to it a release mechanism for the fire extinguishing ball. This mechanism will be entirely designed and manufactured by the members of this team. The UAV is going to be built using parts already in existence and this team is going to put them together in order to construct a vehicle that is able to comply with all requirements to extinguish, prevent and inspect a fire.

The UAV will be capable of delivering the grenade in an area that is hard to approach by conventional methods or is more expensive to do it in other ways. Once this system is up and running, a camera is going to be added to the vehicle. With this, the second application takes place, which is inspection by live video recording and pictures. In addition, the camera is also going to help in taking the vehicle to the place desired by the controller.

## 2.3 Design Specifications

The requirements of the UAV are the following: pick up one fire extinguishing grenade, drop it off in the area chosen by the operator, and have a camera that is recording what is going on in the surroundings of the UAV. In order to do this, this team decided to use a quadcopter vehicle. As seen in Figure 1, a quadcopter is a UAV with four or more rotors with capabilities of lifting and carrying a specific payload.

**Figure 1: Quadcopter Model**

The other main factor in this project is the payload, which is the fire extinguishing grenade shown in Figure 2. It has the form of a sphere, weights around 1.3 kilograms and is filled with a chemical that fights fires. The grenade activates by itself when fire is present (around it); therefore, it can also be used for fire prevention. The grenade can be located in an area prompt to fires, such as the kitchen of a home or restaurant or in a forest that is known for having fires in dry seasons, and once the grenade detects fire, it will activate by itself.


**Figure 2: Fire Extinguishing Grenade [10]**

It is also worth noticing that another one of the most relevant requirements of the multicopter is a GPS system. This will allow the operator to indicate the location of the fire and the release place, and will also specify the exact location of the UAV at all times. In addition with a ground station, the operator can have control of the vehicle in case it goes out of range or the mission has been rearranged. Furthermore, sensors of proximity and altitude will be incorporated to provide the multicopter the ability to avoid a collision with other objects.

## *2.4 Constraints and Other Considerations*

The first limitation faced by the team is the fact that the university does not have the adequate facilities to test a UAV; therefore, designing the main components of the quadcopter according to the exact needs of integration of the release mechanism and placement of the camera was not a possibility.

Furthermore, one of the major constraints is the place in which the vehicle is going to release the fire extinguishing grenade. If the grenade is going to be released in an open space, such as a forest, the purpose of the grenade is for prevention. The open space location cannot be on fire when the UAV arrives, because the flames would melt the UAV. Another thing to keep in mind is that the grenade is more effective when it releases its chemicals inside a room that has a volume of less than 9.5 $m^3$; therefore, a perfect use of this grenade would be when the room of a house or the room of a tall building is on fire. The way to access specific rooms in a structure is through a window. To use the UAV to release the fire extinguishing grenade, this window has to be open and the UAV will release the ball in a way that will fall inside the desired room while it stays outside the area on fire, since the vehicle is in danger of suffering great damages if it is too close to the flames. In this situation, the window has to be open; otherwise the UAV will not have a way to accomplish its goal.

# 3. Design Alternatives

## 3.1 Overview of Conceptual Designs Developed

Three major designs were considered in order to accomplish our goal, which is release a fire extinguishing ball in a determined location, in addition to having a camera in the vehicle that is going to video record what is going on and also take pictures of its surroundings. These two main objectives of the quadcopter are what defined the characteristics of each design that is going to be presented in the following sections.

## 3.2 Design Alternative 1

This design has the purpose of dropping the fireball through a two door opening at the bottom of the box. A box was chosen as a way of protecting the fireball from the fire, so it does not activate before being located at the target. Servo motors control the two doors simultaneously from a computer program that is connected to the quadcopter through radio signal. The material of the mechanism is aluminum, which has a light weight and is easy to manufacture. The disadvantage of this design is the close distance to the fire the quadcopter has to get at the releasing point, since not only the ball has to be protected from the fire during the flight but also the motors and electronic components need to be isolated from high temperatures. This design can be seen in Figure 3.

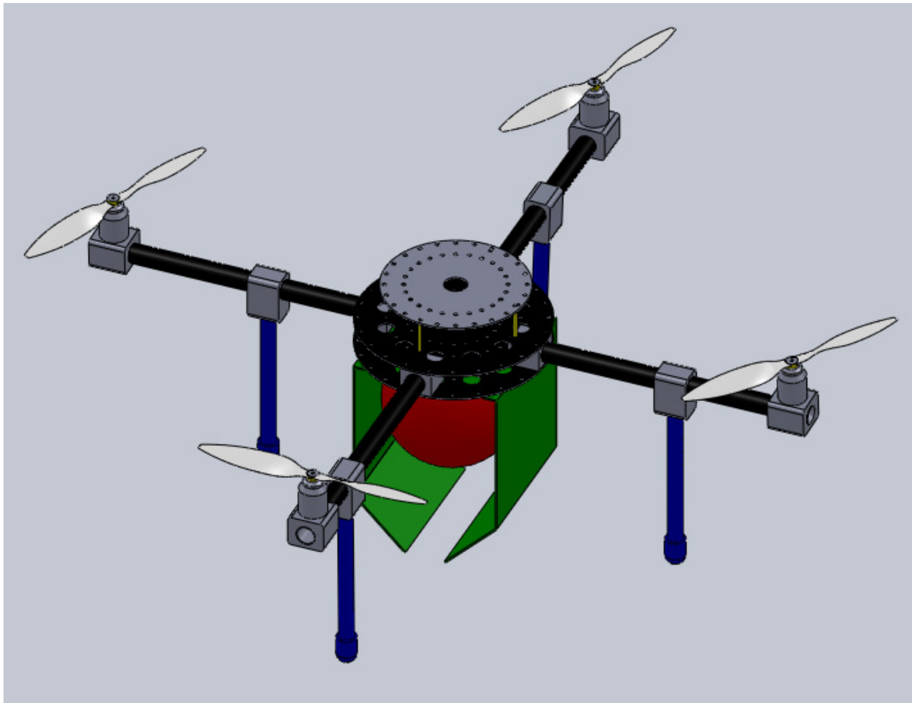

**Figure 3: Design Alternative 1**

## *3.3 Design Alternative 2*

As a way of saving material for the mechanism, a cage design can be used for holding the fireball while making the releasing process easier at the same time. Two solid bars are placed at opposite sides of the bottom of the quad and are surrounded by metallic strings for holding the fireball in place and are connected to controlled locks at the bottom plate. The releasing process takes place when the bars are unlocked making the bottom platform of the mechanism to fall along with the ball. The disadvantage of this process is reloading the fireball. Since we want a system that can do multiple trips if needed, having this type of procedure requires having more than one bottom platform for holding the fireball in place, and putting the parts together can take an approximated time of five minutes. This design can be appreciated in Figure 4.

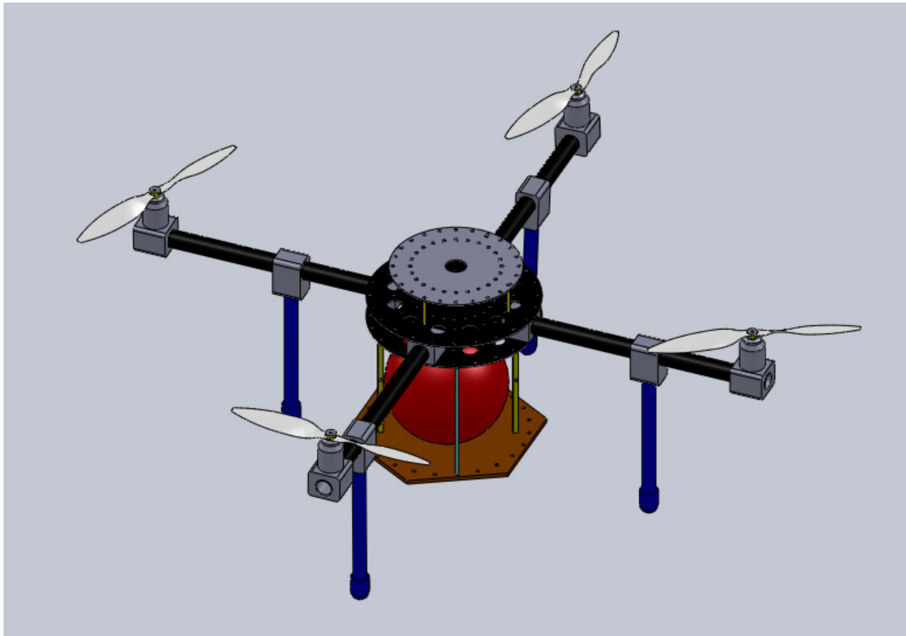

**Figure 4: Design Alternative 2**

## *3.4 Design Alternative 3*

This design consists of having railing system connected to the bottom of the platform that holds the fire extinguishing ball, and this will be the release mechanism.

The cage design from the second alternative still stays attached to the quadcopter and just the rails are added. The rails will serve to guide the fire extingusihing ball to its target while at the same time keeps the quadcopter at a safe distance from the flames. A servo motor controls the angle at which the railing system is going to rotate. This will provide control over the velocity at which the fire extinguishing grenade is released.

When the vehicle reaches the desired location for releasing the grenade, the servo motor activates and lowers the railing system while at the same time it pushes the fire extinguishing grenade from the back of the cage.

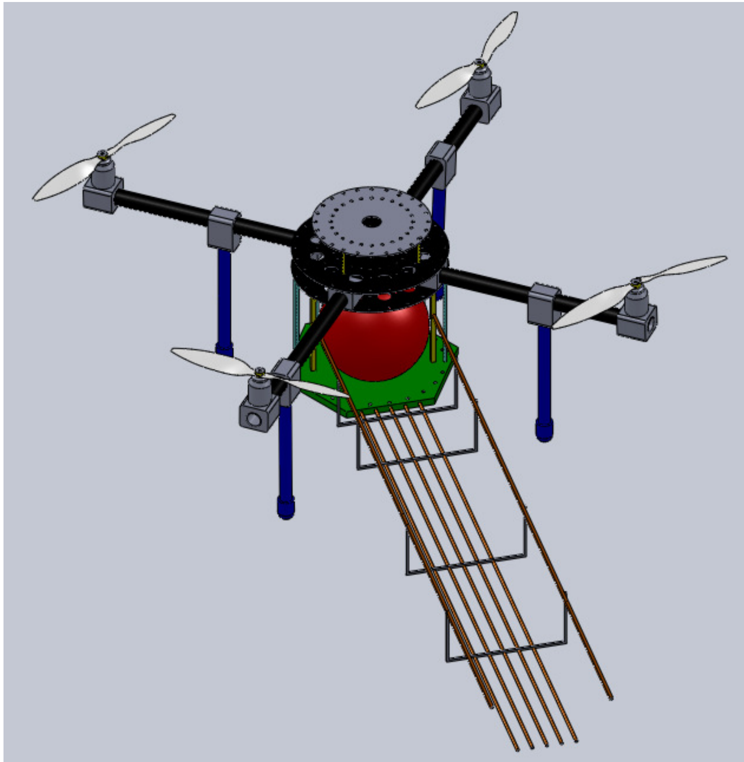

**Figure 5: Design Alternative 3**

## *3.5 Proposed Design*

The chosen design for this senior project is alternative 3. After careful consideration, the members of this team realized that this design will not only provide safe release of the grenade, but also good support for the electronic equipment necessary in order for the vehicle to perform all the tasks defined in the objectives. In Figures 6, 7, 8 and 9 can be appreciated more views of the proposed design.

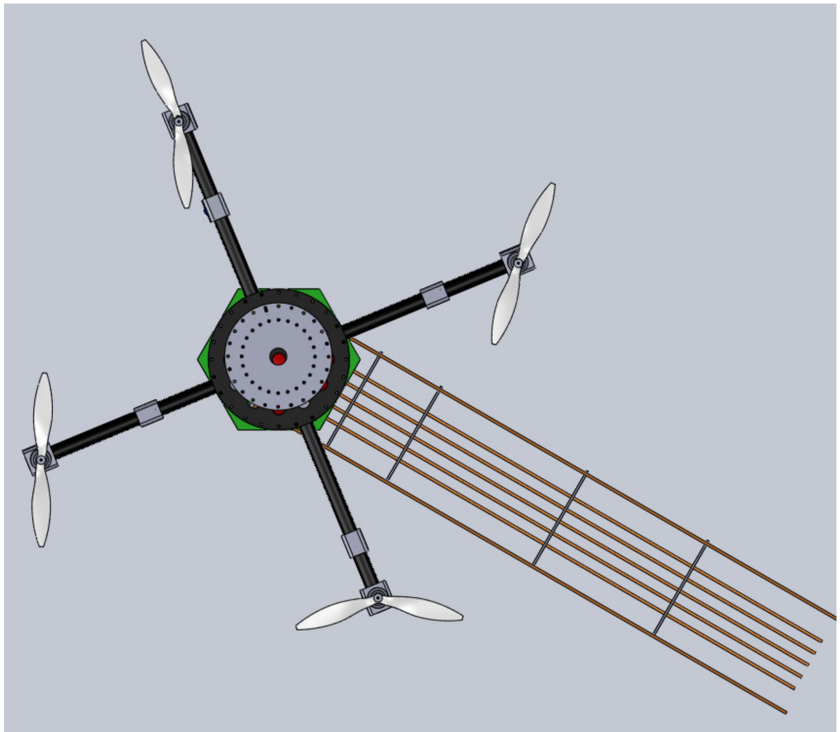

**Figure 6: Top view of the UAV**

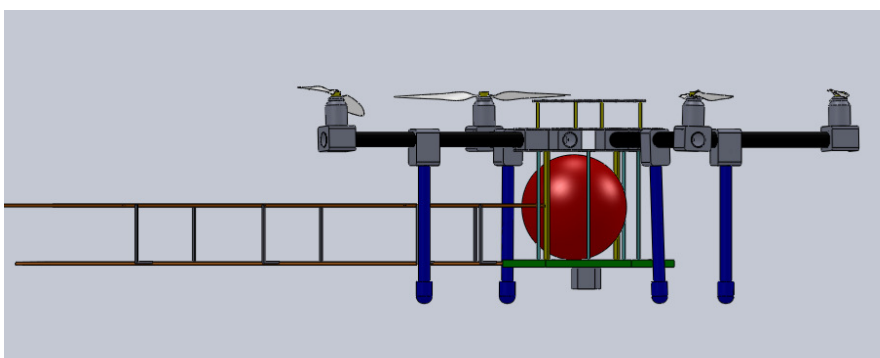

**Figure 7: Back View of the UAV**

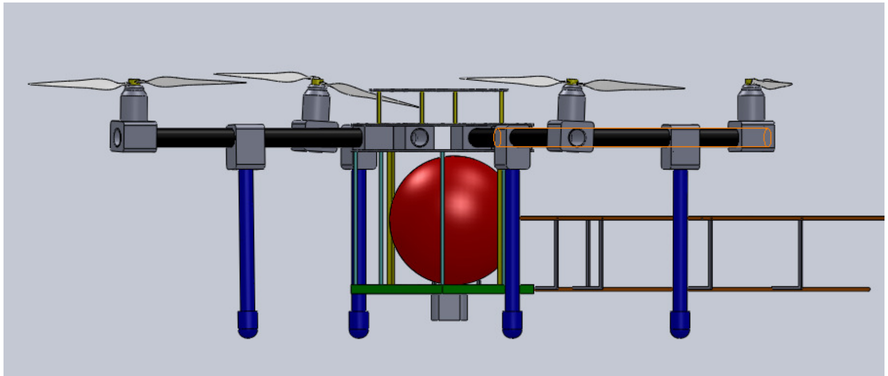

**Figure 8: Side View of the UAV**

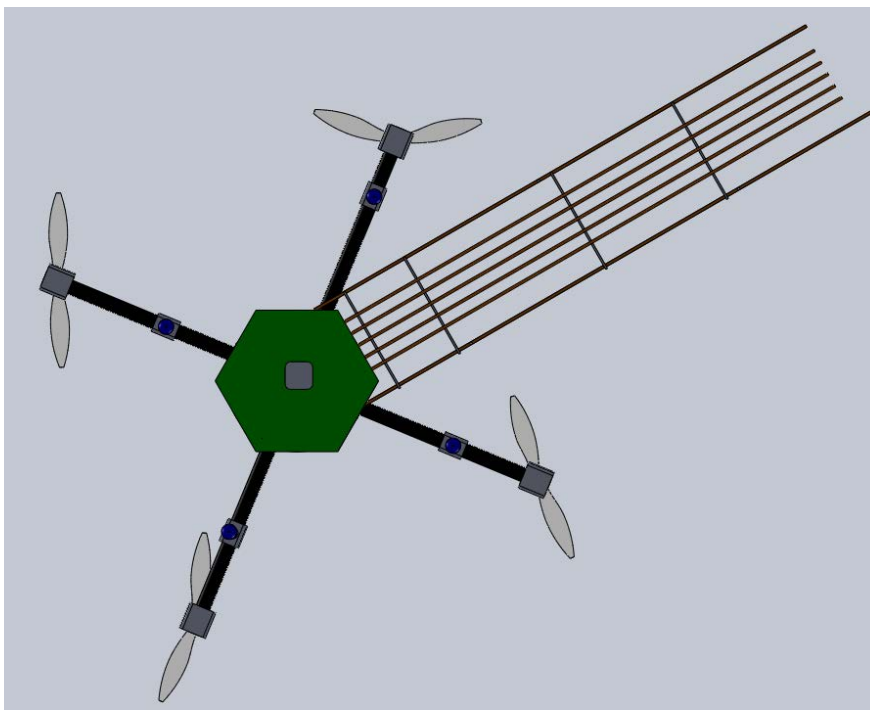

**Figure 9: Bottom View of the UAV**

# 4. Project Management

## *4.1 Overview*

The organization of the tasks needed to complete in order to have a successful project was made having in mind that commitment and efficiency were the keys. Having two semesters to accomplish the goal set up for this project, careful consideration was made choosing what were the main tasks needed to accomplish by the end of the spring semester. Consequently, it was decided that by the end of spring and beginning of summer the design of the release mechanism will be complete. In the meantime, the parts to build the quadcopter were going to be ordered and its construction would start as soon as all of them arrive, estimating that would happen in by the middle of May.

## *4.2 Organization of Work and Timeline*

In Table 1 can be seen the timeline for this senior design project. Each stage of the project is shown along with the time frame required in order to complete all the tasks. In the table can also be seen what are the approximated dates in which each task should be completed.

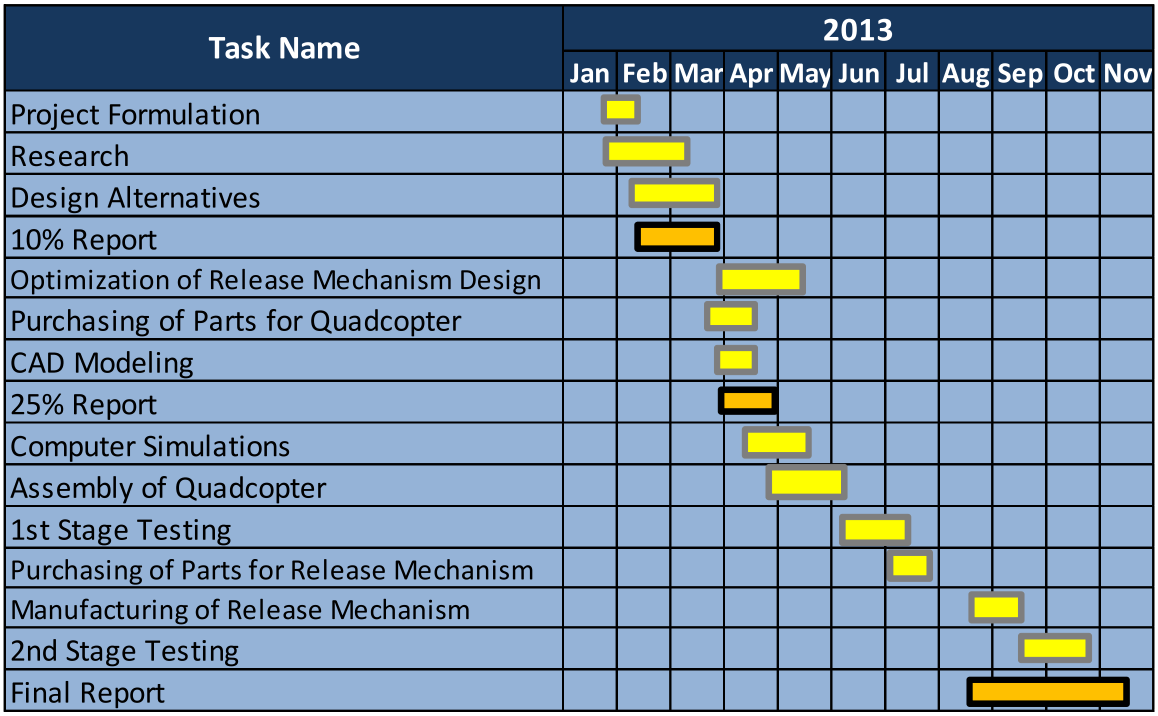


**Table 1: Timeline**

### *4.3 Breakdown of Responsibilities among Team Members*

This team came up with the mains tasks needed in order to complete the designing, building and testing of this project. In table 2 these tasks can be seen along with the members in charge of them. Most of the tasks are going to be shared between the three members of this team, since they require an extensive amount of research and validation of all the team members . There are several tasks that are being performed by one team member. These tasks were distributed according to the level of expertise of each member in that determined area.

| Task | Team Member (s) |
|---|---|
| Prototype Design | Miriam F., Alex M., Cesar B. |
| CAD Modeling | Miriam F. |
| Structural Analysis | Alex M. and Cesar B. |
| Optimization of Design | Miriam F., Alex M., Cesar B. |
| Purchasing of Parts | Miriam F. |
| Assembly of Quadcopter | Miriam F., Alex M., Cesar B. |
| Testing of Flight Capabilities of UAV | Miriam F., Alex M., Cesar B. |
| Testing of Release Mechanism | Miriam F., Alex M., Cesar B. |
| Analysis of Test Results | Miriam F., Alex M., Cesar B. |
| Simulations | Alex M. |
| Cost Analysis | Cesar B. |
| Manufacturing of Release Mechanism | Miriam F., Alex M., Cesar B. |
| Assembly of Quadcopter plus Mechanism | Miriam F., Alex M., Cesar B. |
| Reports | Miriam F., Alex M., Cesar B. |

**Table 2: Breakdown of Responsibilities**

# 5. Engineering Design and Analysis

## *5.1 Major Components*

There are many important components that are part of the quadcopter structure. Therefore, the UAV for fire extinguishing grenade release and inspection could be examined as a set of individual components according to the function of each system that conform a set. There are three main sets shown in the following list:

1) Fire Ball Extinguish Grenade.
2) Quadcopter Componets: Frame, motors, motor controller and flight controller, battery, first person view camera, GPS flight control system and Ardu-Pilot.
3) Release Mechanism: Release mechanism platform, rails and servo motor.

### 5.1.1 Fire Ball Extinguish Grenade

This grenade is filled with an aerosol capable of extinguish fires using nitrogen mixed with potassium. The aerosol compound contains 70% of nitrogen and 30% of very fine particles of potassium. Using these two components, this method of extinguishing fires is successful in fully developed and in early stages fire. This grenade was designed to replace a Halon fire extinguisher, since its method of operation is to cut off the oxygen supply of the area in which is used; therefore, it could cause serious harm to person if used inside a closed room.

The physical characteristics of the fire extinguishing grenade can be appreciated in Figure 1. This grenade has a solid material system that is filled with a minimal amount of extinguishing compound. The compound acts directly on the flame; hence, having an uninterrupted interaction with the burning surface once the fire extinguishing chemicals are released. This device can be activated by thermal reaction, electronically or manually. The grenade is going to eject the potassium solid as aerosol in a 360 degrees direction and the total deployment time will be 40 seconds.


**Figure 10: Fire Extinguishing Grenade**

One of the advantages of this dispositive is that it keeps oxygen levels intact in case humans are in close range when the grenade is activated. Another important point is that it increases the safety of firefighting personal when they try to extinguish a fire. The fire ball can extinguish 3 types of fires. One of them is type 1A, which is fire that blazes fueled by solids such as wood, plastic, paper and cloth. The second type is 5B fire class, which contains substances such as inflammable material. The third type is C fire class, which is used for electrical parts where water cannot be applied. The specifications of the fire extinguishing grenade are shown in Table 3.

**Table 3: Specifications of the Fire Extinguishing Grenade**

| Feature | Value |
|---|---|
| Diameter (m) | 0.145 |
| Weight (Kg) | 1.5 |
| Volume of action ($m^3$) | 9.12 |
| Activate Time (sec) | 3 to 10 |
| Useful life (years) | 5 |
| Extinguish classes | 1A - 5B – C |
| Fire Extinguishing Agent | Mono Ammonium Phosphate |

### 5.1.2 Frame

The frame of the UAV is composed of three plates, two large main plates joined by pins and one small plate of top of them. This allows a configuration of up to 8 arms (or booms); however, this team decided to build a quadcopter, which has a configuration of four arms. The four booms that hold the motors are placed at 90˚ with respect to each other.

The three plates are made of a material called G-10, which is a fiber glass epoxy composite known for its high strength and resistance to high temperatures. Its properties are available in Appendix A.

The diameter of the two main plates is 8.125". These booms are secured to the main plates by screws that are 1-1/8" long and they rest over two U blocks, one behind the other. The second half of the U blocks is added to the top to clamp the boom to the structure. Another main plate is installed on the top of the arms and the whole structure is going to be held together by adding nuts to the screws. For better support, screws of 3/8" in length are added around the main plates to help hold the structure in place. The motor is mounted at the end of each boom over a flat surface that is secured to the arm by two U supports and four 1-1/4" long screws. A small plate is placed at the top of the two main plates and the electronics components are located in this area, between the top small plate and the top main plate. All these data can be better appreciated in Table 4.

**Table 4: Specifications of the Frame of the Quadcopter**

| Feature | Value |
|---|---|
| Main plates diameter (in) | 8.125 |
| Screws (in) | 1-1/8 |
| Outer Screws (in) | 1-1/4 |
| Support Plates Screws (in) | 3/8 |
| Tube length (in) | 13 |
| Material | Carbon fiber |

The configuration of the frame of the quadcopter can be appreciated in Figure 11. The distance from the center of the plates to the center of the propellers is approximately 23” or 0.6 meters. This measurement has to be confirmed once the quadcopter is assembled.

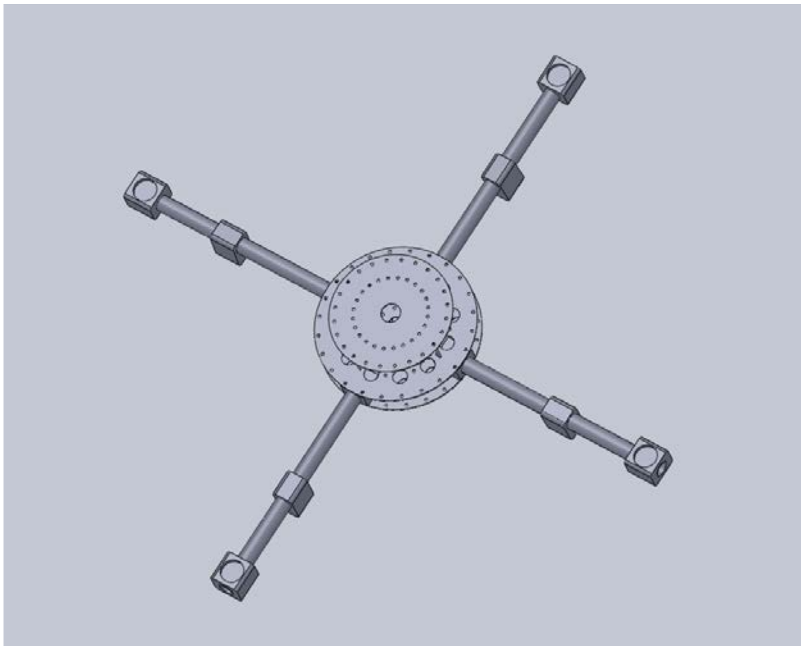

**Figure 11: Quadcopter Frame**

## 5.1.3 Motors

Having a symmetrical vehicle with four motors and placed at the same distance with respect to the center allows the pilot to have great maneuverability and trust. Out of the four motors, two have to rotate clockwise and the other two counter-clockwise to have a resulting net torque over the rotational axis as zero. This means that the quadcopter will be able to travel in any direction without rotating over its central axis. Figure 12 shows the actual motor.


**Figure 11: Motor**

The model of the motors used for this UAV is "SunnySky X2820 KV800" and its specifications are listed in Table 5.

**Table 5: Specifications of the Motor**

| Feature | Value |
|---|---|
| Stator diameter (m) | 0.028 |
| Stator Height (m) | 0.02 |
| Outside Diameter (m) | 0.035 |
| Body Length (m) | 0.04 |
| Shaft Diameter (m) | 0.005 |
| Motor Kilovolts | 800 RPM/Volt |
| Motor Weight (Kg) | 0.14 |

### 5.1.4 Motor Controller and Flight Controller

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 vehicle suddenly loses balance, for a reason such as a wind current, the motor controller (Figure 13) and the flight controller (Figure 14) have the capability of resetting the quadopcter to its initial position and generate the final decision to operate the motors in such way 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 with the structure or lose steadiness and crash with the ground.


**Figure 12: Flight Controller**


**Figure 13: Motor Controller**

The specifications of the flight controller and the motor controller are shown in Table 6.

**Table 6: Specifications of Motor Controller and Flight Controller**

| Component | Feature | Value |
|---|---|---|
| Motor Controller | Current (A) | 40 |
| | Weight (Kg) | 0.06 |
| Flight Controller | Voltage (V) | 5 |
| | Current (A) | 3 |
| | Weight (Kg) | 0.0115 |

## 5.1.5 Battery

The element that is going to provide energy to the quadcopter will be a set of two batteries that are going to offer approximately 20 minutes of flight. Having this period of time, the vehicle will have the ability of deploying and recharging the ball grenade several times, even though this still needs to be confirmed when the tests are performed. One of the batteries can be seen in Figure 14.


**Figure 14: Zippy Battery**

The batteries will have their own compartment in the quadcopter. This will allow a faster change of batteries in case the mission requires more time. The specifications of one battery are shown in Table 7.

**Table 7: Specifications of the Battery**

| Feature | Value |
| --- | --- |
| Voltage (V) | 22.2 |
| Weight (kg) | 0.834 |
| Length (m) | 0.156 |
| height (m) | 0.051 |
| Width (m) | 0.053 |

### 5.1.6 First Person View Camera

The camera selected to install in the quadcopter transmits a real time image to a remote viewer. With this system on board, the controller will have the capability of doing an inspection of the fire situation, coordinate the fire extinguishing operation, and at the same time will assist the controller in maneuvering the vehicle. This camera has a transmitter with a power of 250 mW and a frequency of 5.8 GHz.

The video this camera provides can be seen by the controller when he or she puts on goggles that show the images transmitted from the UAV. The first person view camera and the goggles can be seen in Figure 15.


**Figure 15: First Person View Camera and Goggles**

### 5.1.7 GPS Flight Control System

This system can be used to convert this quadcopter in a fully autonomous vehicle capable of performing programmed missions. However, in the vehicle, this device will be used as a locator while the mission is being performed. This system will work in conjunction an Ardupilot. This will provide refinement of the movements and behavior of the quadcopter during flight. The GPS weight is 0.2 kg and its frequency is 915 Mhz. The GPS can be seen in Figure 16.

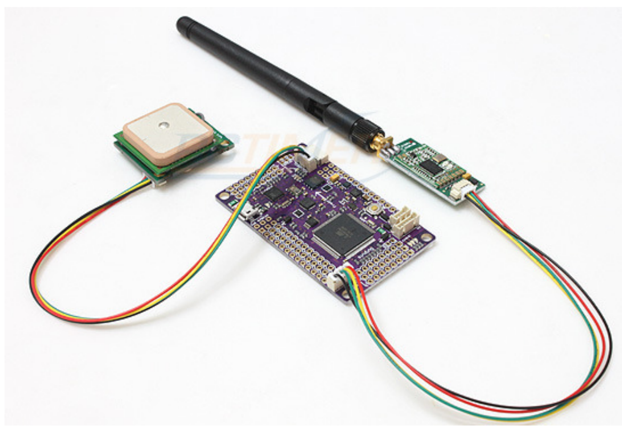

**Figure 16: GPS**

### 5.1.8 Ardu-Pilot

ArduPilot is a software system based on the Arduino platform, which is an open computing system (hardware). This software contributes to autonomous stabilization and GPS navigation to allow the vehicle to accomplish missions without human control. Another important function is that quadcopter will have autonomous landing in case the pilot loses visibility of the vehicle. In Figure 17 the Ardu-Pilot device can be seen.


**Figure 17: ArduPilot**

### 5.1.9 Release Mechanism Platform

According to the proposed design, the fire extinguishing grenade is going to be held below the second main plate inside the release mechanism. One of the main components of the release mechanism is the platform. This platform will hold the grenade, plus it will have the columns attaching the release mechanism to the quadcopter. The proposed design of the platform can be seen in Figure 18.

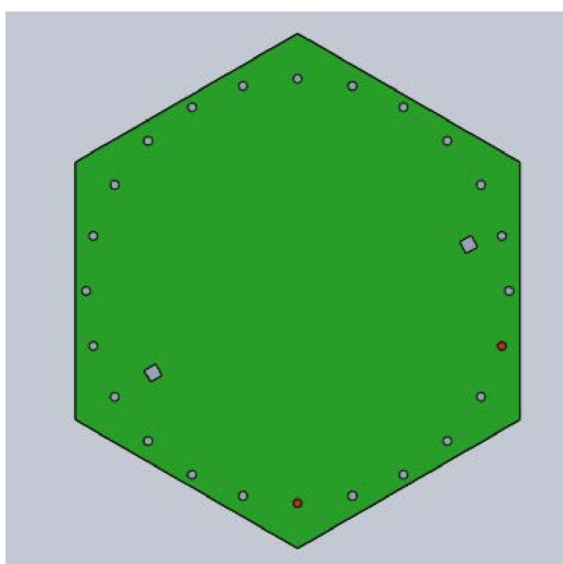

**Figure 18: Release Mechanism Platform**

The platform has to have a diameter bigger than 145 mm, which is the diameter of the grenade. Since there have to be enough clearance for the columns and to charge the grenade inside the mechanism, it was decided that the diameter of the platform is 170 mm. The material has not been decided yet, even though using carbon fiber is a strong possibility.

### 5.1.10 Rails

The rails in which the fire extinguishing grenade is going to roll will be possible made of carbon fiber bars. They will have the shape of a cylinder and an approximate diameter of 4mm and their length will be approximately 1 meter. In Figure 19 the rails can be seen.

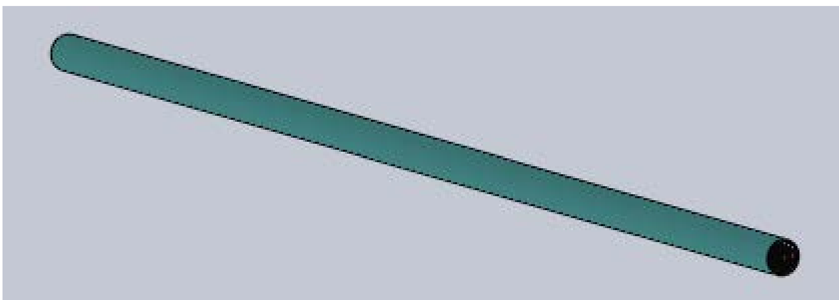

**Figure 19: Rails**

### 5.1.11 Servo Motor

In order to move the rails to the angle desired in order to release the grenade, a servo motor will be used. The specifications of this servo motor are not known yet, since this team is waiting to assemble the quadcopter and perform some tests in order to decide what will be the best servo motor for our mechanism.

## *5.2 Structural Design*

The main focus of this project is the mechanism to release the grenade; therefore, the main factors taken into account to satisfy the requirements of the release mechanism are: Ease of access to load the fire extinguishing grenade, light and resistant materials, resistance to high temperatures and that the design cannot interfere with the aerodynamics or stability of the vehicle. These factors are going to be explained in the following sections.

### 5.2.1 Ease of Access to Load the Fire Extinguishing Grenade

Since the quadcopter will be used for emergency situations, it is required that the person in control can mount the fireball into the quadcopter without much work, also the reloading process has to be simple. A lock and load mechanism will be implemented for this purpose.

### 5.2.2 Light and Resistant Materials

The use light and resistant materials in order to construct the quadcopter and the release mechanism are of extreme importance, since it is necessary that the copter moves fast to the objective and can also withstand the stresses that the load carried can produce. The high reliability of the materials is also a main factor in the decision making about what material should be used for the structural components of the vehicle.

### 5.2.3 Resistance to high temperatures

Testing will be necessary to provide information about how close to the fire the copter can get, since not only the frame of the release mechanism will be closer to the flames, but also the electronics components of the quadcopter, such as motors, cables, antenna, and camera, will be in a considerable short distance to the high temperatures during the release process.

### 5.2.4 The design cannot interfere with the aerodynamics or stability of the quad

Normally, a quadcopter has a weight distribution that contributes to stability. An example of this is that heavier components, such as batteries and camera, will be mounted in the center of the body. In this design, the release mechanism has an extension that works as a slide to deliver the fireball as close as possible to the fire.

Even though the flight controls can adjust the motors to work accordingly to the position of the quad, an abnormal weight distribution, like a heavy release mechanism coming outside of the center of the body, will require one or more motors to produce more thrust in order to maintain stability. Also, the motors need to be isolated at the top and bottom, so thrust can be created in an effective manner; therefore, the release mechanism has to have the most aerodynamic shape available and weight as less as possible.

## *5.3 Analytical Analysis*

### 5.3.1 Problem understanding

The first task when this project started was to define what type of loading would be used in order to release it from the UAV. With the results obtained from this investigation, the team created a guide to follow in order to accomplish the goals established for this project. The first step was to understand the quadcopter components and how they related to each other. Once the team knows exactly how a UAV, the team will be capable of designing the release mechanism that will transport the grenade with and release it with precision. The second step is to make simulations about force, stress, strain and thermal analysis of the entire vehicle and the proposed design for the release mechanism. Having this simulation in place, the team will be able to choose the best configuration to deliver the grenade.

### 5.3.2 Mathematical Model

In order to identify the essential physical restriction of the release mechanism design, the team will translate all the parameters into a mathematical representation of the problem. The first stage is to calculate the thrust and the efficiency of the vehicle. The second stage is to represent the release mechanism as close as possible using CAD software. Once these two stages are completed, the team will be accurate in their calculations and we could predict with high precision how the quadcopter is going to perform the mission.

### 5.3.3 Computational Methods

The software selected to perform all the CAD modeling and simulations is SolidWorks 2010.

### 5.3.4 Force Analysis

Force analysis is an important parameter to be accounted for at the time of static distributed loads and dynamics effects in the quadcopter. The team will perform a careful analysis of these forces. This will provide a better approach in the design of the release mechanism.

It is worth noticing that the stresses are caused by loading coming from the weight of the grenade and the release mechanism. These stresses will be distributed along the release mechanism and the quadcopter frame. This distributed load is going to be variable because at the time of release, the grenade will be rolling throughout the deployment rail until the end. Having this ball in motion will make the linear momentum change at all times with respect to the UAV center. For that reason, the team will consider all the simulation results with this change of linear momentum in the deployment process.

### 5.3.5 Shear analysis

Shear stress data from the results of the CAD simulation will be compared to analytical analyses done on paper, and values from this should not vary from real life scenarios. Three point supports for each boom are taken into account when performing the shear calculations on the main plates, and the forces acting on the structure are caused from the weight of the components and the thrust produced by the four motors. The release mechanism will have these calculations performed separately, since this is our main concentration of the design. The weight of the ball along with the lifting force of the main frame are the principal forces acting on the device. Information about the young modulus of the material is provided so calculations about how much shear stress is felt on each joint of the structure can be performed.

### 5.3.6 Thermal analysis

The estimate of how high temperatures can be experimented on the quadcopter depends on the amount of time it is exposed to heat when on the process of releasing the fireball. Not all the parts are made of a metallic fabric, but a small range of time can be used before the parts begin to show changes due to high temperatures. This will determine how close and what period of time is needed to perform the task, which is to get close to the fire location and eject the fireball through the slider-like mechanism. Using Lindemann's criterion for predicting the melting point of a substance, the maximum temperature can be determined for exposed parts of the quad.

## *5.3 Cost Analysis*

Project cost analysis is the first step in the process of building the prototype. This will provide guidance in choosing the best components available in the market while taking into account financial constraints. The unmanned aerial vehicle for fire extinguishing grenade ejection and inspection project cost will be focused in three areas: Design cost, Prototype cost and Report and presentation costs.

### 5.3.1 Design cost

Design cost is calculated as the rate per hour that an engineer is paid to do a design. However, this project will be designed by students and software provided by Florida International University. For that reason, a traditional design cost analysis is not possible, since it would not reflect the real design cost. Instead, in Table 8 this team will provide an estimate of time spent in each task to develop this project.

**Table 8: Design Cost**

| Category | Task | Hours Spent | Total Hours per Category |
|---|---|---|---|
| Research and Design | Literature Survey | 20 | 100 |
| | Parameters and Restrictions | 15 | |
| | CAD Modeling | 30 | |
| | Conceptual Drawings | 20 | |
| | CAD Prototype | 15 | |
| Analysis, Assembly and Testing | CAD Simulation | 20 | 125 |
| | Frame Grenade Holder | 40 | |
| | Grenade Deployment Frame | 40 | |
| | Stability | 10 | |
| | Flight Testing | 15 | |
| Report and Presentations | Senior Reports | 100 | 131 |
| | Presentations and Rehearsals | 6 | |
| | Engineering Drawings | 10 | |
| | Poster | 15 | |
| **Total Time Cost (Hours)** | | | **356** |

### 5.3.2 Report and Presentation Cost

The cost associated with the report and presentation is relevant to be accounted into the final prototype cost. The printing cost of the reports required by the Senior Design Class is to be added to the calculations because a hard copy of the document has to be presented each time the dead line is reached. The process of printing a final document and a poster is an indicator of real world expenses that companies invest when presenting a final design. The costs of printing the report and poster for the presentations is described in Table 10.

**Table 9: Report and Presentation Cost**

| Description | Price | Quantity | Partial Total |
|---|---|---|---|
| Print 25% Report | $15 | 1 | $15.00 |
| Print 50% Report | $30 | 1 | $30.00 |
| Print 75 % Report | $40 | 1 | $40.00 |
| Print 100% Report | $50 | 1 | $50.00 |
| Print Poster | $80 | 1 | $80.00 |
| **Total** | | | $215.00 |

# 6. Prototype Construction

## *6.1 Prototype System Description*

The main structure of the quadcopter is conformed of three plates and four ooms. Two main plates are at the center of the quad. They are attached together by screws at four different but symmetrical positions. A smaller plate is placed at the top for holding the batteries and antenna. In between the main plates the arduflyer, three battery adapters, four flight and four motor controllers are connected together and hold in placed by screws and metallic straps. The four booms come out of the center of the main plates, and are secure in two points by plastic blocks and screws. Motors at the end of each boom are hold by squared metallic plates and their cables connected to the flight controllers are hidden inside the booms since these come hollow. The four legs are placed at an angle and attached to each leg to give the quadcopter a stable stand when in land. The delivery mechanism, which holds the fireball, is located at the bottom of quad; the position of the cage-like system is aligned in between two of the booms at a 45 degree angle, so it does not interfere with the thrust produced by the motors.

## *6.2 Prototype Cost Analysis*

Prototype cost analysis for this project is important because the members of this team will pay for all the expenses this project requires. The largest up-front cost is the purchasing of the components to build the quadcopter.

The motors are one of the most relevant components of the vehicle, since they need to provide enough thrust and lift; therefore, motors with high revolutions per minute (RPM) have to be chosen. These motors are in the range of $20 - $80, even though the motor selection was based in the high RPM and torque obtained from them. Once the initial calculations have been made, the motors will be purchased and added to the vehicle. During testing the performance of the motors will be confirmed and if necessary, the quadcopter arms are able to adapt one more motor in the opposite side of the motor already in place to provide more lift force.

Another important component is the first person view camera (FPV). This device will provide a real time video of what the quadcopter has in front and can provide the pilot a better perspective to guide the vehicle. The cost of this camera is $280.

The second largest cost concern is the components of the release mechanism. This team made a rough estimate of $500 for these systems. However, these two structures have many factors to be considered. The deployment component has to be light and strong enough to allow the quadcopter lift the load and structure of the grenade without losing its balance. Proper balancing is necessary to complete the mission of deploying the grenade with precision. The quadcopter will be controlled by an ardupilot, which is an arduino based component that gives the quadcopter the ability to improve the stability and maneuver accuracy autonomously.

A detailed list of the parts necessary in order to build the quadcopter plus the release mechanism is provided in Table 9.

**Table 10: Prototype Cost**

| Item | Description | Price | Quantity | Partial Total |
|---|---|---|---|---|
| 1 | Frame | $ 105.00 | 1 | $ 105.00 |
| 2 | Motors | $ 57.50 | 8 | $ 460.00 |
| 3 | Battery | $ 59.11 | 2 | $ 118.22 |
| 4 | GPS | $ 139.99 | 1 | $ 139.99 |
| 5 | Motor Controller | $ 20.50 | 8 | $ 164.00 |
| 6 | Propellers | $ 5.50 | 8 | $ 44.00 |
| 7 | Landing Gear Adjusters | $ 12.00 | 4 | $ 48.00 |
| 8 | Arm Tubes | $ 15.00 | 4 | $ 60.00 |
| 9 | Antenna | $ 34.89 | 1 | $ 34.89 |
| 10 | Camera Mount | $ 4.99 | 1 | $ 4.99 |
| 11 | Micro Camera FPV | $ 79.43 | 1 | $ 79.43 |
| 12 | Camera Signal Receiver | $ 198.99 | 1 | $ 198.99 |
| 13 | Camera Signal Transmitter | $ 69.99 | 1 | $ 69.99 |
| 14 | Camara FPV (First Person View) | $ 279.99 | 1 | $ 279.99 |
| 15 | Materials for Release Mechanism | $200.00 | 1 | $ 200.00 |
| 16 | Fire Extinguishing Ball | $ 75.00 | 1 | $ 75.00 |
| | | | **Total** | **$ 2,082.49** |

# 7. Testing and Evaluation

Several tests were planned in order to confirm the capabilities of the vehicle and the release mechanism. In the following sections, explanations of each test planned to perform will be provided.

## *7.1Vehicle Performance Test*

This is the first stage in the testing plan designed for the quadcopter. The tests included in this section will be performed as soon as the quadcopter is assembled. Since these tests are only for the structure and electronic systems of the vehicle, the release mechanism will not be attached to the quadcopter while performing them.

During this stage, the vehicle will be tested in regards to its flight capabilities. At the moment, the tests included in the plan are: time taken for takeoff and landing, ease of maneuverability once the vehicle is flying; if the quadcopter loses stability, how much time does it take for it to have balance again, how much time takes the vehicle to get to certain altitudes, how fast is the response of the vehicle if a change of direction is made, how accurate is the image received from the camera, how accurate is the GPS and if the vehicle can go to a point specified by the operator if the UAV goes out of range.

## *7.2 Release Mechanism Performance Test*

Once all the parts of the release mechanism are manufactured and assembled, this mechanism by itself is going to be tested.

The types of tests planned to perform on this mechanism are: time to load the ball, time to drop the ball, time it takes the rails to move to the desired angle, how much time it takes the ball to start moving once the command to do so is given. If at the moment of performing the tests, the members of the team realize that more tests need to be done, the tests will be added to the design plan.

## *7.3 Overall System Performance Test*

Once the release mechanism is attached to the quadcopter, the effectiveness of the overall system will be tested by dropping the fire extinguishing ball in open and closed spaces and recording the time it took for the vehicle to perform the entire mission. It will also be tested the time it took for the operator to load the grenade to the UAV and how much time it takes to place the quadcopter in position to drop the grenade if the space provided to do so does not have that much clearance from the rails. Another important test to perform in this section is how the vehicle will behave if stability is lost and the vehicle is carrying the grenade. These are the tests in the current design plan of this section; however, the plan will change according to the criteria of the team.

# 8. References

1. *National Report of Wildland Fires and Acres Burned by State. Figures from the Fire and Aviation Management Web Applications Program.* Year: 2012. Retrieved from http://www.predictiveservices.nifc.gov/intelligence/2011_statssumm/fires_acres.pdf
2. Gabbert, B. (2012, March 2). The *cost of saving money on wildfire suppression*. Retreieved from http://wildfiretoday.com/2013/03/02/the-cost-of-saving-money-on-wildfire-suppression-2/
3. (1997) *UAC Commercial Applications Overview*. Retrieved from http://www.uavm.com/uavapplications.html
4. Cox, T., Nagy, C., Skoog, M. & Somers, I. (2004) *Civil UAV Capability Assessment – Draft version.* Retrieved from http://www.uavm.com/images/NASA_UAV_Capabilities_Assessment-2004.pdf
5. Briggs, J. (1935) *HowStuffWorks "Who invented the radio?".* Retrieved from http://science.howstuffworks.com/innovation/inventions/who-invented-the-radio.htm
6. (1920) *World War I.* Retrieved from http://www.history.com/topics/world-war-i
7. Aaldering, J. (2008) *DSPA.nl*. Retrieved from http://www.dspa.nl/en/products/dspa-5-product-specificaties.html
8. (2011) *Fire Suppression Systems | Fire Protection Equipment, Fire Safety Products | Ara Safety*. Retrieved from http://www.arasafety.com/products/fire-suppression-systems/
9. (2005) *Clean Agent Suppression Systems: Fire Fighting Strategies for Mission Critical Facilities - Facilities Management Fire Safety Feature*. Retrieved from http://www.facilitiesnet.com/firesafety/article/HighTech-Fire-Fighting--3517#
10. *Elide Fire Ball Product Description*. Retrieved from http://gulfbusiness.tradeholding.com/default.cgi/action/viewproducts/productid/190554/productname/Elide_Fire_Extinguishing_Ball/
11. (2008) *DSPA-5 Product Information*. Retrieved from

http://www.dspa.nl/en/products/dspa-5-product-specificaties.html

12. (2013) *Fire sprinkler*. Retrieved from http://en.wikipedia.org/wiki/Fire_sprinkler

13. (2013) *Wildfire Prevention Tips.* Retrieved from http://www.wa-imt2.org/wildfirepreventiontips.htm

14. (2013) *Firefighting*. Retrieved from http://en.wikipedia.org/wiki/Firefighting#Use_of_water

15. (2013) *Elide Fire*. Retrieved from http://www.idttrade.com/en/ozellikler.php

16. (2013) *G-10 Fiber Glass Epoxy Laminate Sheet*. Retrieved from http://www.matweb.com/search/datasheetText.aspx?bassnum=PGLAM04

17. (2013) UAP2 X8 Frame Product Information. Retrieved from http://www.shop.aglhobbiesllc.com/ Rusty-s-UAP2-Frame-Kit/UAP2-X8-Frame.html

18. (2013) Avroto 2814 Short Shaft Product Information. Retrieved from http://hobbyking.com/hobbyking/ store/__9965__ZIPPY_Flightmax_5000mAh_6S1P_40C.html

19. (2012) *ZIPPY Flightmax 5000mAh 6S1P 40C Product Information*. Retrieved from http://hobbyking.com/hobbyking/store/__9965__ZIPPY_Flightmax_5000mAh_6S1P_40C.html

20. (2012) *915Mhz ArduFlyer-UAV GPS Flight Control System Product Information*. Retrieved from http://www.rctimer.com/index.php?gOo=goods_details.dwt&goodsid=822&productname=

21. (2013) *ZTW 30A ESC- SimonK Product Information*. Retrieved from http://www.shop.aglhobbiesllc.com/Motors-ESCs-and-Props/ZTW-30A-ESC-SimonK.html

22. (2013) *5.8GHz Circular Polarized spiroNet Antenna Product Information.* Retrieved from http://hobbyking.com/hobbyking/store/__27750__5_8GHz_Circular_Polarized_spiroNet_Antenna.html

23. (2013) *Fat Shark PredatorV2 RTF FPV Headset System w/Camera and 5.8G TX Product Information*. Retrieved from http://www.hobbyking.com/hobbyking/store/__28342__Fat_Shark_PredatorV2_RTF_FPV_Headset_System_w_Camera_and_5_8G_TX.html

# 9. Appendices

## 9.1 Appendix A: Properties of G-10 from MatWeb

| Physical Properties | Metric | English | Comments |
|---|---|---|---|
| Density | 1.80 g/cc | 0.0650 lb/in³ | ASTM D792 |
| Water Absorption | 0.10 % | 0.10 % | 24 hrs.; ASTM D570 |

| Mechanical Properties | Metric | English | Comments |
|---|---|---|---|
| Hardness, Rockwell M | 110 | 110 | ASTM D785 |
| Tensile Strength at Break | 262 MPa | 38000 psi | Crosswise; ASTM D638 |
| | 310 MPa | 45000 psi | Lengthwise; ASTM D638 |
| Flexural Strength | 448 MPa | 65000 psi | Crosswise; ASTM D790 |
| | 517 MPa | 75000 psi | Lengthwise; ASTM D790 |
| Flexural Modulus | 16.5 GPa | 2400 ksi | Crosswise; ASTM D790 |
| | 18.6 GPa | 2700 ksi | Lengthwise; ASTM D790 |
| Compressive Strength | 448 MPa | 65000 psi | ASTM D695 |
| Izod Impact, Notched | 6.41 J/cm | 12.0 ft-lb/in | Crosswise; ASTM D256 |
| | 7.47 J/cm | 14.0 ft-lb/in | Lengthwise; ASTM D256 |

| Electrical Properties | Metric | English | Comments |
|---|---|---|---|
| Dielectric Constant | 5.0<br>@Frequency 1e+6 Hz | 5.0<br>@Frequency 1e+6 Hz | ASTM D150 |
| Dielectric Strength | 31.5 kV/mm | 800 kV/in | Short Time; 1/8 inch; ASTM D149 |
| Dissipation Factor | 0.019<br>@Frequency 1e+6 Hz | 0.019<br>@Frequency 1e+6 Hz | ASTM D150 |
| Arc Resistance | 100 sec | 100 sec | ASTM D495 |

| Thermal Properties | Metric | English | Comments |
|---|---|---|---|
| CTE, linear | 9.90 µm/m-°C<br>@Temperature 20.0 °C | 5.50 µin/in-°F<br>@Temperature 68.0 °F | Lengthwise; ASTM D696 |
| CTE, linear, Transverse to Flow | 11.9 µm/m-°C<br>@Temperature 20.0 °C | 6.61 µin/in-°F<br>@Temperature 68.0 °F | Crosswise; Transverse to Flow; ASTM D696 |
| Thermal Conductivity | 0.288 W/m-K | 2.00 BTU-in/hr-ft²-°F | ASTM C177 |
| Maximum Service Temperature, Air | 140 °C | 284 °F | |
| Flammability, UL94 | HB | HB | |