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Phoenix Y6

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PHOENIX Y6

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PHOENIX Y6

By

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SENIOR DESIGN PROJECT REPORT

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Abstract

The mission of this project is to design and fabricate a vertical take-off and landing (VTOL) fixed-wing drone for use by firefighters and other emergency services. This vehicle will be designed for uses that include surveying wildfires, as well as spotting vehicular accidents, urban fires, and floods. Current drones available on the market are expensive or not designed specifically for emergency response. Our goal is to develop a working prototype of a vehicle that will be able to collect and relay important data such as live video and thermal images in addition to other measurements such as air velocity and humidity.

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Nomenclature

$\dot{m}$ Mass flow rate

$\eta_{coaxial}$ Propulsive efficiency of a pair of coaxial contra-rotating motors and propellers in dimensions of force per electrical power applied

$\eta_{propulsion}$ Efficiency of the propulsion system in g/W

ρ Density of air

τ Torque

A_{drawn} Amperage drawn from the battery at any given time

C Discharge rating of the battery

C_D Coefficient of drag

C_L Coefficient of lift

$C_{d,axle}$ Coefficient of drag on the front axle

$C_{d,motors}$ Coefficient of drag on the motors

$C_{d,body}$ The coefficient of drag on the body

D Propeller diameter in inches

D_{axle} Diameter of the front axle

D_{motors} Diameter of the motors

F_{Drag} Drag force of the aircraft

F_{Lift} Lift force of the aircraft

L_{axle} Net length of the exposed sections of the front axle

L_{motors} Length of the coaxially mounted motors

$Pitch$ Propeller pitch in inches per revolution

q_∞ Dynamic pressure, equal to $\frac{1}{2}\rho V^2$

r Length of moment arm

RPM Rotations per minute of the rotor

S_w The wing planform area

T Thrust

$T_{dynamic}$ Dynamic thrust

T_{net} Net static thrust of the aircraft in multirotor flight mode

$T_{Planemode}$ Total static thrust in plane mode

$T_{Rotorpair}$ Thrust of a pair of rotors

$T_{Singlerotor}$ Static thrust of a single rotor

V Speed of the aircraft relative to the surrounding air

V_e Exit velocity

W Weight of the aircraft

W_{Rotors} Combined weight of rotors

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1 Introduction

1.1 Background

In emergency situations, responders need quick access to information on the scene while limiting the danger that accompanies acquiring that information. One emergency situation where this is most apparent is assessing a forest fire in its early stages. Time-sensitive information about a fire, such as where the edges of the fire extend to, hot spots, and movement patterns, are critical to a fire department's ability to contain and combat a wildfire. This information is typically unknown as the first responders arrive on scene, and gathering it quickly can greatly increasing the abilities of a fire department. Additionally, visual data is invaluable for emergency services to quickly locate problematic situations that are inaccessible by traditional means. If a wild animal is on the loose in an urban area, it must be located swiftly and accurately to maintain public safety. Also, eyewitness accounts are often unreliable, specifically with traffic accidents. Knowing the specific location of accidents, including which side of a highway they may be on is essential to properly direct the ground response.

In order to reduce emergency response times, one potential solution is an unmanned aerial vehicle (UAV) with mounted cameras that can relay visual data to the fire department. It would also need a GPS for location data. It would be deployed after the initial reporting of the emergency and would then fly to the area reported where it will pinpoint the exact location of the incident. It would also be able to scout the area for additional information. In the event of a wildfire, the drone would be transported to and deployed on-site. From there it would scout the perimeter of the fire and determine the locations of hotspots. Because it would be used by non-technical firefighters, ideally the drone would be semi-autonomous so that it is not difficult to control.

1.2 Project Objectives

Our project proposes to design and construct a fixed wing unmanned aircraft capable of vertical take-off and landing. This vehicle should be capable of surveying expansive areas affected by fire using both traditional cameras and thermal imaging. Ideally, this vehicle should be easily operated, semi-autonomous, capable of 2+ hour flights, resistant to heat, and capable of live-image communication with ground operators. Its surveying capabilities will allow the drone to be used by first responders to provide location information for a variety of potential emergency situations, such as fires, traffic accidents, animal control, and other events.

1.3 Review of Field

Currently, UAVs, or drones, are an emerging industry. They are mostly used by hobbyists or for military purposes. Regulations from the Federal Aviation Administration (FAA) have limited the ability for drones to be used for various civil applications. As more information is learned about UAVs, it is possible that these restrictions could be loosened, resulting in an expansion in these areas. Drones that meet our specifications that are currently available are, for the most part, overly expensive and not specifically designed for the purpose of fire surveillance. With all of this in mind, it was apparent that there was a place on the market for the drone we intended to design.

In order to achieve our criteria, or even basic flight, a significant amount of design research was necessary. To this end, both *Small Unmanned Aircraft Theory and Practice* [1] and *Designing Unmanned Aircraft Systems: a Comprehensive Approach* [5] were recommended by our advisor, Dr. Mohammad Ayoubi. These books contain detailed information about designing and developing control systems for a variety of fixed wing aircraft, as well as presenting a well-rounded overview of UAV design. "Gust Simulation As Applied to VTOL Control Problems" [7] describes how VTOL craft respond in hovering mode to gusts of wind, and presents a large set of test data. This was of special concern to us, as an unstable craft would be exceedingly dangerous to nearby persons. "Controlling a VTOL in 2-DOF Subspaces" [11] provided a different way of designing VTOL control systems. It suggests breaking down the problem of VTOL control into a series of subsystems, and gives a set of constraints that were built into the control system to simplify control system design. This source proved to be especially useful as most sources on control systems relate either to fixed wing aircraft or multi-rotors, while this source is specific to VTOL. Courses through SCU in finite elements have given us the necessary understanding of the finite element method to successfully use an FEA software such as Abaqus to analyze and design different components of our drone in regards to heat transfer and deflection.

2 Systems Level Chapter

The initial design had four rotors oriented vertically and one in the rear oriented horizontally to allow for both multirotor and plane flight. All hardware is located within or underneath the body of the drone. This hardware includes a GPS device, a transmitter, a live video camera, a thermal video camera, a pitot tube, and a hygrometer. The transmitter sends all measurement data and video feeds to a receiver located at the ground station. The receiver translates this signal into readable information, which is displayed on an easy-to-understand interface on a monitor. To operate the drone, the user should indicate a location on mapping software and press launch. The drone will then fly to this location and hover until it is either called back or its battery drops below a certain threshold. It will then return to the location from which it was launched automatically.

Following more detailed analysis of this original design, we pivoted to a flying wing tiltrotor. Instead of four propellers, there are now three propulsion systems: two in the front and one in the back. The back propeller only functions during vertical take off and multirotor mode. The front two propellers rotate such that in vertical mode, they are provide lift during takeoff. Additionally, they rotate 90 degrees such that they provide horizontal thrust during forward flight mode. The two front propellers rotate in unison, actuated by the connecting rod going through the nose of the aircraft. The wings are modeled after a NACA 4412 airfoil with a trapezoidal shape and winglets at the tips.

2.1 Customer Outreach

Through meetings with retired firefighters and emergency response experts Sean and Pat Lanthier and the Palo Alto Fire Department, a broader perspective on the applications of Phoenix Y6 was gained and the expected accomplishments were developed. Previous to these meetings, the only uses considered for the Phoenix were wildfire related applications, however, the meeting with the firefighters helped to develop alternative drone applications such as urban vehicle accidents, wildlife management, and small urban fires. If designed and constructed correctly, this drone will be deployable for countless types of disaster or emergency responses. For example, if hikers are lost in the mountains, a drone could be sent to survey the general area the hikers are believed to be located. A drone could spot and track wild predators in urban areas so that they cannot attack humans unexpectedly. A drone with hovering capabilities could be used to identify a car crash and any pertinent location details that would allow responders to more quickly tend to the situation. Overall, the meetings with consumers have added further defining parameters for our design and more situations in which this drone could be useful to the public.

The questions and answers below are the result of a long interview with multiple members of the Palo Alto fire department, including their chief. Also present at the meeting was Sean Lanthier, a retired firefighter who is now an entrepreneur in the first response technology sector.

- Do you have data on temperatures at certain altitudes above fire?
    - All fires are different and therefore the temperatures above the fires vary correspondingly. However, they were not very concerned with the temperatures our drone would experience as our drone would not be flying directly over forest fires.
- Do you currently use any drone technology? If so, how would you like it improved?
    - No, however a nearby fire department in Menlo Park does. (Palo Alto Fire Dept. could not give us any information regarding how Menlo Park Fire uses their technology.)
- How would you want to use it? Launch from a truck, backpack it in, etc.?
    - First responders already have their hands full with a plethora of tasks and therefore want as little interaction with flying the drone as possible. They want the drone launched with a push of a button.

- What sort of interface would you want, how would you want data presented? Live stream? What telemetry matters to you?
  - Receiving platform should cycle through thermal images, live color video. Environmental data should also be present in an easily digestible manner. Should have info regarding wind velocity (speed+direction) and humidity. Minimize the amount of text, focusing on graphs and pictures.
- How would you prefer to control this? Are you able to hire a pilot? Can firemen be trained?
  - They want the drone to fly itself. Hiring a pilot is not realistic and firemen have too many other tasks to be asked to dedicate training time.
- What information about the fire would you like the drone to relay? What telemetry matters?
  - Thermal imaging is extremely important for wildfire situation. For urban applications, a high resolution camera should be included. The drone should have the capability to stream both of these videos live.
- What factors would prevent drone use in disaster response?
  - Drones flying in conjunction with other helicopters and planes can be problematic.
- Would you only like information regarding the perimeter of the fire or about the interior?
  - The exterior of the fire is their main concern, specifically, the location and intensity of hotspots. The drone would most likely be deployed during the beginning of fires, and grounded by the time other helicopters and planes are in the air.
- Would you use this product for anything else besides fires?
  - Yes. Search and rescue for lost hikers. Locating dangerous wildlife for animal control. Getting crucial information for EMS responding to car crashes.

- What conditions does it need to fly in?
  - Technically want it to fly at all times day or night, in any type of weather. Realistically we want it to be able to fly during the night and in rain.

After these meetings, the answers and general needs were consolidated into a set of potential opportunities, which are listed below:

- The most significant opportunity for improvement is the cost of the product. Many of these products are extraordinarily expensive, especially when the consumers are hesitant cities with limited budgets.
- Ease of use: we intend to provide a full product that can be easily and autonomously controlled. Many of the existing products do not have a full software package capable of easy to use mission planning that we intend to provide.
- Portability of product: many existing products are large and bulky. Our drone should easily be taken apart and reassembled for transport.

Through this general needs assessment, the team was able to analyze which design aspects to focus the most attention. It was determined that the first priority would be given to ease of use and the control system, since fire departments and first responders do not have the resources to hire a pilot or train their team members on drone flight.

2.2 User Scenario

Wildfire

In the case of a remote fire, the drone is transported by the first firefighters to the scene, likely the Battalion Chief. The drone is launched in a clearing or open space autonomously, and given way points to travel to or loiter at. This enables the operator of the ground-station to continue working while the drone gets in position. Once in position, the operator learns from the infrared camera the locations of the hot spots of the fire, as well as other telemetry information, and can set new way points if desired. If too long passes, Phoenix Y6 will return to the takeoff location and land, and batteries can be quickly exchanged and the aircraft relaunched. Similarly, once sufficient information has been gathered, the drone can return and land, its mission completed. It is crucial that this entire process happen quickly so that the drone can be safely landed before any emergency aircraft delivering water to the wildfire are in the same airspace as Phoenix Y6

Urban Disaster Response

Upon receiving a 911 call, Phoenix Y6 is autonomously launched and traverses as quickly as possible to the way point set by the 911 call. The groundstation is carried in the emergency response vehicle. Phoenix Y6 will arrive on scene before the vehicle, given its ability to fly a straight line path to the destination. The emergency responders can then pinpoint the location of the disaster and assess severity. Once its task is completed, Phoenix Y6 will return to its take off location. Or, if further surveillance or documentation of the scene is desired, Phoenix Y6 can be landed in an open area, the batteries exchanged, and the drone relaunched to continue its mission.

2.3 Functional Analysis

Phoenix Y6 is powered by a rechargeable Lithium-Polymer battery. The hardware of the drone is located inside the fuselage of the drone with the exception of the thermal camera, the live camera, the pitot tube, and the receiver antennae, which are situated below and outside the fuselage base. The hardware located inside the fuselage consists of a hygrometer to measure air humidity, a GPS sensor, a Pixhawk flight controller, and electronic speed controlleirs to control the speed of the motors. The major constraint of this drone will be its weight, as the lift force provided by the drone must exceed the weight of the drone. In addition, the drone should be relatively small such that it is easily storable and portable. Finally, the drone should be robust. It should be able to weather light to moderate usage for at least three years. It must also be able to fly in rainy and snowy conditions.

2.4 Market Research

A variety of existing commercial drones were examined and researched in our preliminary design stages in an effort to optimize our design to improve on these commercial products. Drones researched include the eBee by Sensefly, the ScanEagle UAS, the AG Drone by Honeycomb, the FireFly6 Pro by BirdsEyeView Aeronautics, the Draganflyer X4-P by Draganfly, and the DJI Matrice 200 by DJI (distributed by SkyFire

Table 1: Market Research

Product	Cost	Flight Time	Coverage Area	Top Speed
eBee	$17,000	50 minutes	12 km^2	25 m/s
ScanEagle	$3,200,000	28 hours	Unlisted	25 m/s
AG Drone	$10,000+	Not Listed	3.5 km^2 per hour	36 m/s
Firefly6	$6,000+	45 minutes	2.4 km^2	17 m/s
Draganflyer X4-P	$13,000	16 minutes	Not Listed	30
DJI Matrice 200	$43,000	38 minutes	Not Listed	22 m/s

Consulting). Various flight specifications and qualities regarding these vehicles are listed in the table below.

The researched drones are a collection of products with various design parameters such as autonomy, launch system, and imaging hardware. The two primary qualities we wished to improve upon were the cost of the drones and their maximum flight times. These commercial drones are expensive, which creates an immense barrier for fire departments that want to purchase a drone. While some of these drones, such as the AG Drone by Honeycomb, are marketed towards agricultural uses where they would be used in calm environments over flat expanses of land, fire departments would be using drones in rougher terrain and environments and it is reasonable to expect the occasional flight accident to occur and a drone will be damaged beyond repair. A fire department should be able to replace damaged drones without spending a significant portion of their budget.

Flight time was another significant consideration in our design in an effort to improve over existing products. The majority of the drones that were researched are powered by battery and had maximum flight times under one hour, according to each drone's manufacturer. The goal of designing our drone to be capable of one hour flight times was established. However, if battery technology was not able to permit the Phoenix Y6 to reach one hour flight time, it was found during the customer outreach stage of design that if the Phoenix Y6 was capable of flying for at least 20 minutes, it would be acceptable to land the drone three times an hour to swap the drained battery for a fresh one.

2.5 Definitions of Subsystems

Phoenix Y6 is decomposed into a number of subsystems in order to simplify the design process and better organize the project, listed in Table 2.

Table 2: Definitions of Subsystems

Subsystem	Description
Airframe configuration	The geometric layout of the body including the rotors
Power and propulsion	This system stores the energy to use during the flight, and translates that energy into the thrust forces used for flying.
Body	The plane shape of the body, holding all of the internal components and generating lift in forward flight mode.
Electronics and Hardware	The antennae, internal actuators, telemetry, computers, and sensors including camera and camera stabilization
Controller	The computing system responsible for controlling the position, orientation, and linearly and rotational rates of the aircraft based on the input from the sensors.

2.6 Team and Project Management

At the beginning of the academic year, we met as a team to determine what we wanted to pursue for our senior design project. As four of us are minoring in aerospace engineering, we elected to work on a project involving aerospace engineering. We narrowed this field down to a desire to design and build a drone. A design mimicking the flapping motion of a bird's wings was considered, but ultimately this design was deemed too difficult to implement properly with a limited number of engineers and a relatively low budget. Therefore, we decided to build a VTOL fixed-wing drone for the purpose of emergency response, after meeting with Santa Clara University's Frugal Innovation department.

Following our project decision, we all initially worked on the preliminary design stages, such as market research and customer outreach, together but quickly found this to be an inefficient method. Therefore, we assigned ourselves to various specific aspects of the design, while understanding that these roles would be fluid, such that we would assist with each other's work, even if that work was outside of our individual sectors. In this way, Bruce was in charge of running computational fluid dynamics analysis, John was in charge of running finite element analysis, Sean was in charge of electronics and controls, AJ, Bruce, Brian and Michael worked on modelling the design using CAD software, and Brian, AJ, and John were tasked with constructing the body of the drone. AJ was designated the role of team leader.

3 Subsystems

3.1 Airframe Configuration

The airframe configuration is an integral subsystem component of our design, as its decision will significantly impact design decisions made in other subsystems. The airframe configuration had to be chosen such that it would be capable of being aerodynamic as well as able to provide lift. Furthermore, it needed to enable the drone to have characteristics of high speed and durability. This decision was constrained slightly by the necessity of producing it reasonably easily and for a low cost, so the number of different airframes considered was limited.

For the airframe of the drone, six different configurations were considered: quadcopter, 4 tilt-rotor propellers, ducted fans, four fuel-cell powered propellers, a quadplane with a front propeller, a quad plane with a rear propeller, and a tilt rotor configuration with ducted fans in the wings. These design ideas were scored based on design, build, and test time, total cost, weight, reliability, payload capacity, speed, agility, and transportability. The quadcopter idea was deemed easy to implement, but would not have the necessary range nor flight time required by emergency response situations such as wildfire surveillance. As the usage of fuel cells in drones has not been well documented, the concept involving fuel cell-powered propellers was abandoned, as this research was deemed to be beyond the scope of this project. The quad-plane with a front propeller was thought to be an extremely viable design decision, but reflection found that the four vertical propellers would be sources of excess drag during forward flight. Furthermore, the quad plane configuration was deemed to be bulky and heavy, leading to poor performance in the category of transportability. The quad plane with the rear propeller was eliminated in a similar fashion. With the tilt rotor configuration, it was found that the vehicle would be light, relatively small, efficient, and reliable. Upon further research, it was determined that the four tiltrotor design would not be exceptionally effective due to the rear propellers functioning in the same streamline as the front propellers in forward flight. For this reason, it was decided that the single-axle tilt-rotor configuration would be used in our design. However, the ducted fans in the wings presented a significant manufacturability issue. Therefore, the design was slightly altered such that the front axle would still rotate and provide thrust in both tri-copter mode and plane mode, but the rear co-axially contra-rotating propellers would remain static, providing lift in tri-copter mode and stabilization effects in plane mode.

3.2 Body

Another critical subsystem involved with the design of Phoenix Y6 was the overall material selection for the drone in terms of the various components of the physical craft, including the wings, fuselage base, fuselage cover, and landing gear. The primary criteria that the materials used needed to fit were strength and weight. Essential to this subsystem was the necessity of the materials being durable enough to weather usage, but light enough to allow for satisfactory performance in terms of flight time, flight range, and speed. Manufacturability and cost were secondary considerations in our materials selection process.

Materials considered for the wings and fuselage of the drone included Styrofoam, steel, aluminum, carbon fiber, cardboard, and plastic. Considered against constraints such as manufacturability, cost, and, especially, weight, steel and aluminum were eliminated from consideration. Cardboard, though light, was deemed to be not rigid or durable enough for the purposes of this vehicle. Cardboard's relatively high flammability also proved to be a negative characteristic. As a lightweight, rigid, and strong material, carbon fiber was the ideal choice for our drone, but due to a limited budget and manufacturability issues regarding the material, carbon fiber was not chosen for our design. Plastic was deemed to be the next best material in terms of strength to weight ratio, but manufacturability issues again presented a problem in the production of the wings from plastic. The fuselage base was designed in such a way that 3D-printing could be easily accomplished, so ABS plastic was used for this physical component. The cover for the fuselage was created by vacuum forming styrene plastic over a mold of the top half of the NACA 4412 airfoil. After plastic and carbon fiber, the next best material for the wings of this vehicle proved to be Styrofoam. Research into this category yielded EPS Styrofoam as the specific material for the wings due to its relative durability in comparison to other Styrofoam types, such as EPP Styrofoam. Clear packing tape was used to over the Styrofoam not only to increase the aerodynamic characteristics of the wing, but also to slightly increase the strength of the Styrofoam as well as to protect the Styrofoam from reacting with spray paint used for aesthetic purposes. Finally, research into other custom-designed drones yielded the idea to use PVC piping for landing gear. PVC, in a small volume, is lightweight and strong. By cutting a $\frac{3}{4}$" sliver of a 6" diameter PVC pipe and then cutting this circle in half, we were left with a 3" diameter semi-circle. Putting this material in hot water allowed the material to be formed into an elastic shape which would absorb force when the drone impacts the ground upon landing. In future models, similar plastic should be used to construct landing gear that can retract.

3.3 Control System

The selection of the control system technology was crucial to fully realizing the functionality of Phoenix Y6. This subsystem includes the selection of flight controller hardware, the flight stack firmware loaded onto this autopilot, and the software package used to interact with it. The most important design considerations for this subsystem were maximizing compatibility and functionality for our complex VTOL design. Ease of use and the ability to modify parameters were additionally important.

Since compatibility was a primary consideration for the control system selection, two main all-inclusive autopilot systems were considered. Both are industry standards and compatible with all other aircraft hardware (sensors, motors, electronic speed controllers, etc.) The first was the ArduPilot Open Source Autopilot system. This includes the Arducopter flight controller, APM flight stack, and APM Mission Planner software. The second system was the Pixhawk Flight Controller Hardware Project, consisting of Pixhawk flight controller, PX4 flight stack, and QGroundControl software. While these systems are cross compatible (one could, for example, load a Px4 flight stack onto an Arducopter controller and access it with either APM Mission Planner or QGroundControl), they are optimized for use within their respective suites. The Ardupilot system features an advanced, robust set of control algorithms that is superior to that of the Pixhawk system. However, the relative simplicity of the control algorithms for Pixhawk lead to it having wider functionality, including support for VTOL aircrafts. Not only this, but the PX4 flight stack has a plethora of fully realized VTOL airframes including quadplanes, tiltrotors, and more. Additionally, QGroundControl has video streaming already integrated into its user interface. Due to our project′s intended purpose of visual information gathering, this was deemed a crucial design component. Because of these factors, the Pixhawk system was selected for Phoenix Y6 due to its greater functionality, inclusive compatibility, and video streaming capabilities.

For implementation of the control system, calibration and modification were necessary to fit our specific drone design. This involved connecting the Pixhawk flight controller to a computer and loading on the up-to-date PX4 flight stack. After this, the package for our specific airframe configuration (Y6 tiltrotor flying wing) was selected and loaded onto the flight controller. All of this was accessed and completed within QGroundControl. With this done, we could then move on to calibrating all of the sensors. The accelerometer, gyroscope, and compass within the Pixhawk needed to be calibrated to optimize stability in addition to a variety of external sensors (airspeed, external GPS, RC units). With this, the hardware was connected and ready to fly. Finally, with all of the motors mounted on a static test bed we altered various parameters within QGroundControl to further customize it to our design specifications (wingspan, tilt angle, etc.) and ensure stability. Once the full prototype was manufactured, PID tuning was completed in the same software.

3.4 Electronics Selection

Receiver and Transmitter

When the aircraft is used as planned, the transmitter is not often needed, as the flight plane is loaded onto the aircraft controller. However, for testing, general or more refined control, a transmitter and receiver are necessary. The FRSky Taranis Plus X9D transmitter and Fr Sky D4R-II Receiver, which have a range of about 1 kilometer, more than enough for any manual controlling purposes, as FAA law dictates that the operator should always maintain a line of sight with the vehicle.

Camera and Camera Stabilization

It is important that the video captured by cameras on the aircraft is easy to see and useful. Therefore, the Tarot TL3T02 T-3D IV 3 Axis Brushless Gimbal is selected in order to stabilize the video. This component has a flat plate connected firmly to the body of the aircraf, and a second flat plate onto which the rest of the system is attached mounted to the first flat plate by means of rubber cylinders that damp vibrations. Below the second flat plate hangs a small gyroscope and accelerometer connected to a series of three orthogonal servo motors, at the end of which the cameras are mounted. These servos are controlled to smooth jerky motions of the aircraft, yielding smooth and ease to see footage. For normal video streaming capabilities, a GoPro Hero Sessions 4 is selected based on its robustness and because it compresses video in h.264 format, which is standard for video streaming purposes. An infrared camera is also included so that objects can still be seen in low light scenarios.

Video Streaming

A raspberry pi handles video transmission and in future improvements will handle image processing and recognition. The GoPro and thermal camera are both connected to the raspberry pi by means of a wifi connection and a wired connection respectively. The raspberry pi in turn is connected to the pixhawk controller, and receives commands from the pixhawk to start filming, take a picture, which camera to use, and the video or image settings such as frame rate and quality. The raspberrry pi has a script that takes the command and then relays it to camera, which then streams the image via the onboard wifi back to the raspberry pi. While the existing MAVLink connection between the pixhawk and the ground station was initially considered for video streaming, QGroundControl only supports USB Video Class (UVC) video input, and does not support MAVLink video input. Therefore, the raspberry pi streams the live image back to the groundcontrol station via User Datagram Protocol Real-time Transport Protocol (UDP RTP) through an onboard 5.8 GHz antennae. While this data transfer is codec-agnostic, UDP RTP generally works best with h.264 encoding, the same type used by both of the selected cameras.

Tilt Servo

For the servo motor that was used for the tiltrotor mechanism, it was required that the motor be able to precisely and accurately rotate at least 90 degrees as well as being able to supply enough torque to tilt the axis and propellers mid-flight. The torque created by the weight of the rotors was calculated using

$$\tau = r * W_{rotors} \tag{1}$$

where τ is torque, r is the length of the moment arm, and W_{rotors} is the combined weight of the rotors. Due to the difficulty of determining the true location of the center of mass of the rotors, it was assumed that the center of mass was located at the top so that the highest minimum value of torque was calculated, essentially providing an upper bound of the torque. This value was found to be 3.4 kg·cm. In addition to the mass and geometry of the rotors, the torque was also dependent on various aerodynamic factors. To be certain that any unexpected forces do not cause the total torque on the rotors to be too high for the motor to handle, a factor of safety of 5 was used on the initial torque calculations in determining the minimum required torque for the servo motor. Ultimately, the LewanSoul LD-20MG Full Metal Gear Standard Digital Servo with 20kg High Torque was selected, which has a maximum torque of 20kg·cm, which was more than sufficient for its intended purpose.

3.5 Propulsion

The propulsion and power types of brushless motors with propellers and a Lipo battery were selected during the airframe configuration selection process. The next step is to select specific hardware that meets the requirements of the design. The motor, electronic speed controller (ESC), and battery need to be selected, and the initial propeller size of 10" diameter reconsidered. In order for a multicopter to fly with sufficient agility, the optimum lift to weight ratio is about 4:1, and the minimum is about 2:1. The weight of the aircraft is estimated based on the material properties, estimated volume of the body, and the weight specified by manufacturers for components that were previously selected, such as the controller, gimbal, camera, etc, totaling 3.06 kg.

Each of the components in the power chain relate to each other. Brushless motors have a 'kv' rating, which specifies the RPM per volt applied to the motor for zero loading conditions. Therefore, the speed of the motor is determined by the voltage of the battery and the load of the propeller. Lipo batteries are comprised of a series of internal cells, each with a nominal voltage of 3.7 V. A three cell battery has a nominal voltage of 11.1 V, a four cell battery would have 14.8 V, and so on. As the battery discharges the voltage drops. The maximum voltage for a cell is 4.2 V, and the minimum acceptable voltage is 3 V per cell. Lipo batteries have two other characteristics: a discharge rating and a capacity, usually in mAh. The discharge rating corresponds to how much power the battery can supply. The capacity is the amount of energy the battery can store. Most brushless motors are only compatible with a few sizes of battery, as detailed by the manufacturer. Information regarding the amperage that individual motors pull at different throttle levels and with different voltage batteries is also usually provided by the manufacturer.

The motors are sized for multirotor flight mode, as the thrust requirements for a multirotor are more stringent than for a plane. All thrust estimations are calculated using static thrust. The mathematical model of the propulsion system were derived from the momentum thrust equation, Eq. 2 [6], [8]. Because the propeller is modeled in static thrust conditions, the initial velocity of the flow V_o is taken to be 0 [8].

$$F = \dot{m}_e V_e - \dot{m}_o V_o = \dot{m}_e V_e \tag{2}$$

$$T_{rotor} = \frac{d}{dt} m V_e = \dot{m} V_e \tag{3}$$

$$\dot{m} = \rho A_{prop} V_e \tag{4}$$

$$A_{prop} = \frac{\pi D^2}{4} \tag{5}$$

$$T_{singlerotor} = \rho \frac{\pi D^2}{4} Ve^2 \tag{6}$$

V_e is assumed to roughly equal to the pitch speed of the propeller. Propeller pitch is given in inches per revolution (equal to how far the propeller would travel through a semi solid, like a screw into wood).

$$V_e = V_{pitch} = RPM_{prop} * Pitch \tag{7}$$

Plugging these equations into Eq. 3 and dividing by the force of gravity, Eq. 8 is obtained. While the units of this project are imperial, in this case it is useful to calculate the thrust in grams, as manufacturer data on thrust is given in units of grams, and all weights for internal components are given by manufacturers in grams.

$$T_{singlerotor} = \frac{1}{g_o}\rho\frac{\pi D^2}{4}(RPM * Pitch)^2 \tag{8}$$

This theoretical equation is not entirely accurate, especially for smaller sized propellers. Based on experimental data from a variety of motors and propeller diameters and pitches, a non linear correction factor is added, yielding Eq. 9. This simplifies to Eq. which is used to estimate static thrust for a single rotor in grams.

$$T_{singlerotor} = \frac{1}{g_o}\rho\frac{\pi D^2}{4}(RPM * Pitch)^2\left(\frac{D}{3.295Pitch}\right)^{1.5} \tag{9}$$

$$T_{singlerotor} = \frac{1}{9.81\frac{m}{s^2}}0.001225\frac{g}{m^3}\frac{\pi(0.0254D)^2}{4}(\frac{RPM}{60} * 0.0254Pitch)^2\left(\frac{D}{3.295Pitch}\right)^{1.5} \tag{10}$$

$$T_{singlerotor} = 1.89586 * 10^{-15}RPM^2D^{3.5}Pitch^{0.5} \tag{11}$$

Phoenix Y6 utilizes contra rotating coaxial propellers. Because the bottom propeller is mounted close to the top propeller in each pair, it is downstream of the top propeller. The air is already moving quickly by the time that it reaches the bottom propeller. From Newton's second law, Eq. 3 holds true for static single propellers, but for a propeller moving through air the equation becomes Eq. 12.

$$T_{dynamic} = \dot{m}\Delta V = \dot{m}(V_e - V_o) \tag{12}$$

This configuration is difficult to model theoretically given the complex nature of the flow, with the bottom rotor both taking in new air and utilizing the air from the top rotor. A NASA study of many different coaxial contra rotating propeller systems found that 'The often used equivalent solidity, single-rotor approach to modeling coaxial rotors in hover has been shown to require approximately 5% more power for a given thrust.' Therefore the thrust is calculated using Eq. 11 for each individual propeller, and the efficiency is adjusted according to the finding of the study, with $\eta_{Coaxial} = 1.05$. The increase in efficiency is attributed to the contraction of the wake of the upper rotor allowing the lower rotor to take in new air from a slightly side ways angle, as seen in Figure 22, increasing the effective disk area. It is also found that the optimal efficiency condition is when neither the upper wake nor the lower wake dominates, as occurs during hovering conditions, as occurs with the Phoenix Y6 when gathering video data. Additionally, efficiency is increased by means of swirl recovery due to the rotors spinning in opposite directions, although this is generally a secondary mechanism. The static thrust of a pair of propellers is calculated in Eq. 13. It is assumed that a pair of contra rotating propellers draws exactly twice the power that a single rotor does. Voltage and amperage data are given by the manufacturer for maximum thrust conditions. The net maximum thrust of the Phoenix Y6 aircraft in multirotor flight mode is calculated using Eq. 14.

$$T_{rotorpair} = 2 * \eta_{Coaxial} T_{single} = 1.99065 * 10^{-15} RPM^2 D^{3.5} Pitch^{0.5} \tag{13}$$

$$T_{net} = 3 * T_{rotorpair} = 5.97195 * 10^{-15} RPM^2 D^{3.5} Pitch^{0.5} \tag{14}$$

Using these equations, a wide range of different motors and propellers are considered and weighed against the design requirement of 2:1 lift to weight ratio. The weight of Phoenix Y6 is estimated using manufacturer information for all components except for the body of the aircraft, which is conservatively estimated at 1 kg based on engineering judgment and through analysis of similarly sized aircraft. The T-Motor 2216 1100 kv motor is selected with a propeller D = 10" and Pitch = 4.7. This motor was chosen based on its exceptional thrust output. Larger propellers would generate more thrust, but due to the geometric constraints of the rotating front propellers D = 10" is selected.

Using Eq. 11, the static thrust for the T-motor MS2216 1100kv motor with D = 10" and Pitch = 4.5, the maximum static thrust is calculated to be 1213 g, while the given value from the manufacturer for the same propeller and motor is 1170 g. Eq. 11 estimates the static thrust at 104% of the given manufacturer value. Using Eq. 13 a pair of contra rotating coaxial propellers with D = 10" and Pitch = 4.7 has a static thrust of 2239 g. The net static thrust of Phoenix Y6 is calculated using Eq. 14 at 6717 g. The design requirement was a minimum of 2:1 lift to weight ratio for in multirotor mode. A full breakdown of the weight estimation can be found in Figure **??**, and the estimated weight is 3060 g. the lift to weight ratio is 2.20.

According to the manufacturer, the T-motor 2216 1100 kv motors can handle a maximum of 3 cell batteries (11.1 V, nomimally). Using this size of batteries, the manufacturer specifies that they draw about 20 A of current at maximum throttle. Therefore, the ESC's (one per motor) are sized at 30A, leaving a margin for peak values.

The last characteristics to determine are the battery capacity and the discharge rate of battery, which describe how much energy a battery can hold and much power the battery can supply respectively. The battery capacity is calculated using Eq. 15. $A_{Drawn}(t)$ is the amount of current drawn at any given time, and is assumed to be constant. The efficiency of the propulsion system can be estimated by dividing the maximum thrust by the maximum power draw of the rotor systems, $6717g/(20.2A * 11.1V) = 30.0\frac{g}{W} = \eta_{Propulsion}$. It is assumed that this efficiency applies for any level of throttle. In order to just stay aloft in multirotor flight mode, the thrust must equal the weight of the aircraft. $\frac{W}{\eta_{Propulsion}} = \frac{3060}{30} = 102W$. The amperage drawn is $A_{Drawn} = \frac{102W}{11.1V} = 9.19A$. Because the aircraft will not just be hovering, this is rounded up to $10A$, which will still yield a best case value. Batteries only come in select capacities, and are generally discharged only 80% of the way. Using Eq. 16 and a battery capacity of 5000 mAh, the flight time is $t_{Flighttime} = \frac{0.8*5Ah}{10A} = 5AH = 0.4h = 24min$. A 5AH capacity battery will yield a best case flight time of 24 minutes, for hover only conditions. Because the voltage of the battery is (relatively) constant, the discharge rating largely describes the maximum amps that a battery can supply. Since the motors draw 20.2 A each at constant throttle as specific by the manufacturer in Figure **??**, the battery needs to be able to supply $6 * 20.2A = 121.2A$. The minimum discharge rate for the battery is calculated using Eq. 18 at $C = 121.2/5 = 24.24$. The discharge rate is selected at 25 C.

$$80\% E_{Battery} = A_{Drawn}(t) t_{Flighttime} \tag{15}$$

$$t_{Flighttime} = \frac{80\% E_{Battery}}{A_{Drawn}} \tag{16}$$

$$A_{max} = C * E_{Battery} \tag{17}$$

$$C = \frac{A_{max}}{E_{Battery}} \tag{18}$$

The final propulsion system components and the propulsion system characteristics can be found in Tables 3 and 4 respectively. The goal flight time for the Phoenix Y6 aircraft is 30 minutes. The flight time calculated in this section is for multirotor mode only. It is assumed that during use the aircraft will be in multirotor mode for 70% of the time, leading to a desired multirotor flight time of 21 minutes.

Table 3: Propulsion Components

Component	Product
Motor	T Motor MS2216 1100 KV
Propeller	10" x 4.7 Slow Fly
ESC	Turnigy Plush 30A Speed Controller w/ BEC
Battery	3S 25C 5000mAH LiPo Battery

Table 4: Propulsion and Power Characteristics

Characteristic	Requirement	Value
Estimated Weight	–	3060 g
Flight time (best case, multirotor)	21 min	24 min
Maximum Thrust (multirotor)	$> 2W = 6120$ g	6717 g
Lift to weight ratio (multirotor)	2:1	2.2:1

3.6 Flying Wing Design

Initial Flying Wing Design

After selecting the hardware and estimating the characteristics of the propulsion system, an initial design of the flying wing body was completed. This was done on a flat plane through the body of the aircraft (or the planform area). First, the three propeller locations were laid out, and a rough body was designed based on the constraints of going far enough forward to hold the front axle, having wings that were sufficiently far back and swept so that they would not interfere with the front propellers including during flight mode transition, and minimizing the length of the front axle. Figure 23 shows the final iteration of this layout. Wing span of $4'$ and sweep of 25 deg were chosen based on design constraints of transportability and flight stability as well as engineering judgment, with the assumption that the wings would be able to detach. Wing tips are added to reduce drag and add stability.

Aerodynamic Design of the Flying Wing

In the design of the flying wing body, the objective is to ensure that the aircraft generates sufficient lift, maintains stability during horizontal flight, and that the center of mass and the center of pressure are balanced. Additionally, the aerodynamic coefficients of the model are obtained through computational fluid dynamic (CFD) analysis for use in evaluating the capabilities of the design and for use in finite element analysis (FEA). The position of the center of mass of the plane is designed by placement of the internal components of the aircraft. Because the aircraft has more than one flight mode, the position of center of lift for both modes of flight must be considered. The ideal design would have the center of mass and center of lift for multirotor mode in the same location, and the center of lift for flying wing flight mode slightly behind that position. The remaining design criteria are addressed through the design of the flying wing body.

First, the lifting capabilities of the aircraft are addressed. While for multirotors the optimal lift to weight ratio is about 4:1, a small sized flying wing aircraft in forward flight has a desirable lift to weight ratio of about 1.5:1, with the minimum ratio being 1:1. Due to the relationship between lift and velocity, there is a minimum velocity in order to generate at least enough lift to keep the plane airborne. Therefore the aircraft is designed such that the minimum speed to keep the aircraft aloft is below the maximum speed of the aircraft while in multirotor mode. This is especially important as the short period of time while the aircraft is transitioning has little meaningful thrust, and the aircraft will be largely carried by momentum for a short while. As it is nearly impossible to calculate the maximum forward velocity of a multirotor, this speed is estimated by comparison to known values for other multirotors. According to DJI, the Phantom 3 drone has a maximum speed of 16 m/s = 36 mph. The maximum forward flight speed is conservatively estimated at 30 mph, less than the DJI Phantom 3 drone. While our aircraft is more powerful than a DJI Phantom 3, it also has far more surface area, making it difficult to say how the Phoenix Y6 speed will compare to the DJI Phantom 3 while in multirotor mode. It is assumed the speeds will be roughly similar. Additionally, when transitioning from multirotor mode to flying wing mode there is a short moment where there is essentially no propulsion. Phoenix Y6 must have sufficient momentum to carry it forward until the flying wing propulsion can be activated. A design margin is to be included to account for discrepancy due to these scenarios. The design requirement is that the minimum flight speed in flying wing flight mode to stay aloft must be close to 27 mph, 0.75 times the maximum speed of the Phantom 3 leaving a margin for the design requirements given above.

A model of the initial aircraft design is imported into XLFR5, a CFD software specifically designed for aircraft analysis. As such, the software has its own modeling environment, which is slightly limiting. The XFLR5 model is identical to the designed body except for a very small section which is removed from the rear center of the model, as shown in Figure 1 of the Appendix, and the elevons were treated as part of the wing. This discrepancy is extraordinarily small and can be ignored since the rear section is rounded, which does not cause significant vortices. However, the fact that the propellers are in front of the wings is not accounted for. Academic experiments [2] published in the International Journal of Micro Air Vehicles compares the 'tractor' and 'pusher' configurations (propeller at the leading and trailing edge of the wing, respectively) for micro air vehicles (MAVs), and concludes that having propellers in the tractor position at the leading edge of the wing is superior to the pusher configuration. Therefore, effects of propeller wash on the downstream wings is neglected to simplify modeling and to make all estimations conservative.

With a flying wing, the concept of an angle of attack is best defined as the difference in angle between the flying wing and the free stream of the air. It is assumed that the angle of attack of the flying wing will naturally adjust to maintain equilibrium (within reason). Throughout the design, angles of attack are chosen based on engineering judgment. The simulation is set up with Ring Vortex Analysis Method (VLM2) and inviscid flow. At an angle of attack of 8 deg, Cl = 0.814. The lift equation, Eq. 19 [1] can be used to calculate the minimum flight speed by setting the lift equal to the estimated weight of the aircraft. Note that this minimum flight speed value relates to the design requirement of a minimum 1:1 lift to weight ratio.

$$F_{lift} = \frac{1}{2}\rho V^2 C_L S_w \tag{19}$$

$$V = \sqrt{\frac{2F_{Lift}}{\rho C_L S_w}} \tag{20}$$

Using Eq 20, the estimated flight speed for the initial design is 31 mph, well above the design requirement, indicating that the design needed to be altered to increase the lifting capabilities.Note that the coefficient of lift is dependent on the angle of attack. Even with the initial design, by increasing the angle of attack by a few degrees it is possible to fly at lower speeds. Increasing the lifting capabilities means larger wings, correlating to increased drag, and a lower maximum flight speed, which is one of our primary design requirements. However, to ensure that the first iteration of the aircraft is capable of flight and can execute the transition from multirotor flight to flying wing flight smoothly, conservative design choices to increase the lift are made, especially since there are neglected systems that will negatively affect the lifting capabilities of the aircraft, such as the camera system interrupting the fluid flow underneath the wing, the front axle in front of the leading edge of the wing, and the elevons not producing significant lift.

In order to better understand how the weight, lifting capabilities, and position of center of lift change with variation of the wing span and sweep angle, a test matrix is created varying the wing span and the sweep angle of the wings. An angle of attack is chosen at 8 deg. The test matrix varied wingspans in increments of 6” from 4’ to 5’, and wing sweep from 20 deg to 30° in increments of 0.5°. 5’ is chosen as the maximum wing span based on the requirement for transportability and ease of use. Anything larger would be difficult to transport even with the wings detached, and difficult to carry when fully assembled. For each trial of the test matrix, the weight is estimated by using manufacturer density information for the foam of the wings, the net weight of the internal components and hardware, and the estimated weight of the 3D printed baseplate given by the 3D printing slicing software. The results of this test matrix are shown in Table 10. As the span increased, the coefficient of lift increases significantly, increasing by 25% from a span of 4’ to 5’. However, the net weight of the aircraft only increases by 9%. Based on this, the wingspan is selected at 5’. It is also found that sweep angle had little influence on the weight of the aircraft. In order to keep the front axle short and to increase the stability of the aircraft and to move the center of lift back from the nose of the aircraft, a sweep angle of 30° is selected. With an angle of attack of 10 °, $C_l = 0.935$. These parameters correspond to a minimum flight speed of 23.4 mph, below the design requirement. Additional analysis was performed with the same simulation settings on the with the selected wing span of 5’ and 30° sweep angle. Table 10 shows the correlation between angle of attack and coefficient of lift.

A twist angle of 3° is added to increase control over the vehicle when flying near the stall angle. The tip of the wing is set to have an angle of attack of 3° less than at the root chord, such that the airfoil at the tip is angled further downward than at the body. With this added twist, even if the wing begins to stall near the body, the wing will not yet have stalled at the tip. Since the elevons are located near wingtips, the aircraft can theoretically still be controlled even if parts of the wing are at or above the stall angle.

Finite Element Analysis and the Strength of the Flying Wing

Previous to FEA analysis many of the design decisions have been dictated by customer needs or aero dynamic criteria provided by computational fluid analysis. In order to give insight into the structural design of the aircraft, Finite element analysis was completed using the ABAQUS FEA Environment. Structural and frequency analysis was completed on both the wings and motor rods. The structural analysis was performed with the intention of identifying and assessing points of max stress and used to determine the viability of the dimensions and materials of both wings and motor rods. The motor rods were modeled identically to their true geometry, while the wings were modeled with a slightly simplified geometry lacking elevon cutouts due to invalid geometry concerns.

Stress Analysis FEA is used to determine if the drones critical structures can withstand the forces present in the most extreme circumstances of flight. Therefore, the analysis models are not computed with standard lift vs. gravity forces, but instead with the g forces associated with aggressive maneuvers. The forces exhibited on the wing are in response to lift and drag and operate relative to the root cord and are dependent on the angle of attack of the wing. The orientation of these forces can be seen in figure 1.

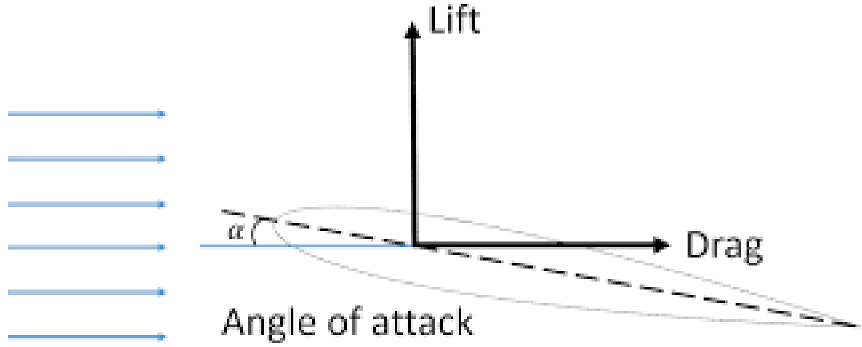

Figure 1: Lift and Drag forces in relation to root cord

Given the root cord is parallel with the z-axis in the ABAQUS model, both lift and drag forces are decomposed into their x, y and z components based on an angle of attack of 10 degrees. Through research of similar sized and powered aircraft it was determined, that the max G forces expected would top out are 20 G's. Taking an estimated max weight of 3 kgs, a force of 60 kgs was distributed over both wings; therefore, a single wing is expected to face 30 kgs of force. In addition, to the lift force, drag was computed based on a max speed of 24 m/s. Such forces would occur pulling out of a high speed dive in horizontal flight mode.

Setup and Analysis (Wing Stress) When performing stress analysis on the wings, the following steps were taken to prepare the model. The boundary conditions were established on the root profile (body side of the wing) by using the encastre setting, disallowing any movement in and about all three axises. The ultimate force was calculated using equation 21 and then componentized for implementation within the model.

$$F_{drag} = C_d \frac{\rho V^2}{2} \tag{21}$$

Where C_d is the coefficient of drag, ρ is the density of air and V is the max velocity of the drone. The resulting force components were then applied to the wing in the form of a body force to account for drag.

The lift force was computed based on the weight of the craft and additional acceleration due to maneuvering. In order to implement the lift force into the ABAQUS model, it must be componentized. Equations 22 and 23 componentize and calculate the force. Note that force in the x direction is equal to zero.

$$L_y = \frac{W}{n} * cos(\theta_{attack}) * g * Gs \tag{22}$$

$$L_z = -\frac{W}{n} * sin(\theta_{attack}) * g * Gs \tag{23}$$

where w is weight, n is the number of wings, f_s is the factor of safety which is equal to two, g is gravity, and G_s is additional acceleration due to maneuvering. The boundary conditions and componentized body loads for both lift and drag can be seen in figure 2 below.

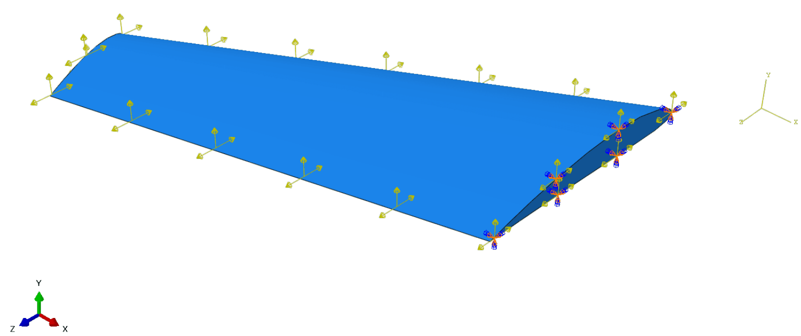

Figure 2: The fixed root profile boundary condition and the lift and drag body forces. Both lift and drag have been componentized in order to act according to a 10 degree angle of attack.

When computed, the max stress in our wing was determined to be 30 Kpa, seven times smaller than its failure stress of the foam according to manufacturer's specification data sheets. The stress distribution can be seen in figure 3 below.

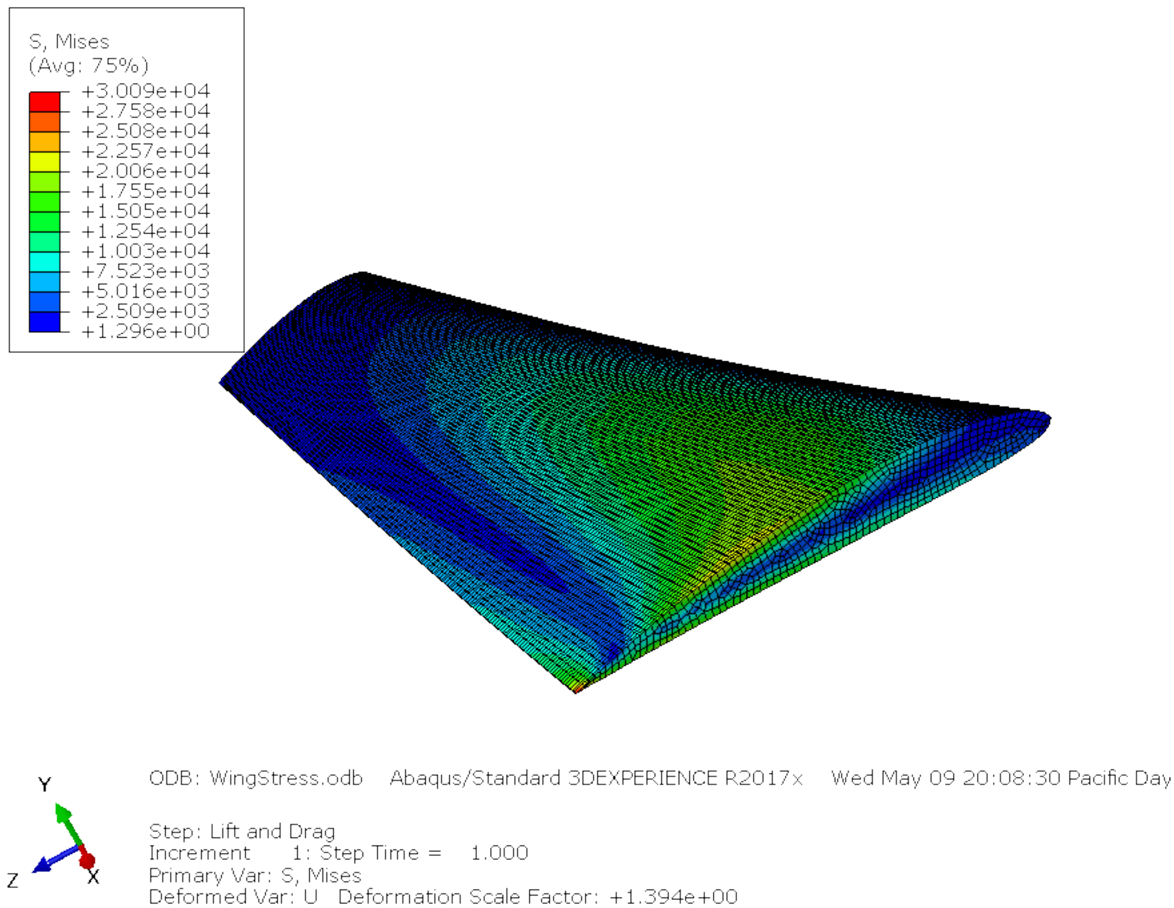

Figure 3: Max Von Mises Stress in Wing

However, while. this max stress was calculated with the assumption of a completely fixed and supported base wing profile. In reality, the wing was to be connected to the body on two shafts protruding from the baseplate. This causes a reduction in wing material, and force amplification in the region where stress was pooling. To combat this, a new wing design incorporated stress transforming rods, which continued from the base into mid wing. By distributing the load and increasing the surface area of the applied force, we are confident that the wing design is safe from failure.

Setup and Analysis (Motor Rod Stress) When performing stress analysis on the motor rods, the following steps were taken to prepare the model. The boundary conditions were established at two points on the front motor rod were the frame bushing make contact with the motor rod. The left bushing contact was fully fixed using the encastre setting, while the right bushing contact was supported in in plane with the applied force and allowed to move in the perpendicular direction. Maximum force on the motor rods was identified to occur during vertical flight recovering from a fall acceleration. The reaction of the rod, with a deformation visual amplification factor of 5.681, and the maximum stresses can be seen in figure 4.

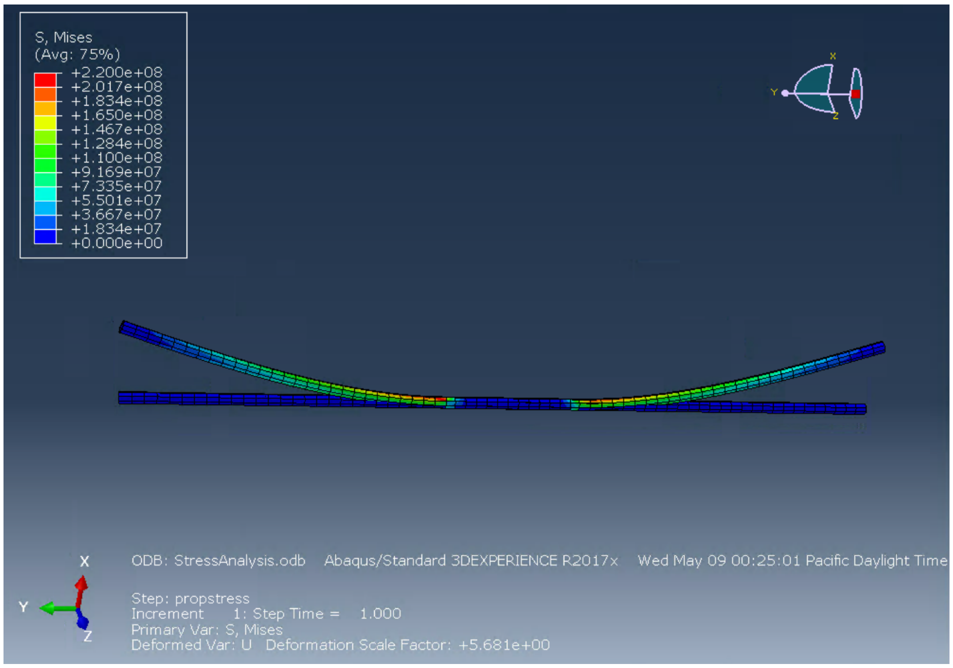

Figure 4: Deformation of front motor rod due to maximum applied load

Given the hollow nature of the rod, the forces experienced can be modeled as compressive or tensile. The max stress was computed to be 220 Mpa, and modeled as a compressive force. This value is greater than two times the compressive failure stress of the carbon fiber rod, 570 Mpa.

Modal Analysis In addition to stress and strength related structural analysis, FEA was employed to examine the mode shapes, or natural frequencies of the wing and motor rods. Forced excitation caused by the the rotations of the motors has the possibility of loss of control, or catastrophic failure it they coincide with a component's natural frequency.

Setup and Analysis (Wing Mode Shapes) Given that modeshapes are independent of loading, setup for natural frequency analysis was brief. The root chord was fully fixed with the encastre setting, and the a linear frequency perturbation selected as the action step. The first five modes shapes were requested and produced. These modeshapes can be viewed in table 5 below.

Table 5: Wing Mode Shapes

Mode Shape	Frequency [Hz]
1	6
2	24
3	29
4	45
5	55

The maximum excitation frequency of the motors was determined to be 200 Hz; therefore, since the motors operate on a sliding scale, the excitation frequency ranges from zero to 200 Hz.

The natural frequencies of the wings, fall within the range of the motors excitation; however it is theorize, that the indirect connection of the motor rod to the wings, should lessen its effect. This will be monitored during future physical testing.

Setup and Analysis (Motor Rod Mode Shapes) The rods modeshaps are also independent of loading, and are calculated after establishing boundary conditions. The boundary conditions are fixed at two points where the frame bushing make contact with the motor rod. The left bushing contact is fully fixed using the encastre setting, while the right bushing contact is supported in the vertical direction. A linear frequency perturbation is selected as the action step. The first five modes shapes were requested and produced. These modeshapes can be viewed in table 6 below.
As seen in table 6, the first mode shape of the rod is 632 Hz, more than 3 times the maximum excitation frequency of the motor, making it safe from resonance.

Final Flying Wing Design

In order to better quantify the abilities of the design, the maximum speed of the aircraft is estimated. This is done by setting the thrust in flying wing flight mode equal

Table 6: Motor Rod Mode Shapes

Mode Shape	Frequency [Hz]
1	632
2	632
3	3861
4	3861
5	8923

to the drag force. Running the rotors at full throttle depletes the energy reserves in the battery very quickly, leading to short flight time. Therefore, it is selected that the motors should not be run at more than one half their maximum potential. Additionally, all calculation use equations for static thrust. As the the relative fluid velocity increases, this thrust value overestimates t he actual thrust of the rotors. In order to account for this effect, the static thrust calculation is halved again. According to engineering judgment, between these two factors, the static thrust is reduced by a factor of $\frac{1}{4}$, as seen in Eq. 30.

A more detailed theoretic aerodynamic model of the aircraft is constructed by examining both the body of the aircraft and the motors and front axle. The motors and front axle are modeled as cylinders in the fluid flow. The coaxially mounted motors are modeled as a single cylinder extending the length of both of the motors and the mount in between them. The motor mounts are ignored as they are largely obstructed from the fluid flow by the motors and because they have complex geometry. The front axle lies directly in front of the leading edge of the wings. The effects from this relative geometry is ignored. Because the wing lies in the wake of the axle, by neglecting this geometry the drag force will be slightly over estimated. Additionally, when considering drag of the rear motors, the drag force will be underestimated because they lie in the wake of the body. Landing gear are neglected in the model as it is expected that retractable landing gear will be developed. Additionally, the camera and gimbal are not considered in the fluid analysis due the complicated shape of the gimbal. This 'assumption' that the camera and gimbal will not affect drag implies that the maximum speed calculated is a best case value and the real performance will be less than the theoretical results. The rear propellers are also not included in the aerodynamic model. In order to account for these additional drag forces, the calculated drag force for our model is conservatively multiplied by a factor of 4, as seen in Eq. 30.

The maximum forward thrust is calculated as $T_{Planemode} = 4\eta_{Coxial}T_{Singlerotor}$. Eq. 32 is derived from the thrust equation, Eq. 11 and from the drag force equation, Eq. 24 [1], using their relationship in Eq. 30. This equation (Eq. 32) is used to calculate the maximum theoretical speed of the aircraft model.

$$F_{Drag,Body} = \frac{1}{2}\rho V^2 C_{d,body} S_w \tag{24}$$

$$Re_{Cylinder} = \frac{\rho V D_{Cylinder}}{\mu} \tag{25}$$

$$F_{Drag} = F_{Drag,Body} + F_{Drag,Axle} + F_{Drag,Motor} \tag{26}$$

$$F_{Drag} = q_\infty (C_{D,Body} S_w + C_{d,motors} D_{motors} L_{motors} + C_{d,axle} D_{Axle} L_{Axle}) \tag{27}$$

$$T_{Planemode} = 4\eta_{Coax} T_{Single} = 4\eta_{Coax}\rho \frac{\pi D^2}{4}(RPM \frac{1}{60} * Pitch)^2 (\frac{D}{3.295 Pitch})^{1.5} \tag{28}$$

$$T_{Planemode} = \eta_{Coax}\rho\pi D^{3.5}(\frac{RPM}{60})^2 * Pitch^{0.5}(\frac{1}{3.295})^{1.5} \tag{29}$$

$$\frac{1}{4} T_{Planemode} = 4F_{Drag} \tag{30}$$

$$\eta_{Coax}\pi D^{3.5}(\frac{RPM}{60})^2 * Pitch^{0.5} \frac{1}{3.295}^{1.5} = 16 q_\infty (C_{d,b} S_w + C_{d,m} D_m L_m + C_{d,a} D_a L_a) \tag{31}$$

$$V = \sqrt{\frac{2\eta_{Coaxial}\pi D^{3.5}(\frac{RPM}{60})^2 * Pitch^{0.5}\left(\frac{1}{3.295}\right)^{1.5}}{16\rho(C_{d,body} S_w + C_{d,motors} D_{motors} L_{motors} + C_{d,axle} D_{Axle} L_{Axle})}} \tag{32}$$

The coefficient of drag for the body $C_{d,body}$ is found using the XFLR5 CFD software. The coefficient of drag for the cylinders are found using academic data for cylinders [10]. Figure 27 shows the coefficient of drag values for a cylinder for a given Reynold's number. The Reynold's number for each cylinder is found using Eq. 25 [1], and the results for a range of fluid flows for both the motors and for the axle can be found in Figure 7. For all given fluid flows and both cylinder sizes, the coefficient of drag is closely equal to or slightly less than 1, as the minimum Re is $3 * 10^4$ and C_d is about equal to or less than 1 for all $Re \geq 3 * 10^4$. The coefficient of drag is taken to be 1 for both the motors and the axle for all flow scenarios as a worst case value for flight with $V > 8\frac{m}{s}$.

Table 7: Reynolds numbers and drag forces on the rear motor pair and the front axle for a range of relative fluid flow velocities

Object	V(m/s)	V(mph)	D(m)	L(m)	Re	C_d	D(N)	Net Drag(N)	Net Drag(g)
Motors	8	17.9	0.034	0.0881	1.46E+05	1	0.117	0.168	17.12
Axle	8	17.9	0.008	0.161	3.43E+04	1	0.050		
Motors	12	26.8	0.034	0.0881	3.28E+05	1	0.264	0.378	38.51
Axle	12	26.8	0.008	0.161	7.71E+04	1	0.114		
Motors	16	35.8	0.034	0.0881	5.82E+05	1	0.470	0.672	68.46
Axle	16	35.8	0.008	0.161	1.37E+05	1	0.202		
Motors	20	44.7	0.034	0.0881	9.10E+05	1	0.734	1.049	106.98
Axle	20	44.7	0.008	0.161	2.14E+05	1	0.316		
Motors	24	53.7	0.034	0.0881	1.31E+06	1	1.057	1.511	154.05
Axle	24	53.7	0.008	0.161	3.08E+05	1	0.454		

At high speeds, it is anticipated that the necessary angle of attack is very low. The angle of attack and corresponding aerodynamic coefficients for the body of the aircraft are found iteratively. A simulation is run with $\alpha = 0°$, and the maximum velocity subsequently calculated using Eq. 32. The lift force is then calculated using the lift equation, Eq. 19. If the lift is less than the weight of the aircraft, then the angle of attack is increased and the simulation ran again. This process is repeated until the lift of the aircraft exceeds the weight of the aircraft.

For angle of attack of $\alpha = 0°$, $C_{D,body}$ and C_L are 0.004 and 0.246 respectively. The maximum velocity is conservatively calculated to be 26.9 $\frac{m}{s}$, or about 60 mph. At this velocity, the lift is calculated to be 5320 g, 1.73 times the estimated weight of the aircraft, leaving a significant margin as the lift is likely overestimated due to none smooth surfaces, the elevons taking a portion of the wing planform area, and the fluid flow underneath the center of the bottom. Typical RC aircraft have maximum velocities between 70 mph and 120 mph. As our aircraft has additional drag and weight due to the VTOL nature of the aircraft, it is expected that the maximum air speed is below these values. Therefore, our maximum speed is about as expected. The flight time traveling at this speed can be estimated using the propulsive efficiency of the rotors $\eta_{Propulsion}$. Eq. 16 can be used to estimate the flight time at this speed. The thrust for this speed was calculated to be 1120 g, corresponding to a flight time of 70 min. The maximum flight distance for the aircraft flying at full speed is $\frac{60mph}{1.19h} = 50miles$. If the drone flies 10 miles, hovers for as long as possible, and then returns 10 miles to its landing point using 80% of the batteries maximum capacity, it would be able to hover for 17.28 minutes, as shown in Eq.s 33 through 37. This was calculated using Eq. 16.

$$t_{PlaneFlightTime} = \frac{20miles}{60mph} = 0.333hours33 \tag{33}$$

$$A_{DrawnInPlaneMode} = \frac{1120g}{30\frac{g}{W}11.1V} = 3.36A \tag{34}$$

$$Ah_{UsedInPlaneFlight} = t_{PlaneFlightTime}A_{DrawnInPlaneMode} = 1.12Ah \tag{35}$$

$$Ah_{remaining} = 0.85Ah - Ah_{Usedinplaneflight} = 2.88Ah \tag{36}$$

$$t_{hover} = \frac{Ah_{remaining}\frac{60min}{hour}}{10A} = 17.28minutes \tag{37}$$

A summary of the calculated aircraft performance can be found in Table 10 in Appendix C.

Table 8: Comparison of goal design characteristics and estimated design characteristics

Parameter	Goal	Design Value
Take off in a small area		Satisfied by VTOL
Transportable		5' span with detachable wings
Ease of use		Semi autonomy
Real time video and telemetry data		Actively streams stabilized video, infrared video, telemetry
As fast a response as possible	$>$ 45 mph	60 mph
Multirotor flight time	$>$ 20 min	24 min
Maximum flight distance	$>$ 30 miles	50 miles

4 System integration

Due to liability concerns only minimal testing was accomplished during the course of this project. First, transmitter and receiver communication and functionality of all motors was tested, including the elevons, T-motors, and the tilt-rotor system.

Additionally, basic ground station functionality was proved to be successful. GPS, compass, attitude, and altitude data were transmitted wirelessly via the telemetry module to a computer and successfully viewed in QGroundControl.

4.1 Testing Safety

For any tests with the props attached and motors running should be enclosed in a secure environment (pictures attached in Appendix 1). We will be doing most of these tests in the plexiglass and plywood enclosure that the RSL lab uses in their testing warehouse, which should suffice as a secure enclosure for our purposes. All component voltages and currents should be checked before test initiation. All members participating will have successfully completed the LiPo battery training through the Maker Lab and will adhere to the LiPo safety procedures and notes outlined in Appendix 2. Protective clothing and accessories must be worn at all times during the testing period; long pants, closed toed shoes, insulated gloves (leather or neoprene electricians gloves) in high voltage/current scenarios (battery is 5000 mAh and the motors draw a 0.9 A current), and safety glasses will be worn at all times. The nearest fire extinguisher will be within 20 ft of the testing location, at the entrance to the RSL testing warehouse. The emergency stop is secured via zip tie to the base of the drone and has been tested using a multimeter. It will also be tested on site as an added safety precaution.

4.2 Test Procedures, Gimbal Testing

Calibrate and check all drone hardware pre-test. Wiring will be internally checked by Sean Backes and Bruce Iverson and then will be externally checked by warehouse supervisor (Anne Mahacek or Mike Rasay). There will be a sign off included in this document for wiring and hardware check. This ensures that all electrical connections are solid, that there are no obstacles such as loose wires or antennas that could possibly be struck or become entangled in the propellers. In addition, the emergency stop will be tested 3 times before initializing test to ensure safe disarming of the drone in the event of any unsuspected results. The Lipo battery will be removed by Bruce from the safety storage container and will be connected in series with the emergency stop and the flight computer on the drone. At this point, all parties present will be notified that the drone has the potential to be energized and will take proper safety precautions as listed above. Check all safety equipment in use for faults, repair if necessary, and mount the drone on the gimbaled test stand inside the plexiglass enclosure using a set of 3 screws, 2 in back and 1 in the front. The screws will mount the drone to the gimbal at the location where the landing gear would have been attached and ensure safe operation. Bruce will press the safety activation switch, connect the emergency power off, and clear the testing area. Conduct last visual check of system and surroundings. Make sure all individuals in the area know that test is taking place. Arm the system. Conduct test for each of the outlined desired results in turn, disarming the system after each test and observing for any potential changes to the system and surrounding. Once the testing is complete, ensure that the system is disarmed and that the propellers have stopped entirely. Disconnect the battery emergency off to disable arming capabilities, and unplug the battery.

4.3 Test Objectives, Gimbal testing

Before any flight tests have taken place, it is unknown whether the control system of the aircraft is properly constructed. It is also highly unlikely that the control system is adequately tuned (our particular system utilizes a PID controller, and PID gains). The goal of testing with the aircraft secured to a gimbal system is to observe the performance of the controller and ensure that it is operating nominally. The system should have a stable and bounded output. For example, the aircraft should not oscillate when attempting to stabilize, it should move smoothly to the commanded position. Or, if a input is given to the aircraft to roll, it should roll to a certain degree, but not to such a degree that it would be in danger of flipping were it not secured. The gimballed testing also allows evaluation of the aircraft's response to input commands, answering questions such as, when told to yaw, does it? Does it go in the proper direction? Table 1 details the commands and their in a more organized way. Finally, testing with the gimbal allows the pilot to gauge the sensitivity of the aircraft to inputs from the transmitter.

4.4 Testing Results

Gimbaled testing was completed in the testing facility provided by the Robotic Systems Lab (RSL) on campus with Santa Clara Universities permission. The aircraft was securely attached to a single axis gimbal system. By giving the aircraft thrust, it is shown that the aircraft did not oscillate in hovering conditions. However, due to the severely constrained conditions and the small amount of friction in the hinge, this may prove to be different in real flight scenarios, requiring PID tuning. It is also shown that the aircraft responds appropriately to forward and backwards commands in multirotor flight mode, as the aircraft tipped forwards and backwards slightly when those commands were given. A rudimentary flight time test was also conducted. At the beginning of the flight test, the battery was about half way charged. At full throttle, the half of the batter capacity was depleted in 9 minutes, yielding a flight time at full throttle of 18 minutes, well over the estimated flight time given that the 24 minute estimated flight time was for half throttle conditions.

5 Costing Analysis

In Fall 2017, this project was funded with $2,500.00 from the Santa Clara University School of Engineering and $500.00 from Xilinx, totaling $3,000.00 in full. The bulk of the cost of Phoenix Y6 stems from the electronics and hardware within the drone, especially the communications system. We initially estimated our expenses to total around $1,400.00. Our finalized expenses were actually $2,698.00. At the conclusion of this project, the budget had remaining $302.00. A detailed breakdown of the expenditures involved in this project can be found in the appendix.

6 Business Plan

6.1 Company Vision

Phoenix intends to be more than just an Emergency Response UAV development company. The team envisions a leadership position in the advancement of the first responder technology sector; leading the way to better cross-team communication, incident response success, and personal risk mitigation, through a variety of innovative products including Phoenix Y6.

6.2 Executive Summary

Problems: The first responder sector of emergency response in the United States, specifically with respect to fire and vehicular accident response, is primed for modernization. In emergency situations, responders need quick access to information at the scene of the accident, while maintaining certain safety standards that accompany acquiring that information. In many situations, the responders have incomplete or incorrect information regarding an accident, which elongates their response time to these time sensitive situations due to the necessity to assess the damage and potential hazards upon arrival. The precious minutes added to this response time can mean the difference between life and death.

Solution: To solve the outlined problem, the Phoenix Y6 was developed to be a fixed wing, unmanned aircraft, capable of vertical take off and landing, live image streaming, and communication relay to a ground station operator. This vehicle has both semi and full autonomy, allowing it to operate without the direct supervision of a first responder and is able to relay key accident statistics; such as wildfire hot-spots, fire movement patterns, locational data, and other critical information, that will allow first responders to arrive on the scene of an accident fully prepared and equipped to begin their response procedures.

Benefits: The primary benefit of the Phoenix Y6 will be in the realm of time savings. It can be determined that by saving as little as 2 minutes in a wildfire situation, the growth and damage can be reduced by a factor of nearly 3 times. This relationship can be seen in the Wildfire Growth and Response Time Relationships appendix section, which indicates that by delaying first interaction with a forest fire by 1 minute, the size and time to extinguish increases substantially. In addition to wildfire fighting benefits, the Phoenix Y6 can aid in vehicular accident response by providing accurate geographical information, vehicle damage images, potential hazards, and potential information regarding the vehicle occupants. Although wildfire and vehicular accidents are the two primary situations explored by the Phoenix Y6 design team, the vehicle has the potential to serve in a variety of other emergency response situations such as floods, missing persons, urban wildlife surveillance, and search and rescue operations.

Industry and Target Market: The Phoenix Y6 has a unique operating market due to the variety of capabilities and benefits previously outlined. It is also unique in that the vast majority of UAVs designed for image processing and information gathering reside primarily in the agricultural industry and the few that are used for emergency response are expensive, ranging from about 7000 USD to the hundreds of thousands. The primary customer will be local fire stations and regional emergency response groups. The Phoenix can, however, expand into other realms such as independent aid organizations like the Union of Medical Care and Relief Organizations (UOSSM), American Red Cross, and National Guard. It is expected that the Phoenix will expand into the international market as well, reaching a similar customer base to its US operators. The Phoenix will capture a portion of this market share initially through direct sale to fire stations and will expand to online sales and licensing to governmental agencies as the full platform progresses.

Market Size and Growth: A 2011 National EMS Assessment, conducted by the U.S. Department of transportation indicates that there are an average of 250 certified first responder organizations per state, with a cumulative total of over 21,000 organizations. A reasonable initial market penetration estimate of 10 percent indicates that the Phoenix would be integrated into about 2100 organizations. Assuming a 5 percent growth in market share per year, after year three, Phoenix's Compounded Annual Growth Rate (CAGR) would be about 19 percent. With the Phoenix's 5000 USD price-point, the initial Serviceable Obtainable Market (SOM) is estimated to be about 10.5 million USD.

Profitability and Valuation: Due to the unique industry opportunity that Phoenix is exploring, the relatively low cost of materials, manufacturing, and software development, it is estimated that Phoenix will break even in the 14th month of operation. Due to the outlined market share assumptions, Phoenix's marketability, and a reasonable growth rate of 5 percent, the company valuation is estimated at about 22 million USD.

6.3 Problem Identification

First responders need access to relevant accident information, while limiting the danger that sometimes accompanies acquiring that information. One emergency situation where this is most apparent is assessing a forest fire in its early stages. Time-sensitive information about a fire, such as where the edges of the fire extend to, hot spots, and movement patterns, are critical to a fire department's ability to contain and combat a wildfire. This information is typically unknown upon contact with the fire, reducing the efficiency of fighting it, and gathering the necessary details quickly, or before arrival, can greatly increase the success of a fire department. In almost all emergency situations, visual data is extremely valuable to first responders as it allows them to quickly locate problematic situations or potential hazards to their teams that are inaccessible by traditional means. In other situations, eyewitness accounts of emergency situations are often unreliable, one such example being vehicular accidents. Knowing the specific location of accidents on the highway is essential to properly direct ground response crews.

1. ***Current Emergency Response Time-line:***
   A recent Fire Brigades Union study on average response time to emergency situations indicates that the national average is about 15 minutes, with a maximum response time of 35 minutes in Wyoming and a minimum in Illinois of 6 minutes. This time is measured from the time of the call until the time that the crew arrives on the scene. In general, the process of responding to a call is simple; the team receives an emergency notification from a civilian witness or regional operator, they depart the station with the necessary tools and units within five minutes, the crew drives to the site of the emergency and begins to assess the extent of the situation and proceeds to respond to the accident. This process is very streamlined, however, the time spent assessing an accident or arriving at the correct location of the incident can be improved significantly.

2. ***Witness Accounts are Unreliable:***
   After speaking with members of the Palo Alto Fire Department, it was understood that many vehicular incidents are misreported due to a sequence of miscommunication issues. For a large portion of reported accidents, the witness will tell the operator that an accident has occurred on a certain side of the road and in a general location. For example, a highway accident could be reported on the southbound side of the highway between exits 4 and 5, however when the response team arrives, it turns out that the accident actually occurred on the northbound side between exits 5 and 6. The added time to reroute to the

correct location significantly affects the success of the response team, which could be minimized if just the simple location of the incident were correct.

6.4 The Solution

The Phoenix Y6 was developed to be a fixed wing, unmanned aircraft, capable of vertical take off and landing, live image streaming, and communication relay to a ground station operator. This vehicle has both semi and full autonomy, allowing it to operate without the direct supervision of a first responder and is able to relay key accident statistics; such as wildfire hotspots, fire movement patterns, locational data, and other critical information, that will allow first responders to arrive on the scene of an accident fully prepared and equipped to begin their response procedures.

1. ***Propulsion System:***
   The primary components of the propulsion system include brushless motors with contra-rotating propellers and a Lipo battery, which were selected due to their high efficiency, light-weight build, and lift capabilities. In order for a multi-copter to fly with sufficient agility, the optimum lift to weight ratio is about 4:1, and the minimum is about 2:1, which this setup accomplishes. With the current propulsion subsystem, the design requirements associated with the above outlined problem are attainable and there is room for further improvement.

2. ***Airframe Design:***
   The airframe configuration is an integral subsystem component of the Phoenix, as its design significantly impacted decisions made in other subsystems, such as the propulsion and controls. It was determined that a Y6 motor configuration would be the most effective in both VTOL and forward flight since the rear propellers would not operate in the same streamline as the front propellers, in forward flight, as they would in a quadcopter design, which increases the overall efficiency of the aircraft. The airframe decision was also constrained slightly by the necessity to manufacture the UAV easily and inexpensively.

3. ***Material Selection:***
   The material selection for the UAV is critical because of the various components in the physical craft; including the wings, fuselage base, fuselage cover,

and landing gear, as well as the necessity to maintain a low weight, high rigidity, and high durability. Essential to this subsystem was the necessity of the materials being durable enough to weather usage and varying weather conditions, but light enough to allow for satisfactory flight performance: the main requirements were flight time, flight range, and speed. The chosen foam wings, 3D printed fuselage, carbon fiber supports and axel, and lightweight hardware allowed the Phoenix to accomplish these flight characteristics. Manufacturability and cost were secondary considerations in our materials selection process, but all materials used are relatively inexpensive and easily replicable.

4. ***Control System:***
   The selection of the control system technology was crucial to fully realizing the functionality of Phoenix Y6. This subsystem includes the selection of flight controller hardware, the flight stack firmware loaded onto the autopilot, and the software package used to interact with it. The most important design considerations for this subsystem were maximizing compatibility and functionality of the Phoenix's complex VTOL-transition design. Ease of use and the ability to modify parameters were additionally important. The selected control system package accomplished the goals of simplistic user interface, semi and full autonomous flight modes, and provided a platform for visual relay and communication with the Phoenix during flight.

6.5 Benefits of the Phoenix Y6

1. ***Societal Impact and Considerations:***
   In the US, fire departments use very traditional means of response to emergency situations, which can lead to numerous factors contributing to delayed response times. In general, a witness will phone in an emergency, the operator will determine which department or region to divert the call to, and the emergency response unit from the nearest department will respond to the call. This relay of information, however, is often misunderstood or incorrectly stated by the witness, causing a delay in response time. In the case of forest fires, this can include lacking information regarding extent of fire, locations of the hottest burning points of the fire (hotspots), movement patterns, and other critical information that the witness most likely does not know. The Phoenix Y6 would

be able to relay precise, real time, position and movement information to the fire department, allowing them to respond more efficiently and effectively, reducing the potential damage of the fire. From an overarching social perspective, the potential to save lives and prevent unnecessary damage in this type of situation is immeasurable, however, there are some likely negative social impacts as well that align with the ongoing controversy over individual security, safety, and comfort. In the case of urban fires, the obstacles that the drone would need to avoid could potentially interfere with the comfort of a community. In addition to physical impacts on a community, there is a growing distrust of autonomous drones with respect to privacy, especially in governmental surveillance situations, which is a significant boundary for the Phoenix Y6 due to its primary function of observation and data relay.

2. ***Environmental Impact and Considerations:***
   The environmental impact of the Phoenix is relatively straightforward. The damage that wildfires are capable of is immense, meaning that longer response times by fire departments directly correlates to more plant and wildlife destruction. The amount of potential destruction from these emergency situations can be seen in the Wildfire Growth and Response Time Relationships appendix at the end of this report. Specifically, the increased size of the fire with just a minute of response time increase should be noted. Phoenix hopes to decrease the amount of time spent assessing the situation upon arrival, which will yield more effective results. With the help of the Phoenix, the firefighters would have a greater opportunity to contain the fire, preventing it from spreading and causing more damage.

3. ***Political Impact and Considerations:***
   The ethical and political perspectives of this project are specifically tied together through the theme of individual privacy. There is inherent danger surrounding autonomy, but especially in autonomous aircraft due to their ability to maneuver with relatively low restriction. A recent increase in privacy related issues in recent years, with the most recent breach occuring this past year with Facebook's collection of personal information, has created a dialogue in the US specific to the safekeeping of individual's personal information and general comfort in their daily lives; that is, feeling like their every move is not under

surveillance. The Phoenix Y6, while specifically for emergency response situations, would theoretical provide a perfect cover for community surveillance and personal information gathering.

6.6 Team Qualifications

- **Sean Backes:** Sean has been intrigued by aeronautics and aerospace since early childhood, and has followed this interest towards a mechanical engineering major and aerospace minor here at Santa Clara. A passionate learner, he will be continuing this focus in graduate school here at Santa Clara with a specific focus on dynamics and controls. Taking the undergraduate dynamics and controls courses in addition to related graduate-level courses has influenced his impact and effectiveness as the control system designer for this project. His passion and patience will be instumental to the development of more customized, robust control algorithms and arrangements as Phoenix continues development.

- **Alastair Hood:** Alastair's qualifications are multifaceted. During his Junior year, he added an aerospace minor to his mechanical engineering curriculum and has taken courses in aerospace propulsion, spacecraft dynamics, and fluid dynamics. In addition to the technical background required for this industry, he has significant team leadership experience; most recently acting as his senior capstone's Team Lead, the mechanical design team lead for SCU's Tiny House competition team for over a year, and through his Eagle Scout project senior year of high school. The experiential knowledge gained from these groups will be helpful as Phoenix becomes established.

- **Bruce Iverson:** Bruce has been building unmanned aircraft since the beginning of high school. He has a lifelong fascination with flying vehicles of all types that he has worked hard to build into professional knowledge. Bruce has worked in the field of robotics and unmanned vehicles for the past 1.5 years and has learned the value of thoroughness, hard work, and attention to detail. During the course of every professional and academic project that he has worked on, collaboration within the design team has been the most critical factor in the success of of the project. Phoenix Y6 was the ultimate example of this, and it is our unity as a team that will enable us to better our product and grow the brand.

- **Brian Meier:** Brian has studied mechanical engineering for the past four years at Santa Clara University in Silicon Valley. During his time at SCU, he acquired a passion for aerospace engineering and declared aerospace engineering as a minor during his junior year. Brian has taken classes in general aerospace engineering as well as propulsion and he aspires to find a career in the aerospace engineering industry.

- **John Strong:** John Strong has had a life long love for tinkering and problem solving. He thanks a series of engineering based projects completed in high school pushing him towards his profesional path. He studied as mechanical engineer at Santa Clara University in the Silicon Valley. He has exposure to rapid prototyping through experience at the bio-medical device company Kali Care. He aspires to work in mechatronic design.

- **Michael Destin:** Since early childhood, Michael has always enjoyed building things. Michael has experience building models, and knows the importance of making sure every part fits together and works correctly. Michael has been interested in autonomous vehicles since he first heard about them. He also loves math and science. This gives Michael the background necessary for this project. He also looks at things differently from most people, and likes to think outside the box, leading to creative solutions to problems.

6.7 Industry Analysis

A variety of existing commercial drones could be used for similar purposes to the Phoenix, however, these drones are generally optimized for the agricultural setting. The image recognition programs of many existing products are built around observation of crops and the specific properties that farmers need to observe, not necessarily quick relay of important emergency information. Drones researched include the eBee by Sensefly, the ScanEagle UAS, the AG Drone by Honeycomb, the FireFly6 Pro by BirdsEyeView Aeronautics, the Draganflyer X4-P by Draganfly, and the DJI Matrice 200 by DJI (distributed by SkyFire Consulting). Various flight specifications and qualities regarding these vehicles can be seen in Table 1 of this report.

The researched drones are a collection of products with various design parameters;

primarily autonomy, launch systems, and imaging hardware. The two primary qualities Phoenix improved upon were the cost of the drones and their maximum flight times. These commercial drones are expensive, which creates an immense barrier for fire departments that want to purchase a drone. While some of these drones, such as the AG Drone by Honeycomb, are marketed towards agricultural uses where they would be used in calm environments over flat expanses of land, fire departments would be using drones in rougher terrain and environments, making it reasonable to expect the occasional flight accident. A fire department should be able to replace damaged drones without spending a significant portion of their budget.

Flight time and speed was another significant consideration in our design in an effort to improve over existing products. The majority of the drones that were researched are powered by battery and had maximum flight times under one hour, according to each drone's manufacturer. The goal of designing our drone to be capable of one hour flight times was established. However, if battery technology was not able to permit the Phoenix Y6 to reach one hour flight time, it was found during the customer outreach stage of design that if the Phoenix Y6 was capable of flying for at least 20 minutes, it would be acceptable to land the drone three times an hour to swap the drained battery for a fresh one. Additionally, the speed of the drone was an important consideration as the overall goal of the Phoenix is to provide relevant emergency incident information to the first responders in the shortest amount of time. Although some of the existing drones are capable of very high speeds, the relationship between cost and higher speeds is directly tied, making them poor options for a local fire department.

The industry research conducted led the team to realize a relatively open market with the ability to gain substantial market share immediately. Although the Phoenix will not immediately provide effective service to the emergency services in the US due to flight autonomy laws and regulations, it is reasonable to predict a large market share, potentially upwards of 50 percent, were the regulations to be updated and more favorable to the Phoenix.

6.8 Sales and Marketing Strategies

The marketing strategy for the Phoenix will be similar to that of many existing commercial products in the UAV industry and will partially mimic the strategies of DJI, GoPro, and 3DR, however, it will be focused on the emergency response sector rather than the average civilian. To begin, the Phoenix will employ similar techniques to GoPro in that promotional videos using the Phoenix will be shot and distributed via a variety of online emergency response publications such as the Emergency Management magazine and website and the OSHA publications. In addition, these videos will highlight all of the potential aid that the Phoenix would provide to first responders, but will be shot in an enthusiastic and interesting manner that mimics real life scenarios and applications. One significant issue that was observed in the initial market research surrounded the indirect customer base: the local community. Due to the recent dialogues on personal privacy and freedom infringements, the Phoenix team believes that a large amount of community education and engagement will be required to integrate this product into the community. The Phoenix team plans to partner with individual local fire departments to provide customer and community informational sessions and outreach to promote the drone's benefits and negate any backlash surrounding the operation of an autonomous vehicle in urban communities.

The 5 P's of Marketing (Products, Price, Promotion, People, and Place):

- **Products:** The primary product will be the physical Phoenix drone and accompanying hardware as previously outlined in the Solution section. As the company sees growth, the product line will expand to further into the realm of emergency response. The team foresees a great need for advanced, but simplistic, technology for first responder teams. More products will be developed to aid in more seamless communication between teams (currently communication is performed via one-way radios). This could incorporate closed broadband connections for the teams, wearable technology that would integrate with the original Phoenix and provide everyone involved with personalized critical information regarding their specific task, and wearable health monitors that would provide updates on individuals conditions to a central coordination group and negate the potential for on-site accidents due to neglected poor health signs.

- **Price:** The Phoenix is marketed at 5000 USD, a price-point set to undercut any competition from pivoting agricultural drone companies by several thousand dollars, will fit more reasonably into local emergency service organizations' budgets. In addition, warranties and service benefits will aid in the longevity of the Phoenix's time with each organization and will provide the client relationship that the Phoenix team would like to foster in our company.

- **Promotion:** The Phoenix team believes that a large amount of community education and engagement with the emergency services organizations will be required to integrate this product into the community. This belief stems issues surrounding drones and the resulting dialogues on personal privacy and freedom infringements. To help remedy the expected effects from these dialogues, the Phoenix team plans to partner with individual local fire departments to provide customer and community informational sessions and outreach to promote the drone's benefits.

- **People:** The target audience for the Phoenix will be emergency response organizations in the United States, however, there are thoughts of expansion to other parts of the world. A stripped down version, one not containing image recognition, thermal imaging, and full autonomy capabilities, could be sold to civilians, however, they will be a secondary market based purely on demand.

- **Place:** The Phoenix team intends on providing the technology for first responder teams in the United States, Canada, and Mexico initially, but has plans to expand to other areas of the world in the future.

The marketing and sales division of Phoenix will be rather small for the first 2 years and will be handled in house by co-led John Strong and AJ Hood. After the team sees growth, the sales and marketing team will be re-evaluated and expanded to fit the need of the of demand. The team will also handle most distribution in the first few years through Amazon's distributor shipping services. The team will also meet with each customer throughout the purchasing and deployment process to ensure that a lasting relationship is built and the product is serving the organization in the most productive way.

6.9 Manufacturing Plans

As previously mentioned, Phoenix will coordinate delivery of the drone through Amazon's shipping and distributor services, which will add to the costs of the product, but will be overall beneficial, more efficient, and less expensive because it will not require the team to have product storage space or coordinate with shipping companies. In addition, the manufacturing coordination will be simpler because the outsourced manufacturing companies that will be used will have an established relationship with Amazon. The manufacturing will initially be in house, with specialized hardware and parts ordered from manufacturers, due to the expected low sales volume in the first year and the short assembly and configuration time. The team expects to expand to a contracted manufacturing facility in the United States during the second year of sales. The initial stocked quantity will be 1500 units, roughly 7.5 million USD in inventory, and will be stored in a leased space. With estimated raw production costs totaling about 1500 USD, this inventory produces a net overhead of 5.25 million USD. The operating costs are expected to be relatively minimal during the first year: the storage facility lease, a small office lease for day to day operations and product assembly, travel expenses for customer meetings and marketing, and a small budget for community outreach and education.

6.10 Service and Warranties

As discussed in the Marketing section of this plan, the Phoenix team plans to develop personal relationships with their clients. This sentiment extends to the service and warranties plan included with the Phoenix Y6. Due to the high level technical skills involved with the development and production of the Phoenix Y6, it is hypothesized that all bugs, technical difficulties, and damage that the Phoenix experiences will not be able to be solved or repaired by the clients. The Phoenix team intends to have a full service warranty plan that includes repair of the drone, excluding human error or accidents incurred by misuse, and will have software updates pushed to the units several times a year to remedy any glitches encountered by the users. The warranty plan will cover any damage that is not tied to human error. This includes any damage during fully autonomous flight, but does not include damage incurred during manual flight. As further issues are realized, the warranty and service plans will be updated to better fit the needs of the customer.

6.11 Financial Plan and Return on Investment

Although a variety of existing commercial drones could be used for similar purposes to the Phoenix, these drones are generally optimized for the agricultural setting. The image recognition programs of many existing products are built around observation of crops and the specific properties that farmers need to observe, not necessarily quick relay of important emergency information. This market hole crates a difficult scenario to analyze as there aren't many commercial examples to aid in Phoenix's financial modeling. Due to this unique industry opportunity that Phoenix is exploring, the relatively low cost of materials, manufacturing, and initial software development, it is estimated that Phoenix will break even in the 14th month of operation. This assumption is based off of the expected monthly sales, raw production costs, employee compensation, and marketing expenditures.

A 2011 National EMS Assessment, conducted by the U.S. Department of transportation indicates that there are an average of 250 certified first responder organizations per state, with a cumulative total of over 21,000 organizations. A reasonable initial market penetration estimate of 10 percent during the first 2 years indicates that the Phoenix would be integrated into about 1050 organizations during the first year. From this estimation, the initial stocked quantity will be 1500 units, roughly 7.5 million USD in inventory. With estimated raw production costs totaling about 1500 USD, this inventory produces a net overhead of 5.25 million, and requires a startup base of 2.25 million USD. The storage space required for 1500 Phoenix Y6 UAVs is relatively small because they will be stored disassembled by component. Once orders begin, the team will assemble each Phoenix on a demand basis. A leased business storage space of reasonable size is estimated to cost roughly 5000 USD per year. The marketing budget will start at 50,000 USD, which mostly covers team member travel expenses for client meetings and a small social media ad presence. Employee compensation will be primarily through company shares to begin, however, will include a stipend of 40,000 USD per member to cover basic living expenses. This compensation structure will be updated upon successful completion of 10 percent market share or at the end of year two. With all of these expenses tallied, the start-up cost for Phoenix is approximately 2.5 million USD. Although this is a relatively high barrier to entry, Phoenix sees the potential upside of this endeavor; due to the outlined market share assumptions, Phoenix's marketability, and a reasonable growth rate of 5 percent, the company valuation is estimated at about 22 million USD. The team plans to seek out venture funding, offering a negotiable company stake, approximately 8 percent, in return for the initial capital. Assuming a 5 percent growth in market share per year, after year three, Phoenix's Compounded Annual Growth Rate (CAGR) would be about 19 percent. With the Phoenix's 5000 USD price-point, the initial Serviceable Obtainable Market (SOM) is estimated to be about 10.5 million USD. This analysis leads to an investor ROI of approximately 33 percent after the SOM is reached. Phoenix believes that this financial analysis illuminates a significant market opportunity, which, if fully realized, would be both beneficial to investing partners, Phoenix team members, and the communities that the Phoenix Y6 impacts.

7 Engineering Standards

Throughout the course of this project, several different engineering standards and constraints presented themselves; both explicitly and indirectly. These topics ranged from potential political repercussions to the manufacturability of the final product. In the following sections, the social, environmental, ethical and political impacts of the project will be discussed and the overall manufacturability and safety precautions associated with these types of devices will be addressed.

7.1 Societal Impact

In the US, fire departments use very traditional means of response to emergency situations, which can lead to numerous factors contributing to delayed response times. In general, a witness will phone in an emergency, the operator will determine which department or region to divert the call to, and the emergency response unit from the nearest department will respond to the call. This relay of information, however, is often misunderstood or incorrectly stated by the witness, causing a delay in response time. In the case of forest fires, this can include lacking information regarding extent of fire, locations of the hottest burning points of the fire (hotspots), movement patterns, and other critical information that the witness most likely does not know. The Phoenix Y6 would be able to relay precise, real time, position and movement information to the fire department, allowing them to respond more efficiently and effectively, reducing the potential damage of the fire. The reduction of response times is also critical in emergencies other than forest fires such as a wild animal encounters in an urban area, traffic accidents, or airplane crashes. In most of these situations, the responders would be able to arrive on the scene much sooner by utilizing the Phoenix to quickly identify the locations of these incidents and would be able to address the situation more effectively due to the situational knowledge that would be provided pre-arrival. Current methods of determining locations of emergency situations such as these are often unreliable and imprecise. One assessment of modern American emergency response system highlights this issue, noting that they "found inaccurate location to be the most important challenge for the existing 9-1-1 infrastructure. Notably, the inability to determine a user's precise location in an emergency often causes calls to be routed to the wrong 9-1-1 dispatch center, wasting valuable time asking a caller to describe their location before help can be sent" ("Quantifying the Impact of Emergency Response Times", 3). From an overarching social perspective, the potential to save lives and prevent unnecessary damage in these situations is immeasurable, however, there are some likely negative social impacts as well that align with the ongoing controversy over individual security, safety, and comfort. In the case of urban fires, the obstacles that the drone would need to avoid could potentially interfere with the comfort of a community. For example, if a drone's propellers were to strike a power line, this collision could disrupt the electrical grid in a neighborhood causing a power outage. Another potential risk in an urban community surrounds the possibility of a malfunction or unforeseen situation during flight, which could cause the Phoenix to crash or otherwise harm an individual or structure in the vicinity. This danger is arguably one of the most important concerns and is a situation that would be further developed and analyzed during a longer project time period. In addition to physical impacts on a community, there is a growing distrust of autonomous drones with respect to privacy, especially in governmental surveillance situations, which is a significant boundary for the Phoenix Y6 due to its primary function of observation and data relay. With these concerns in mind, however, the Phoenix Y6 platform could be further developed to negate any public concern and the overwhelming positive impacts would most likely outweigh initial community distaste.

7.2 Environmental Impact

The environmental impact of the project is much more straightforward than the other engineering standard topics. The damage that wildfires are capable of is immense, meaning that longer response times by fire departments directly correlates to more plant and wildlife destruction. The amount of potential destruction from these emergency situations can be seen in the Wildfire Growth and Response Time Relationships appendix at the end of this report. Specifically, the increased size of the fire with just a minute of response time increase should be noted. Phoenix hopes to decrease the amount of time spent assessing the situation upon arrival, which will yield more effective results. With the help of the Phoenix, the firefighters would have a greater opportunity to contain the fire, preventing it from spreading and causing more damage. One negative effect the Phoenix has on the environment stems from the materials currently used in its production. Styrofoam, from which the wings of our prototype is made, takes approximately 500 years to decompose, and takes up 30 percent of landfill space, according to Washington University. In the event that the drone is damaged beyond repair, the materials would not be reusable. In order to combat this, future models would use more sustainable materials such as recycled cardboard or materials with more longevity and durability like carbon fiber.

7.3 Manufacturability

Manufacturability plays another role in Phoenix Y6′s impact on the environment. Currently, production of the wings of the drone are consists of machining a block of Styrofoam, which is a subtractive process. Thus, producing the wings causes a portion of the original block to be wasted. If the wings for the Phoenix Y6 were produced in this manner during mass production, the wasted Styrofoam would have a severe impact on the environment. After the final prototyping is completed, the wings would be mass manufactured from a more environmentally friendly material, such as carbon fiber or fiberglass. Alternative materials such as these are recyclable and are often stronger and more durable than Styrofoam without sacrificing weight. The remainder of our frame is environmentally friendly, as our fuselage is 3D printed, a process which produces little waste, and the fuselage cover is vacuum formed. Our design includes a LiPo battery which is recyclable and will have little environmental impact if disposed of properly; given to local e-waste recycling center.

7.4 Ethical and Political Impact

The ethical and political perspectives of this project are specifically tied together through the theme of individual privacy. There is inherent danger surrounding autonomy, but especially in autonomous aircraft due to their ability to maneuver with relatively low restriction. A recent increase in privacy related issues in recent years, with the most recent breach occurring this past year with Facebook′s collection of personal information, has created a dialogue in the US specific to the safekeeping of individual's personal information and general comfort in their daily lives; that is, feeling like their every move is not under surveillance. The Phoenix Y6, while specifically for emergency response situations, would theoretical provide a perfect cover for community surveillance and personal information gathering. This danger would fall on the operating parties and, from an ethical perspective, would require all operating organizations to adhere by a standard of good practice in the security realm. In addition, the presence of these vehicles in a community would require the utmost transparency, which could come in the form of educational programs, personal interactions between the community and the emergency responders with the Phoenix present, and question and answer sessions to assure residents of the area that the UAV is there to benefit, not harm, them. On the other side, the political interest in a product like Phoenix Y6 would be high. The platform could be used for covert information gathering that would be helpful in situations like geographical campaigning in which a political party could learn how to best align themselves with the observed values of a community. In order to combat these potential issues, the Phoenix Y6 team would conduct extensive training with the organizations purchasing the technology to educate them on the dangers, both physical and mental, that are present with the operation of this platform in the community. Aside from overarching control of the Phoenix, education and community outreach seems to be the most successful path to ethical operations of UAVs.

8 Summary and Conclusions

Over the course of the 2017-2018 academic year, our senior design group was able to design and fabricate a VTOL fixed-wing drone for the purpose of monitoring emergency response situations. Our goal was to design a vehicle that would be relatively cheap to purchase and customer friendly. We achieved these goals with a price tag of $5,000 and a simple user interface. Due to time restrictions and liability concerns, we were not able to perform extensive testing, but we were able to demonstrate expected communication between our transmitter and the drone, between the drone and groundstation including transmission of basic telemetry such as GPS and compass data, as well as an experimental flight time of 18 minutes.

8.1 Improvements and revision

A number of improvements can still be made to the design of Phoenix Y6. Firstly, the landing gear of the drone could be made to be fully retractable to reduce drag on the aircraft during forward flight. In addition, a sturdier cover could be designed and fabricated to add to the aerodynamics of the drone and further reduce drag. Another short coming in the realm of drag is the non-operation of the rear propellers in forward flight. During forward motion, the rear propellers remain parallel to the ground, meaning that they provide no additional forward thrust in this flight mode, and therefore only serve to increase the drag on the vehicle. Further design iterations could allow these rear propellers to rotate during the transition from vertical to horizontal flight, allow the drone to have increased thrust, and therefore lift, and decreased drag in the forward flight mode.

Another area of improvement presents itself in the form of weight. It is possible, and likely, that lighter electronics components could be found on the market. In addition, the wings and fuselage of the drone could be fabricated from a lightweight, but sturdy material, such as carbon fiber or fiberglass, which would decrease the weight of the drone and increase its durability at the same time.

Finally, some improvements could be made the electronics field of this project. Notably, with a better battery or multiple batteries, the flight time of the drone could be extended. In addition, the range of the receiver and transmitter could be extended to increase the maximum range of the drone.

8.2 Compromises and Shortcomings

One of our design requirements was to be able to fly in all weather conditions including snow and rain. While it is possible to construct multirotor aircraft capable of flying in extreme rain and snow, there are complications such as shortened battery life due to cold and most especially watertightness of the case. As the prototype of the Phoenix Y6 aircraft was constructed, it became apparent that a watertight body was not achievable in this iteration of the aircraft.

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Appendices

A Wildfire Growth and Response Time Relationships

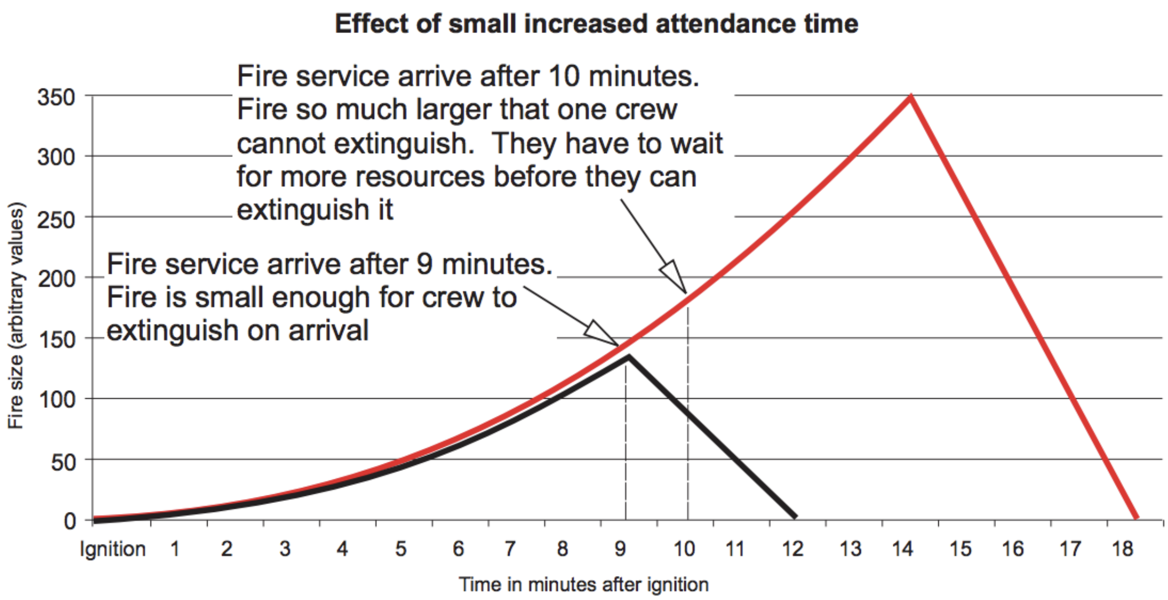


Figure 5: Model of fire size vs. emergency response unit arrival time

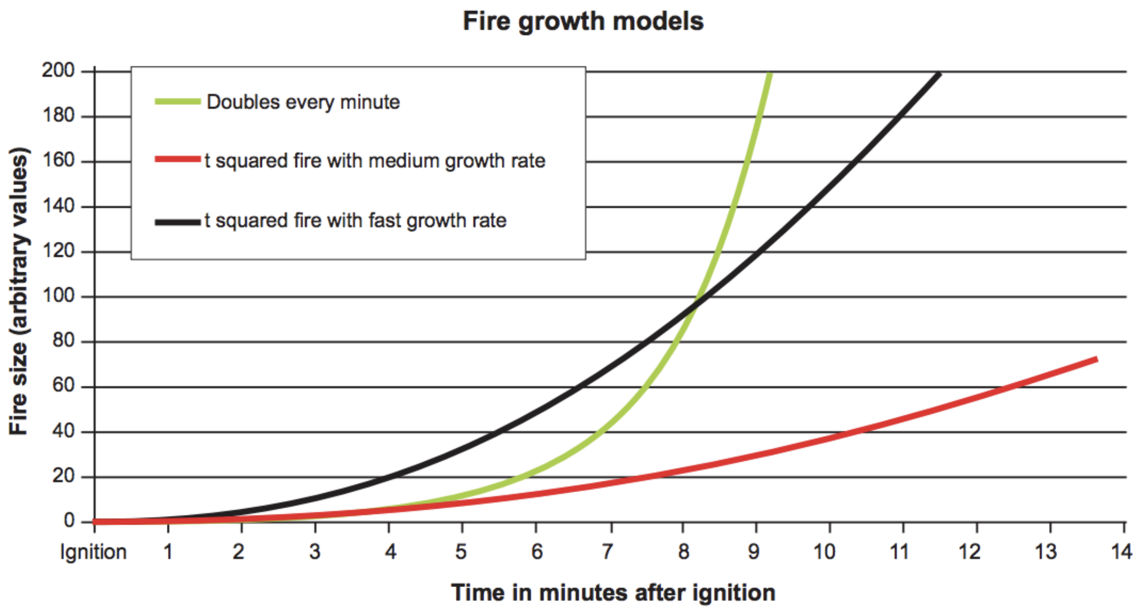


Figure 6: Model of potential wildfire growth with respect to ignition time

B Mechanical Drawings

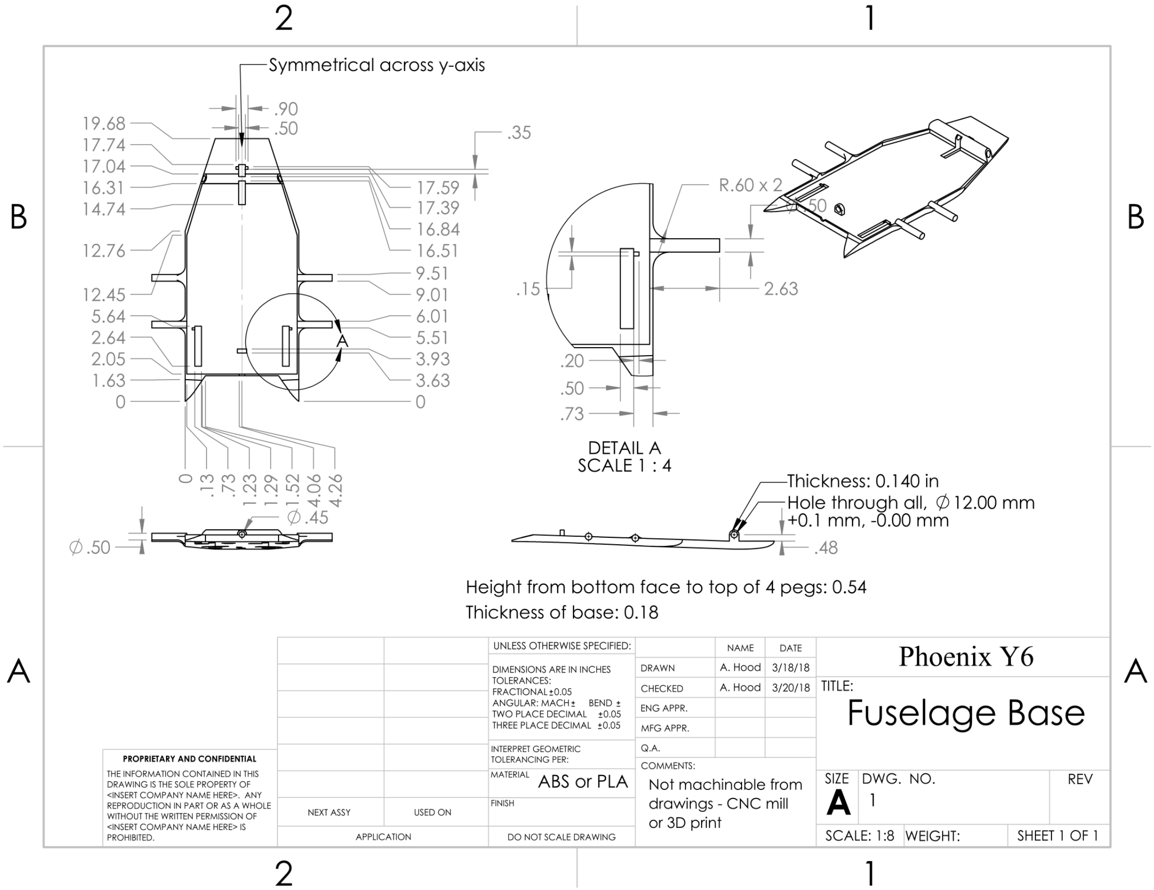


Figure 7: Fuselage Base

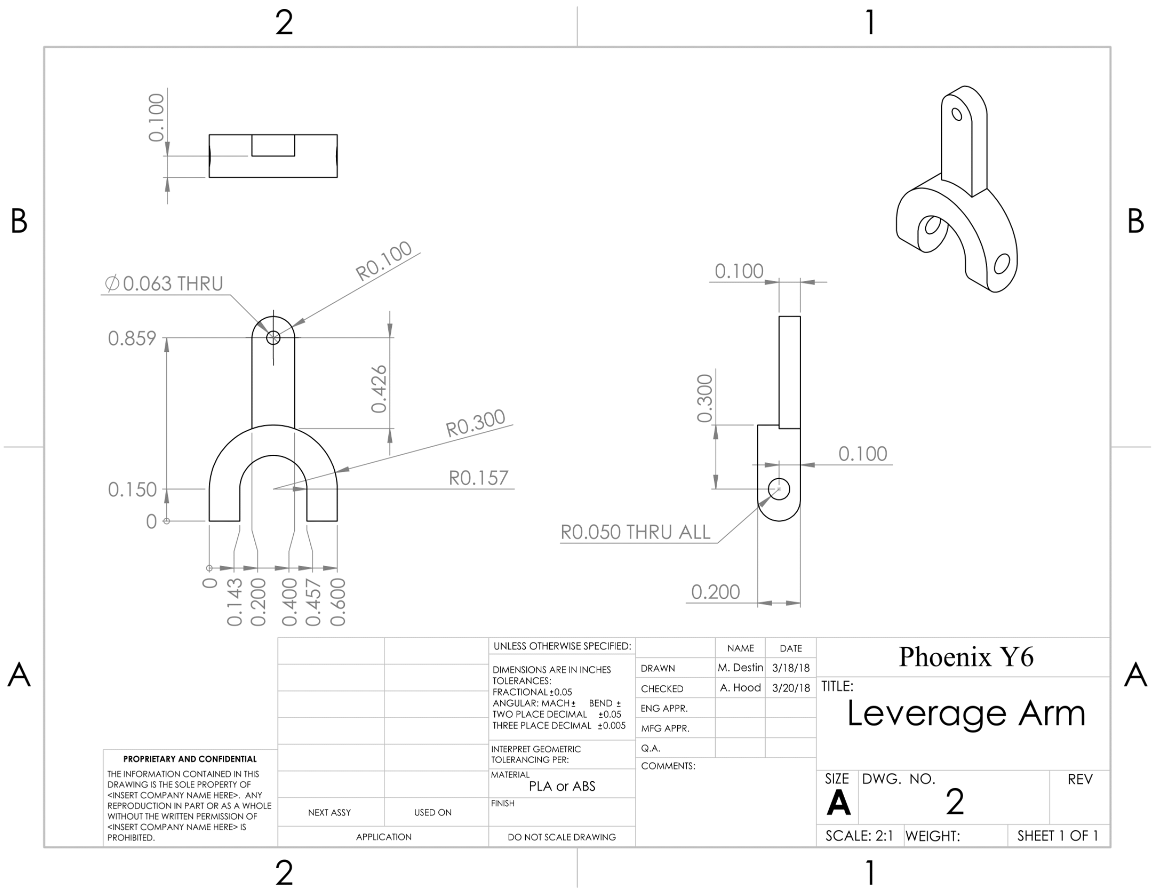


Figure 8: Leverage Arm

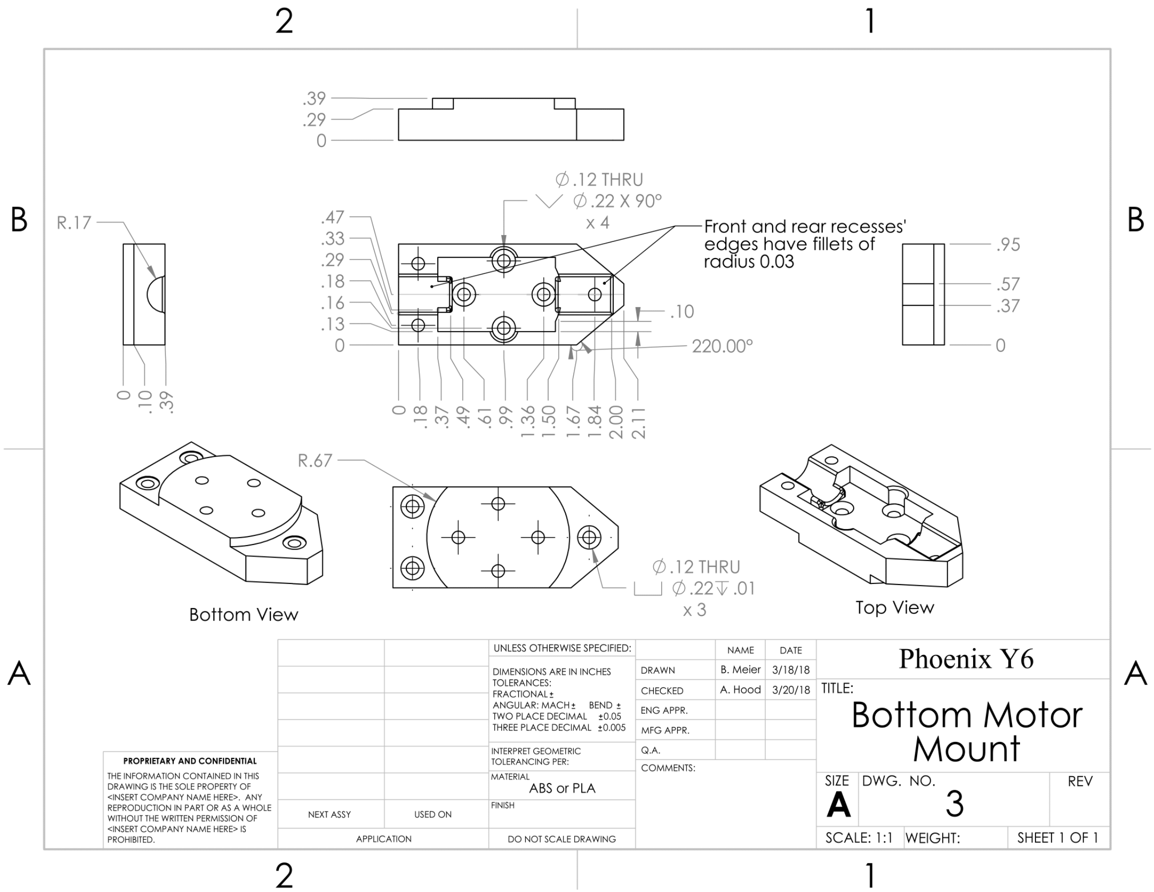


Figure 9: Bottom Motor Mount

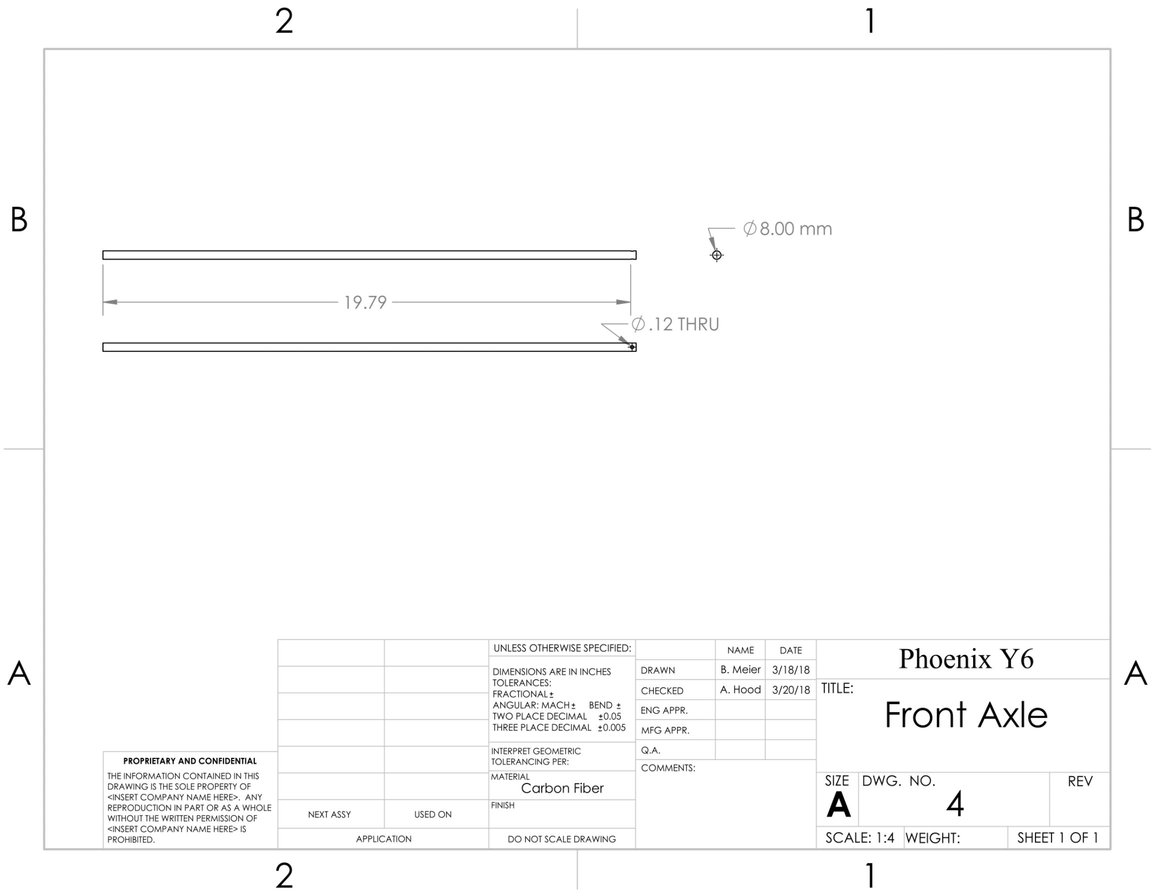


Figure 10: Front Axle

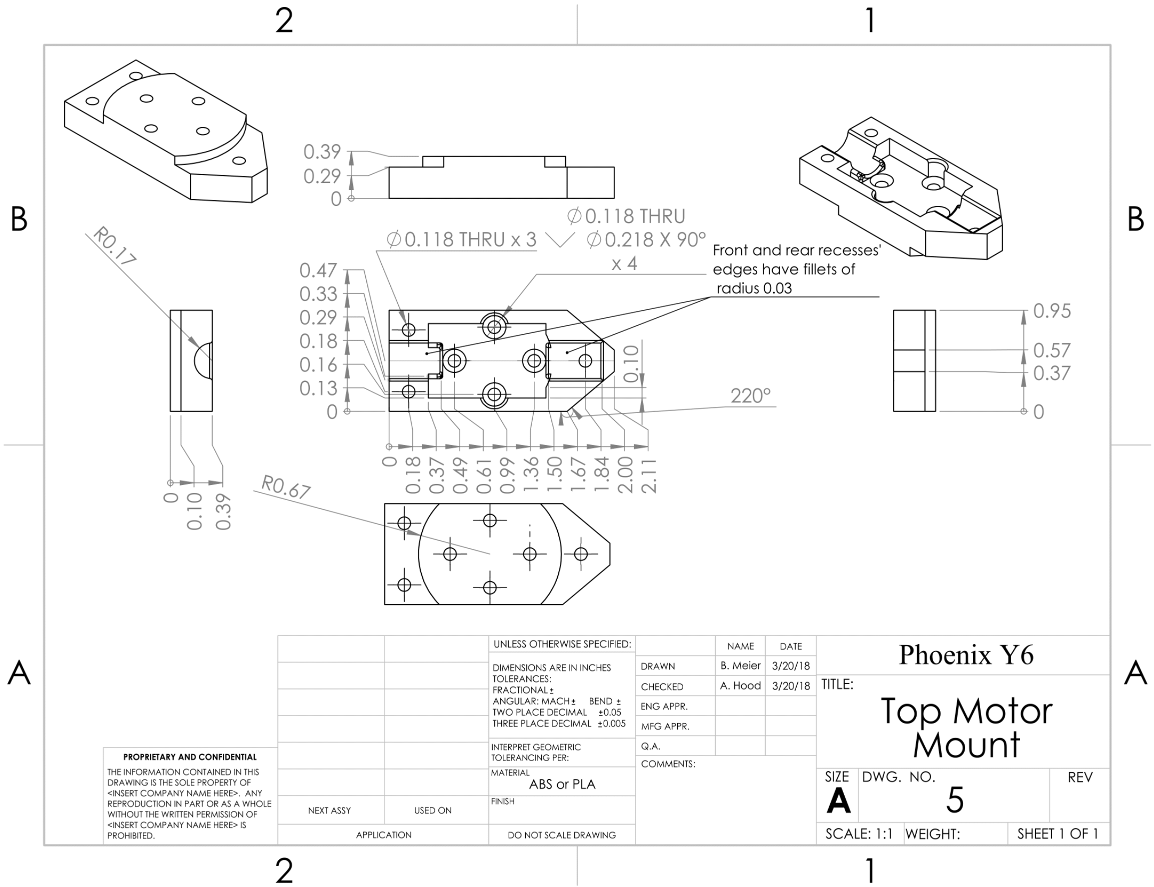


Figure 11: Top Motor Mount

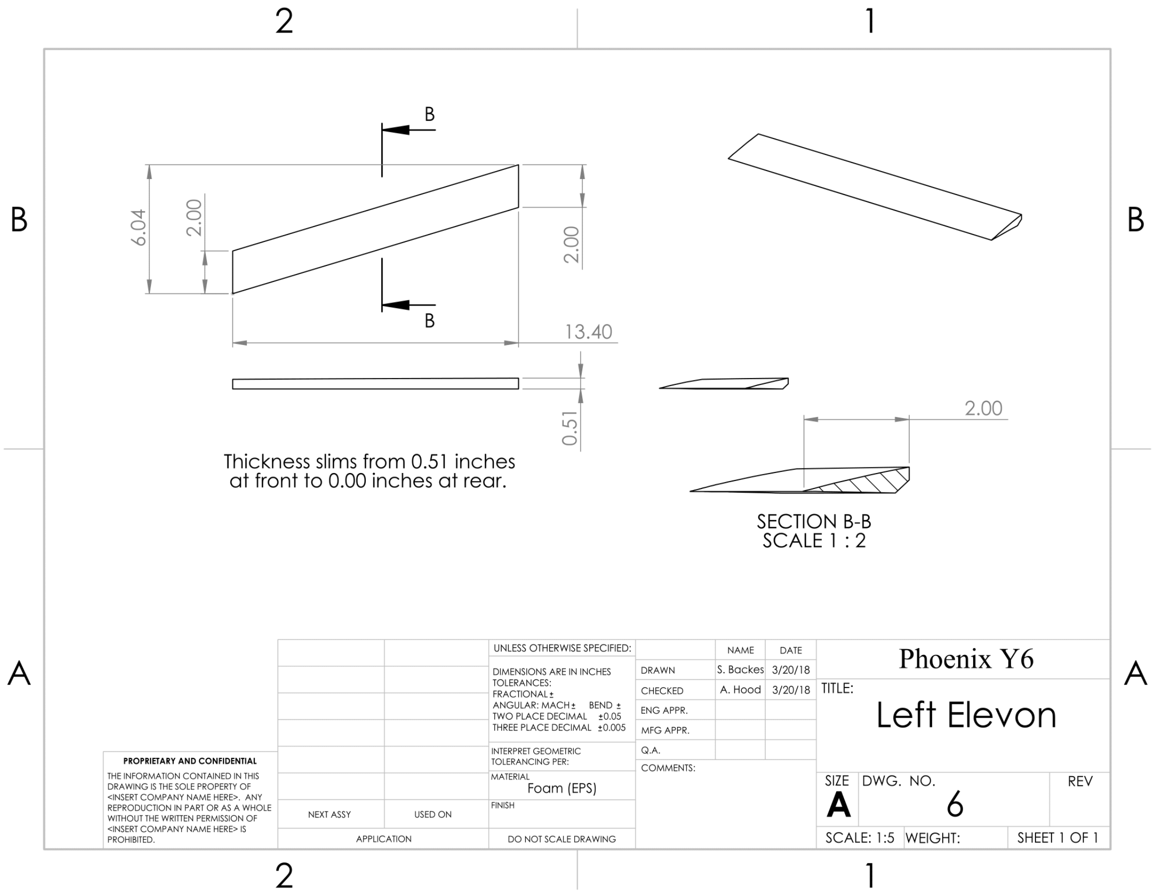


Figure 12: Left Elevon

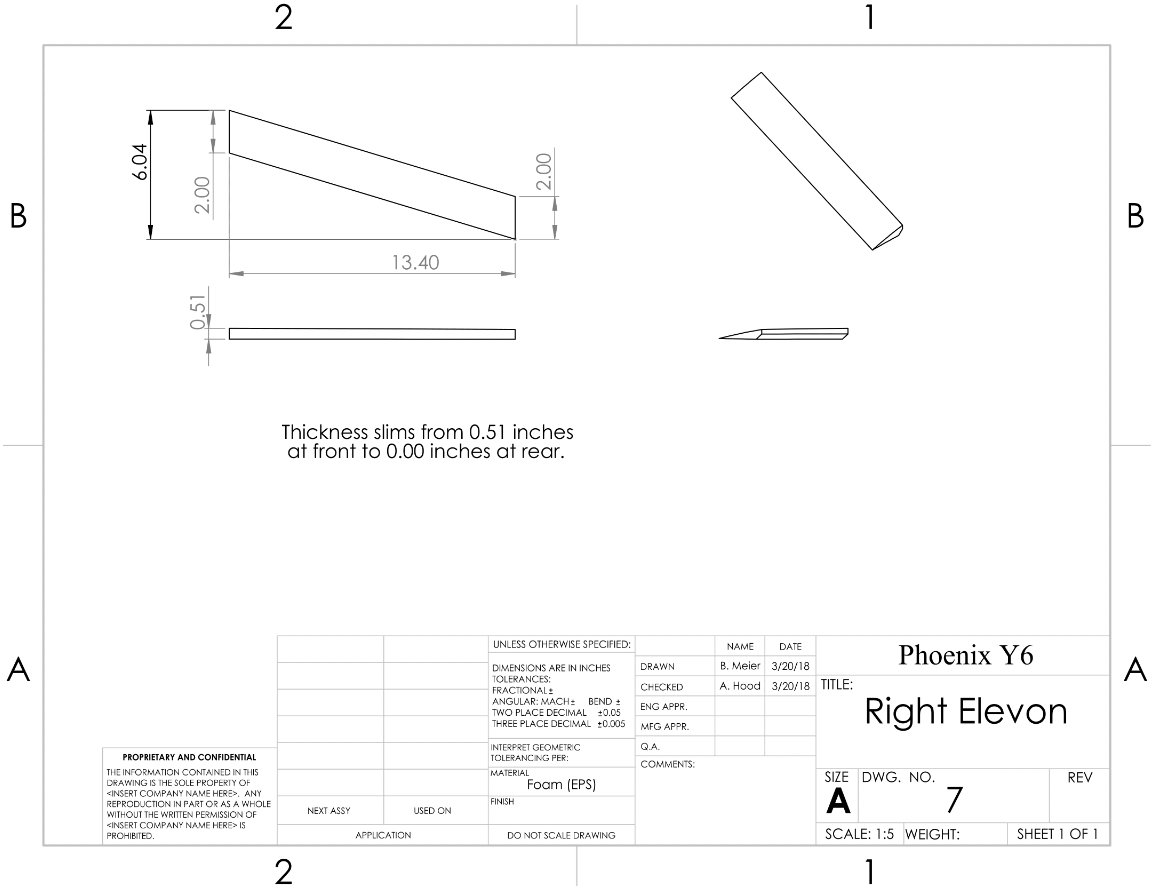


Figure 13: Right Elevon

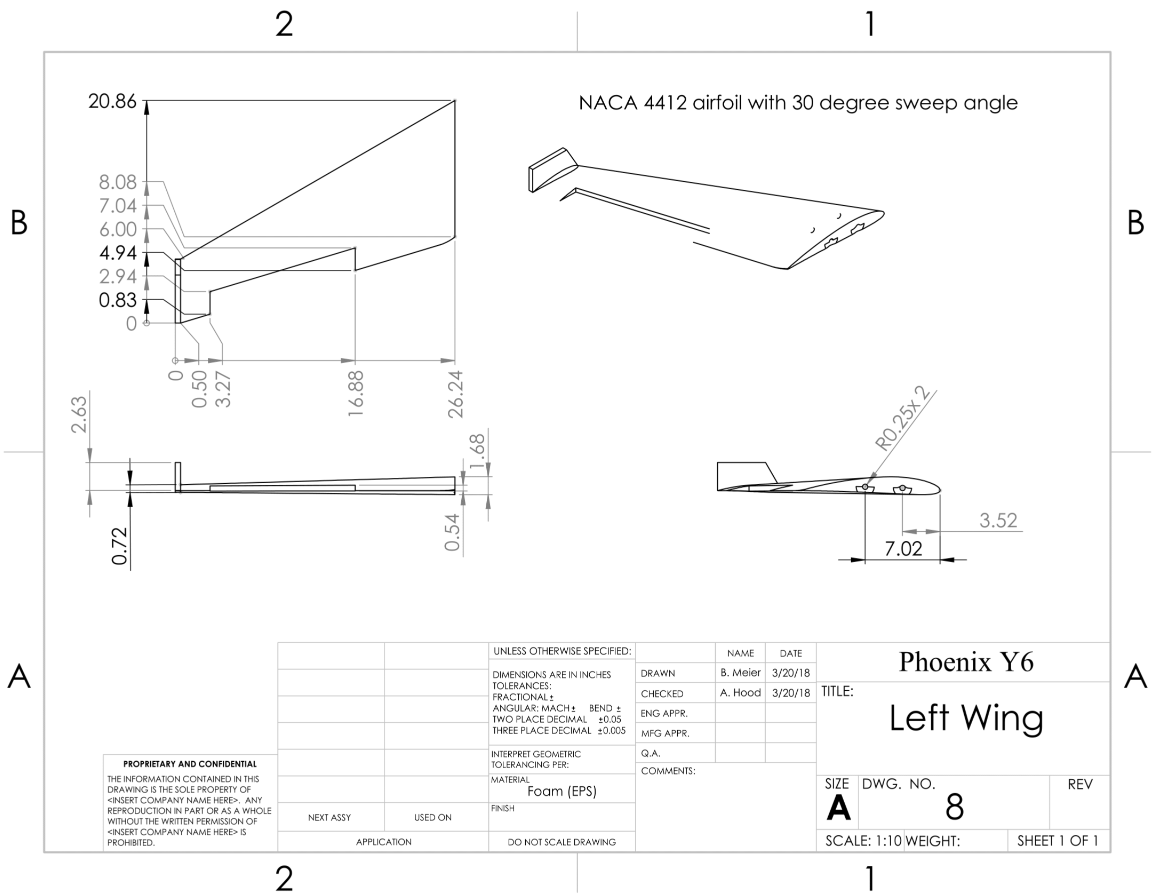


Figure 14: Left Wing

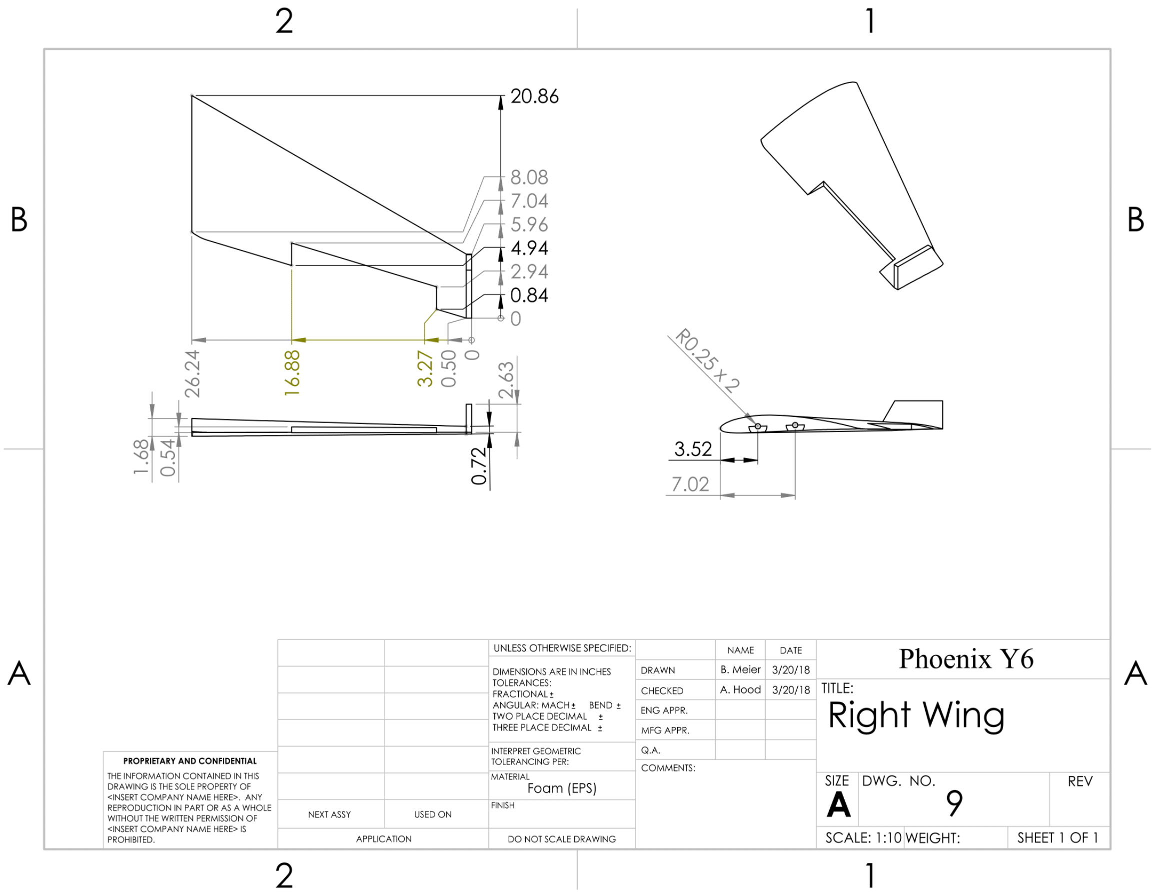


Figure 15: Right Wing

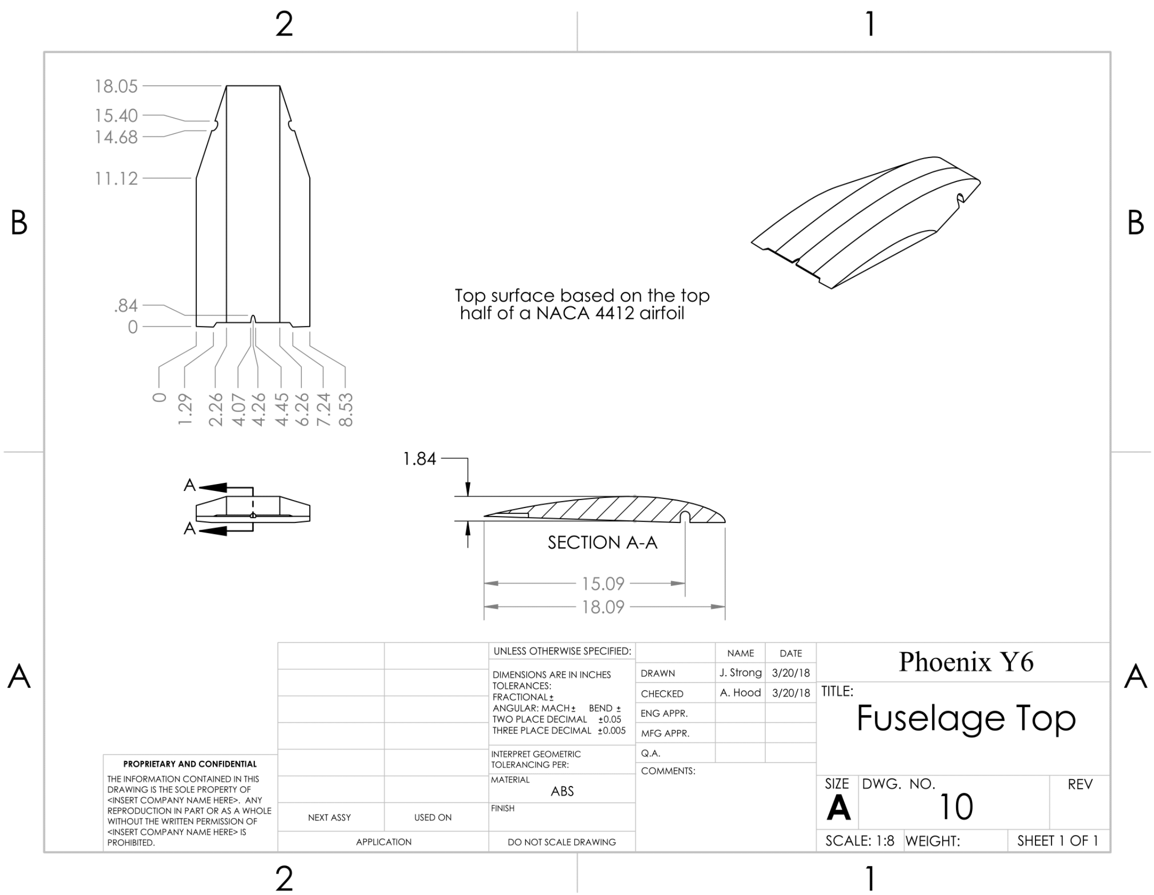


Figure 16: Fuselage Top

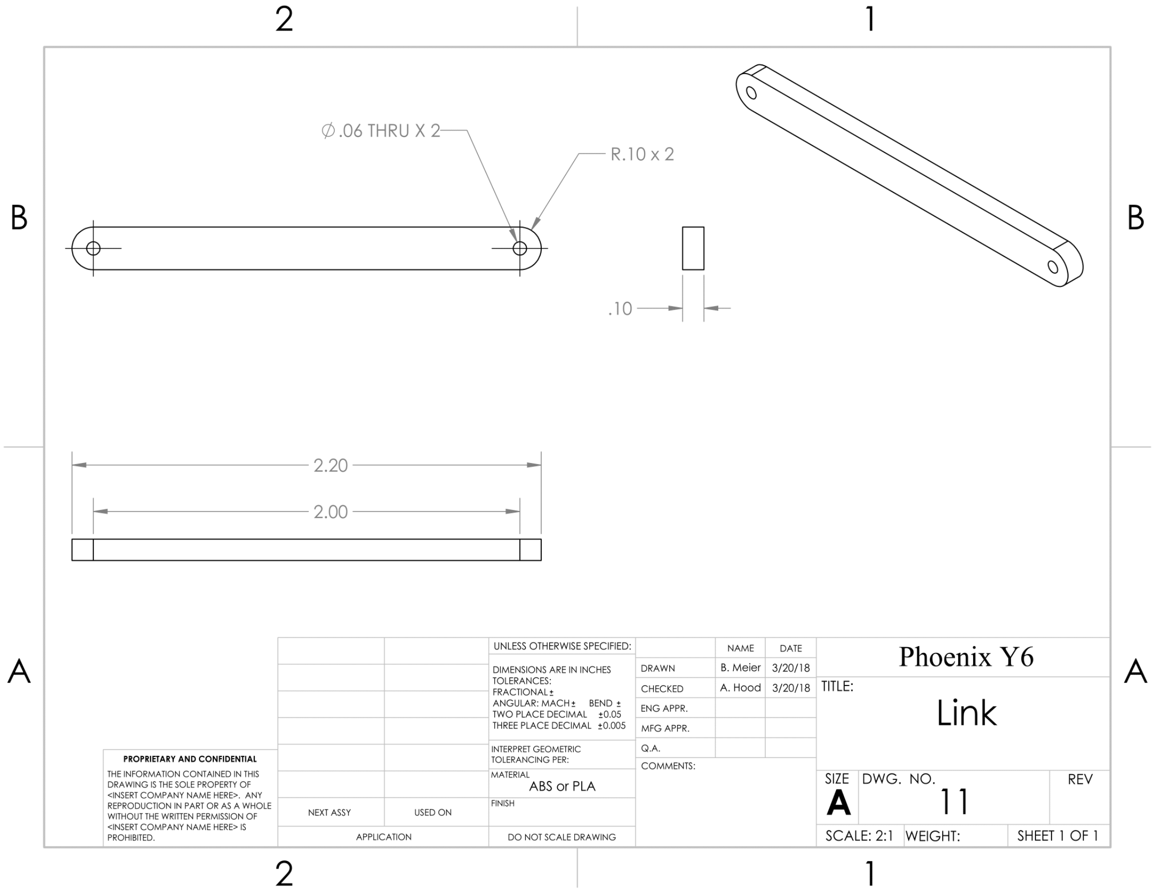


Figure 17: Servo-Front Axle Link

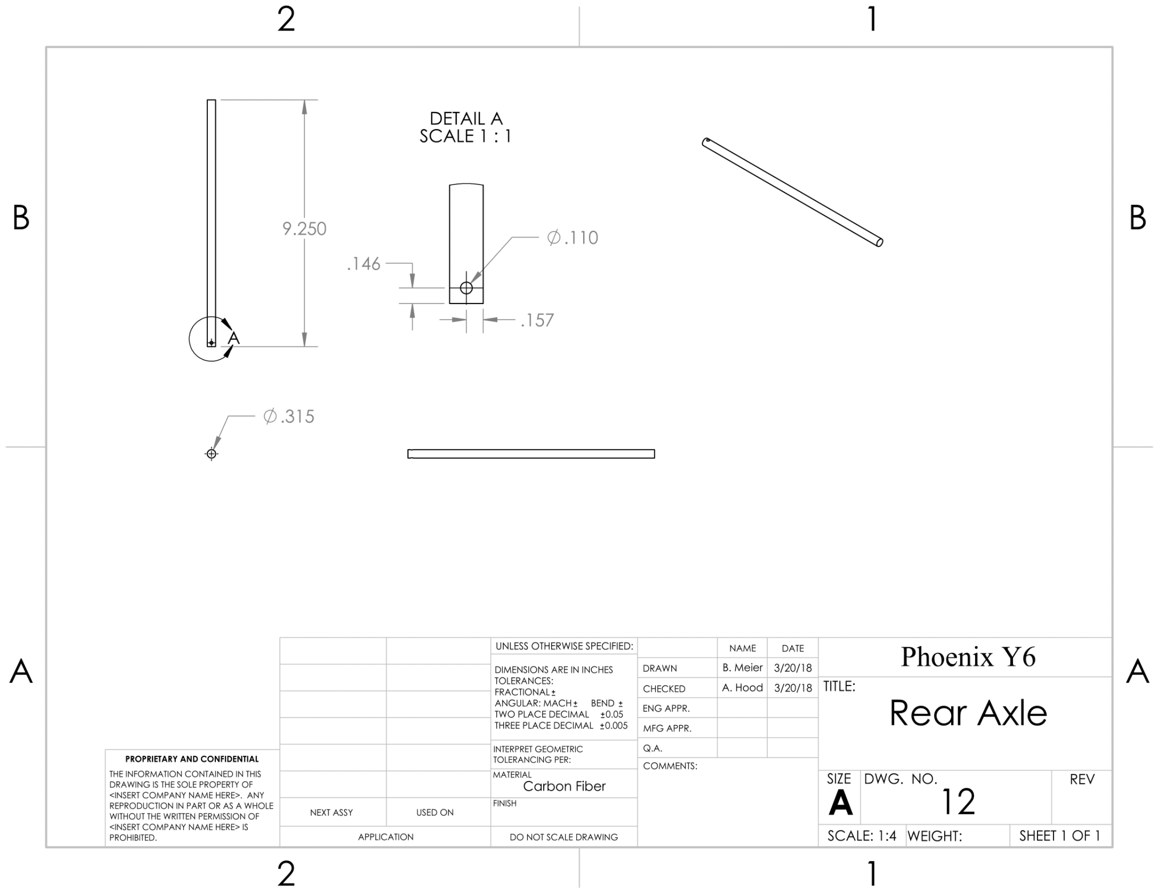


Figure 18: Rear Axle

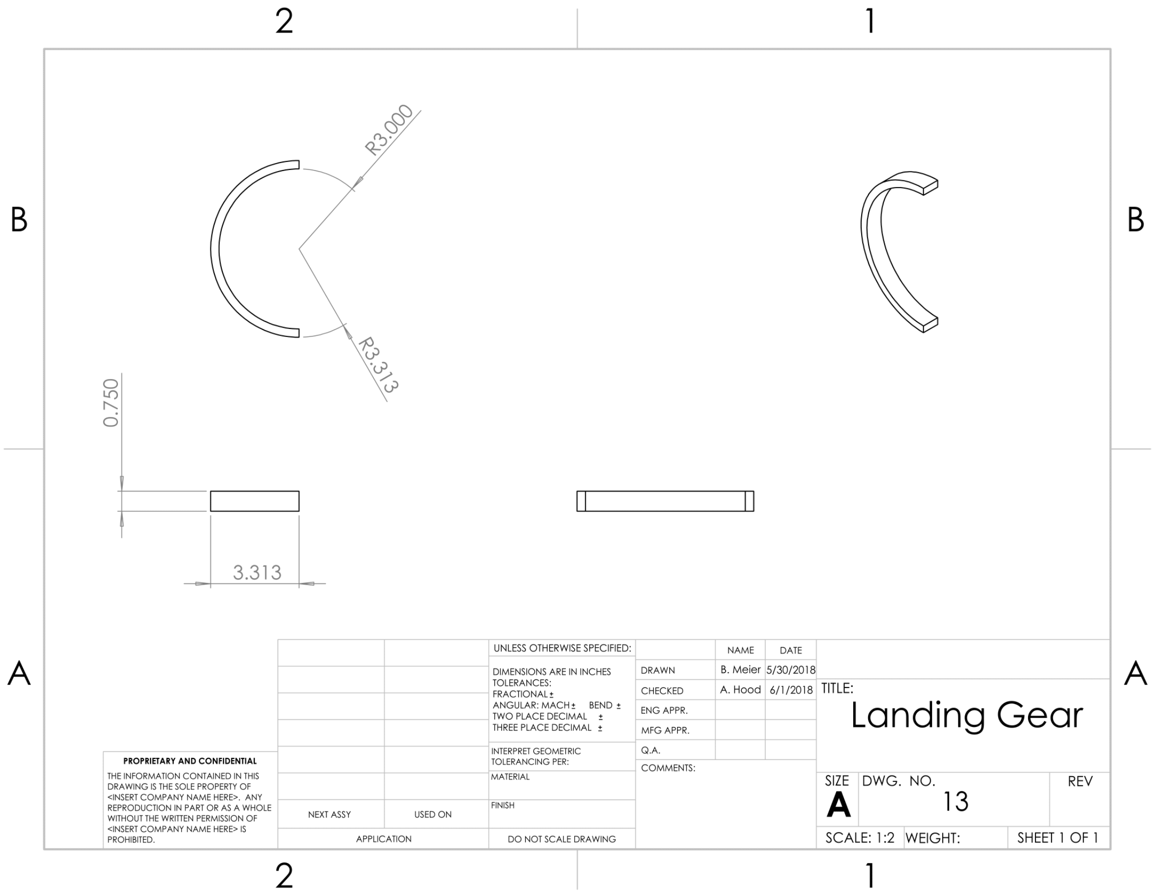
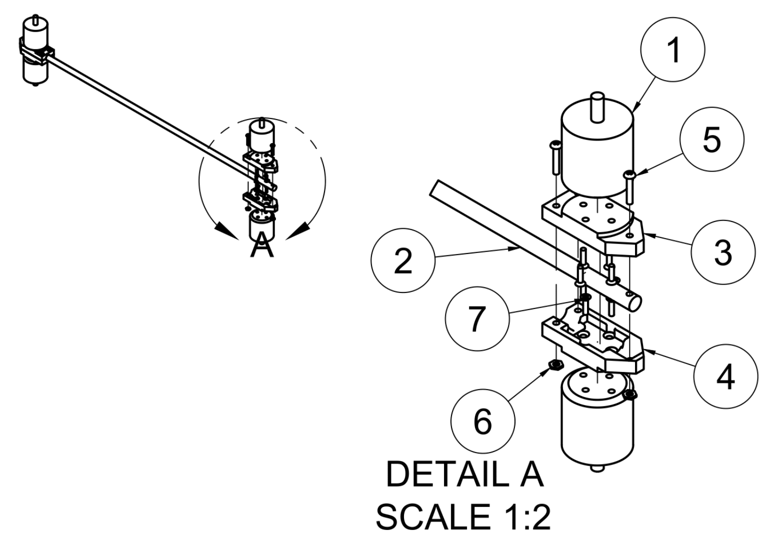


Figure 19: Landing Gear



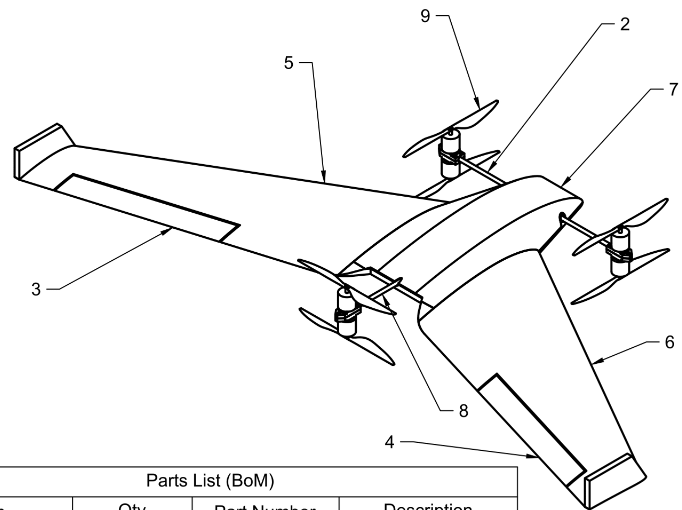
Parts List (BoM)			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	4	N/A	MS2216 Motor
2	1	4	Front Axle
3	2	5	Top Motor Mount
4	2	3	Bottom Motor Mount
5	6	N/A	#4 x 5/8 " screw
6	6	N/A	#4 nut
7	16	N/A	M3 x __ screw

PROJECT
Phoenix Y6

TITLE
Tiltrotor Assembly

APPROVED A. Hood 3/20/18	SIZE	CODE	DWG NO		REV
CHECKED	A		13		
DRAWN B. Iverson 2/11/2018	SCALE 1:6		WEIGHT	SHEET 1/1	

Figure 20: Tiltrotor Assembly



Parts List (BoM)			
Item	Qty	Part Number	Description
1	1	1	Fuselage Base
2	1	4	Front Axle
3	1	6	Left Elevon
4	1	7	Right Elevon
5	1	8	Left Wing
6	1	9	Right Wing
7	1	10	Fuselage Top
8	1	12	Rear Axle
9	2	13	Tiltrotor Assembly

Fuselage Base(under Fuselage Top) - 1

PROJECT
Phoenix Y6

TITLE
Phoenix Y6 Assembly

APPROVED A. Hood 3/20/18	SIZE A	CODE	DWG NO 14		REV
CHECKED					
DRAWN B. Meier 3/18/20	SCALE 1:8		WEIGHT 3.53 kg	SHEET 1/1	

Figure 21: Phoenix Y6 Assembly

C Flying wing design

Table 9: Comparison of goal design characteristics and estimated design characteristics

Component	Name	Quantity	Weight/unit (g)
Camera	GoPro Sessions	1	74.0
TIC	FLIR Lepton 3	1	0.9
GPS Controller	Pixhawk	1	60.0
Communications		1	80.0
Gimbal	TAROT gimbal	1	250.0
Motors	T Motor 1100 kV	6	75.0
Axle		1	5.0
ESC	30 A	6	50.0
Propeller	10 in. x 4 composite	6	21.0
Controller	3DR Pixhawk Mini	1	180.0
Receiver	Leftover from last year	1	5.8
Pitot tube	Pixhawk compatible airspeed sensor	1	18.0
Landing Gear	Custom	3	52.0
Elevon Servos	Servo motor	2	9.0
Tiltrotor servo	Servo motor	1	60.0
Battery	3 cell, 11.1 V	1	180.0
Raspberry Pi	Raspberry Pi	1	45.0
Wiring		1	60.0
Wifi module		1	45.0
Body, incl. supports		1	1000.0
		Net Weight:	3061.9

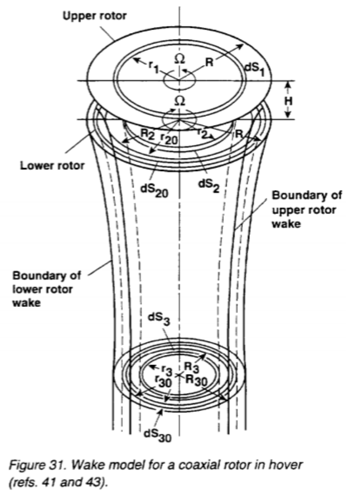


Figure 22: Wake model for coaxial contra rotating rotors

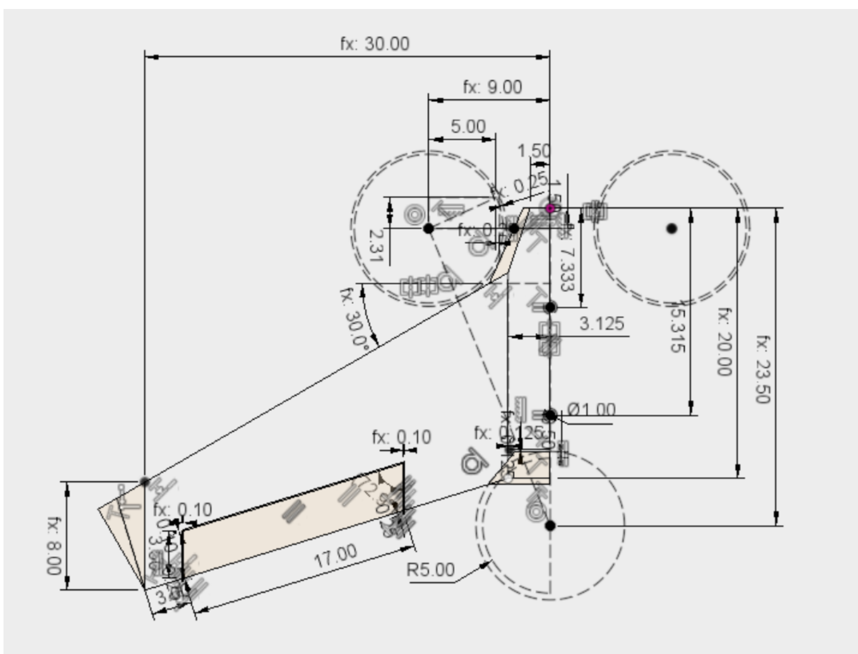


Figure 23: Layout of the geometry and constraints in the planform area.

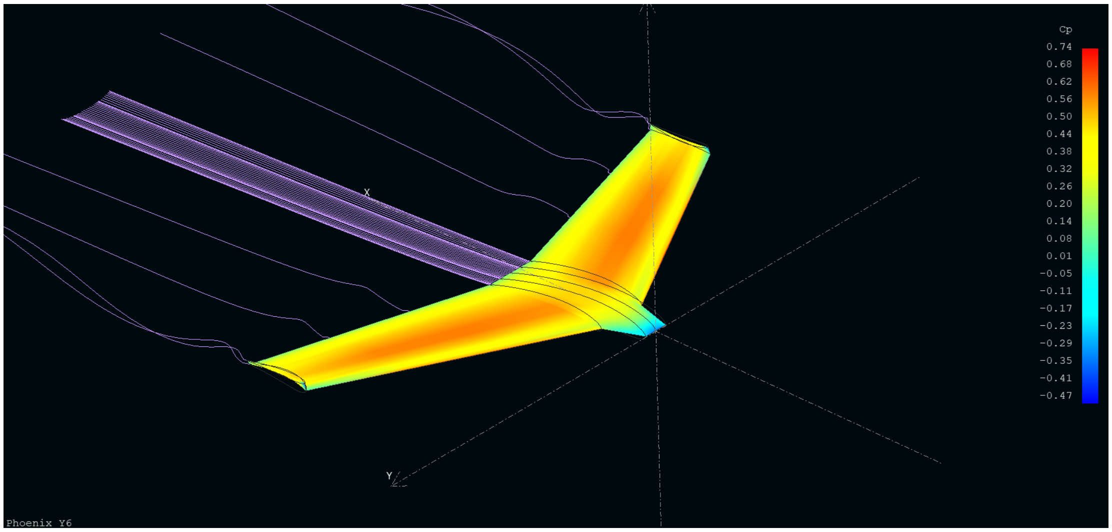


Figure 24: Visual representation of the XFLR5 analysis results on the body of the aircraft showing center of pressure on the aircraft represented by color and streamlines behind the aircraft.

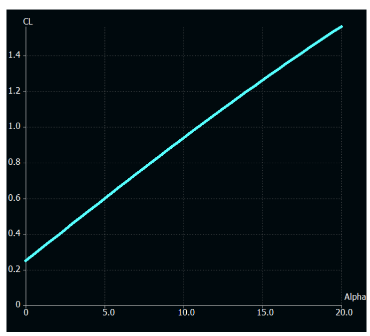


Figure 25: C_l vs. α for the body of the aircraft with 5' Span and 30° sweep produced in the XLFR5 modeling software.

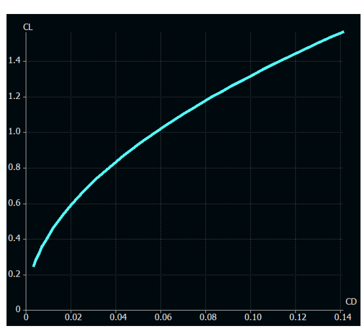


Figure 26: C_l vs. C_d for the body of the aircraft with 5' Span and 30° sweep produced in the XFLR5 modelling software.

Table 10: Aerodynamic coefficients are obtained for each node of a test matrix varying wing span and sweep angle

Test	1	2	3	4	5	6	7	8	9	10	11	12
Span (ft)	4	4	4	4	4.5	4.5	4.5	4.5	5	5	5	5
Sweep angle (deg)	20	25	30	35	20	25	30	35	20	25	30	35
C_l	0.81	0.81	0.81	0.80	0.94	0.94	0.93	0.91	1.06	1.06	1.04	1.02
C_d(body only)	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
S(ft^2)	3.12	3.16	3.21	3.25	3.47	3.53	3.57	3.62	3.83	3.88	3.96	4.00
ρ (slugs/ft^3)	2.38E-3	2.38E-3	2.38E-3	2.38E-3	2.38E-3	2.38E-3	2.38E-3	2.38E-3	2.38E-3	2.38E-3	2.38E-3	2.38E-3
Aspect ratio	5.1	5.1	5.0	4.9	5.8	5.	5.7	5.6	6.5	6.5	6.3	6.2
Min. speed (mph)	31.42	31.29	31.21	31.23	28.14	27.94	27.92	28.00	25.34	25.24	25.12	25.23
Lift (lbf)	14.81	14.81	14.81	14.81	14.81	14.81	14.81	14.81	14.81	14.81	14.81	14.81
Components weight	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17
Frame density (slugs/ft^3)	0.126	0.126	0.126	0.126	0.126	0.126	0.126	0.126	0.126	0.126	0.126	0.126
Frame volume (m^3)	0.21	0.23	0.23	0.23	0.26	0.26	0.26	0.26	0.28	0.28	0.28	0.28
Frame mass (slugs)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04
Net weight (lbf)	6.37	6.44	6.44	6.44	6.59	6.59	6.59	6.59	6.66	6.66	6.66	6.66
Lift/weight ratio	2.32	2.30	2.30	2.30	2.25	2.25	2.25	2.25	2.22	2.22	2.22	2.22

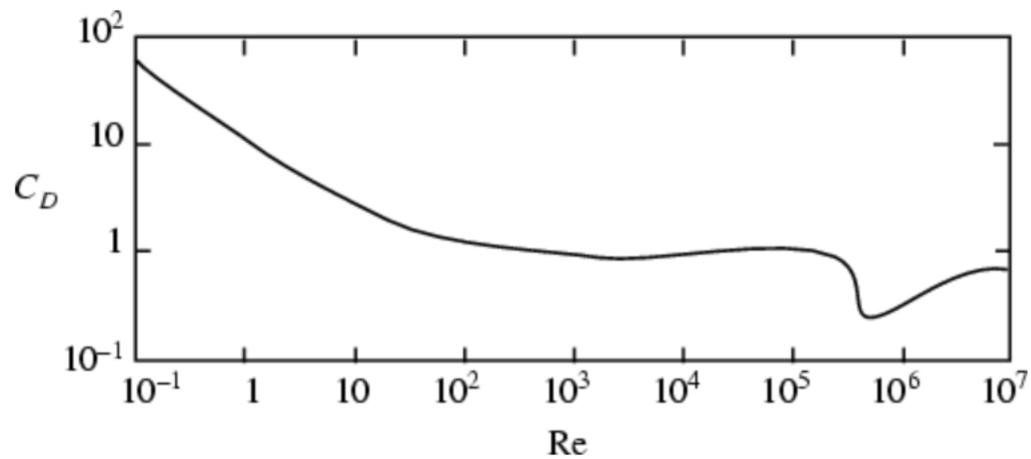


Figure 27: Plot of C_d vs. Re experimental results for a cylinder in fluid flow

D Product Design Specifications

Table 11: Product Design Specifications

Element	Units	Datum	Target Range
Production Cost	USD	2300	1500-2000
Retail Price	USD	5000	5000-6000
Operation Time	hours	1	1-2
Mass	kilograms	12	6-10
Top Speed	meters/second	17	11-15
Altitude	meters	60	70-80
Lift	Newtons	130	60-120
Lifetime	years	5	6-8
Charging Time	hours	0.25	0.15-0.20
Autonomy	percentage	50	semi-autonomous
Control System	type	controller	user operated hand controller
Target Consumer	type	Fire Departments	Cal Fire, emergency response organizations
Camera Resolution	pixels	4K	4k
Receiver Range	meters	300	2000-5000

E Timeline

- General design decisions - October 2017
- Material selections - October 2017
- Manufacturing methods - November 2017
- Hardware selection - November 2017
- Initial CAD model - November-December 2017
- Purchase hardware - January 2018
- Computational fluid dynamics analysis - January 2018
- Finite element analysis - January-February 2018
- Manufacture and construct vehicle - March 2018
- Iterate - March-April 2018
- Senior Design Conference presentation - May 2018
- Write and submit thesis - May-June 2018

F Budget

The budget for our prototype far exceeds what we expect a mass-manufactured model would cost. For the prototype, we needed to purchase multiple versions of certain sensors and motors to ensure top-of-the line compatibility and functionality. Our aircraft was designed to be purchased by emergency responders all over the country, so ideally all hardware components would be bought in bulk. This would reduce the overall cost of each individual product.

Our team received $2500 of funding from SCU Undergraduate Engineering and $500 from Xilinx. Once we had fully researched our project and made decisions on all major subsystems and hardware selections, we prepared the following budget proposal.

Table 12: Budget Proposal, Expenses

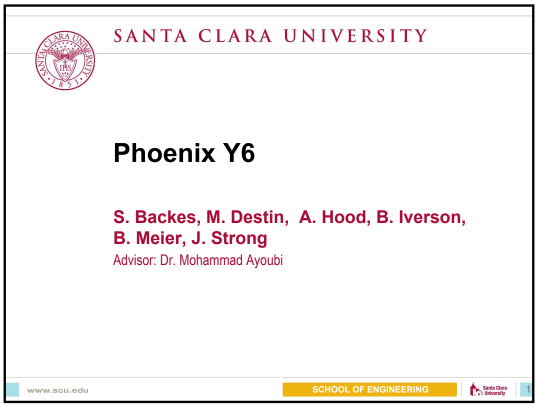
System	**Component**	**Description**	**Qty**	**Price/unit**	**Cost**
Controls	Flight controller	Pixhawk controller	1	$899.00	$899.00
	GPS	Included with pixhawk	1	$0.00	$0.00
	Kinematics sensor	Included with pixhawk	1	$0.00	$0.00
Electronics	Motors	Propulsion	6	$25.00	$150.00
	Battery	Power source	2	$50.00	$100.00
	ESCs	Motor control	6	$25.00	$150.00
	Servos	Tilting mechanism	2	$25.00	$50.00
	Actuators	Elevon control	3	$20.00	$60.00
	Camera	GoPro for visual data	1	$200.00	$200.00
	Fire Sensors	Cameras	1	$200.00	$200.00
	Transmitter/Receiver	For manual control	1	$100.00	$100.00
Body	Propellers	Propulsion	6	$10.00	$60.00
	Frame	Components Housing	1	$200.00	$200.00
General	Licensing	FAA regulations	2	$150.00	$300.00
	AMA Licensing	MAA insurance	1	$50.00	$50.00
	Travel	Transportation	5	$20.00	$100.00
	References	Textbook(s)	1	$79.00	$79.00
Total					**$2,698.00**

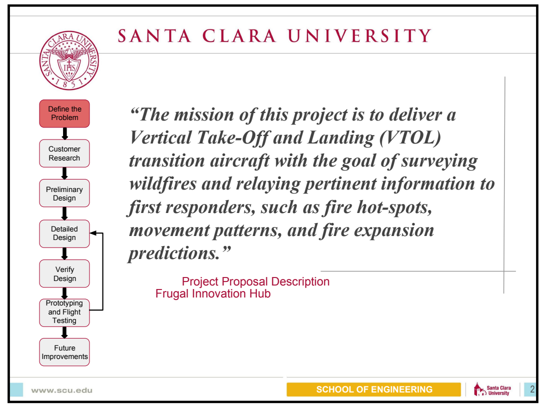
G Experimental Data

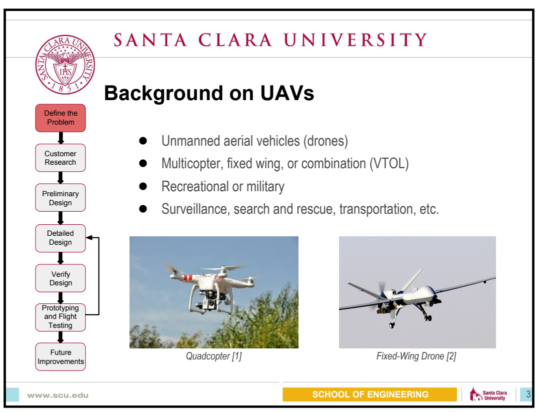
Unfortunately, we were not able to perform extensive testing on Phoenix Y6 due to time constraints and liability reasons. We were able to mount Phoenix Y6 to a gimbal with one degree of freedom to demonstrate communication between our transmitter and the receiver, as the drone responded to manual input. This test showed Phoenix Y6's ability to adjust its pitch and roll to stabilize itself, as well as its ability to transition from vertical to horizontal flight. In addition, we were able to demonstrate a flight time of 18 minutes with the motors at full throttle. Our estimated flight time for hover conditions, which occurs are roughly half throttle, was 24 minutes. Therefore, our flight time is deemed to have exceeded expectations. However, this flight time in dynamic testing would likely be different, as drag and lift would be introduced into the system.

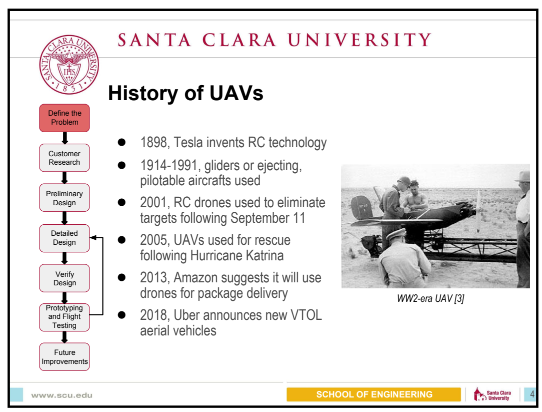
Given more time and permission to transition to dynamic testing, we would run tethered dynamic tests in the SCU Robotics Systems Laboratory's warehouse, then untethered, short range dynamic tests in the same warehouse, then fully dynamic tests at an approved outdoor location. These tests would allow us to determine a true maximum speed and flight time for the drone, as well as to establish the drone's true range. Furthermore, we would be able to tune our controls system to optimize the flight capability of the vehicle.

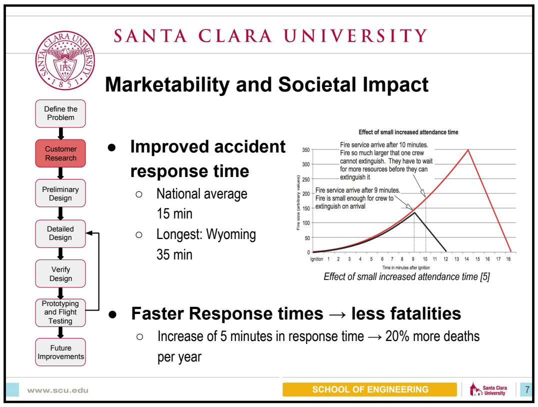
H Senior Design Conference Presentation Slides







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Marketability and Societal Impact
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
Improved accident response time
National average 15 min
Longest: Wyoming 35 min
Effect of small increased attendance time
Effect of small increased attendance time [5]
Faster Response times → less fatalities
Increase of 5 minutes in response time → 20% more deaths per year
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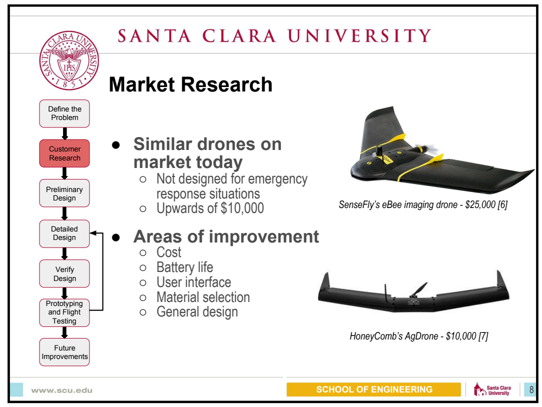
SANTA CLARA UNIVERSITY
Market Research
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
Similar drones on market today
Not designed for emergency response situations
Upwards of $10,000
Areas of improvement
Cost
Battery life
User interface
Material selection
General design
SenseFly's eBee imaging drone - $25,000 [6]
HoneyComb's AgDrone - $10,000 [7]
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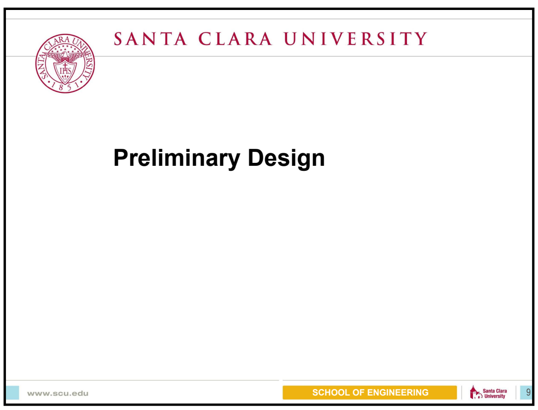
SANTA CLARA UNIVERSITY
Preliminary Design
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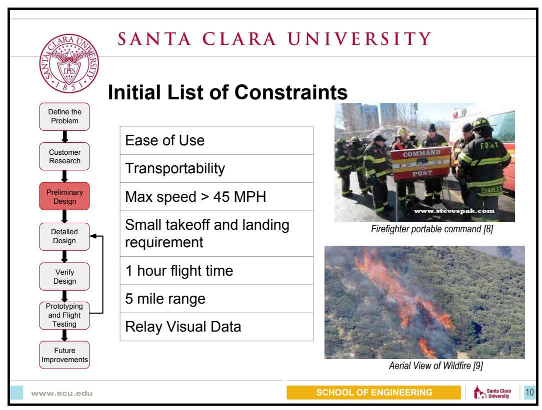
SANTA CLARA UNIVERSITY
Initial List of Constraints
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
Ease of Use
Transportability
Max speed > 45 MPH
Small takeoff and landing requirement
1 hour flight time
5 mile range
Relay Visual Data
Firefighter portable command [8]
Aerial View of Wildfire [9]
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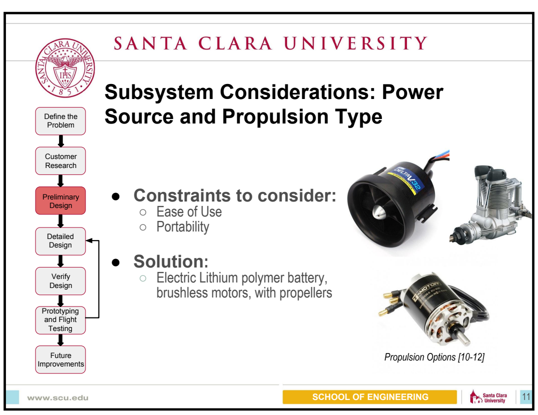
SANTA CLARA UNIVERSITY
Subsystem Considerations: Power Source and Propulsion Type
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
Constraints to consider:
Ease of Use
Portability
Solution:
Electric Lithium polymer battery, brushless motors, with propellers
Propulsion Options [10-12]
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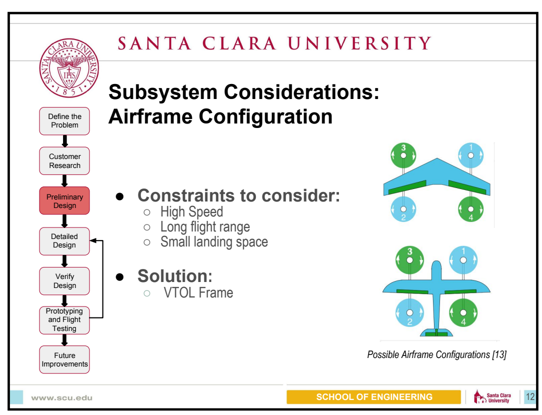
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Subsystem Considerations: Airframe Configuration
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
Constraints to consider:
High Speed
Long flight range
Small landing space
Solution:
VTOL Frame
Possible Airframe Configurations [13]
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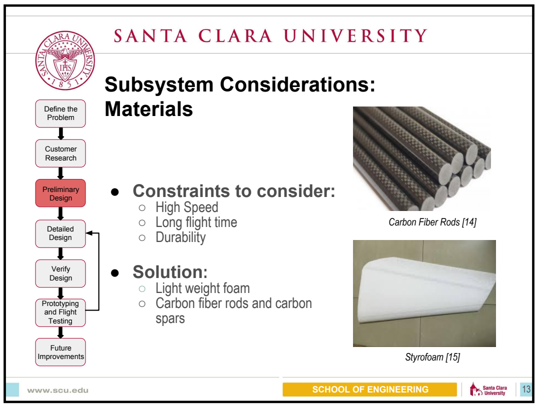
SANTA CLARA UNIVERSITY
Subsystem Considerations: Materials
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
Constraints to consider:
High Speed
Long flight time
Durability
Solution:
Light weight foam
Carbon fiber rods and carbon spars
Carbon Fiber Rods [14]
Styrofoam [15]
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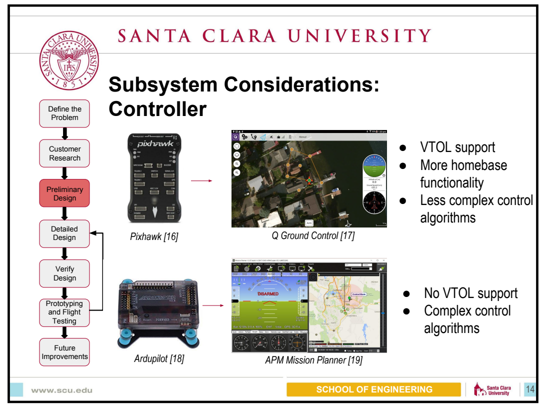
SANTA CLARA UNIVERSITY
Subsystem Considerations: Controller
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
Pixhawk [16]
Q Ground Control [17]
VTOL support
More homebase functionality
Less complex control algorithms
Ardupilot [18]
APM Mission Planner [19]
No VTOL support
Complex control algorithms
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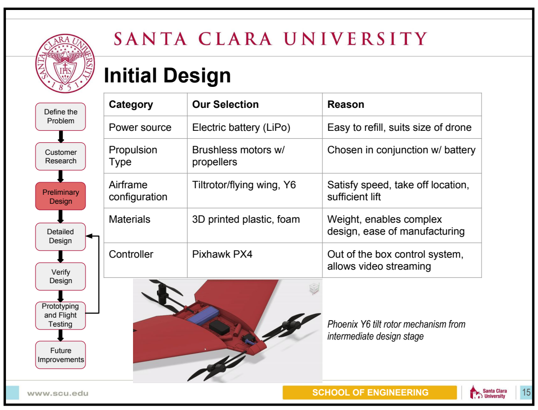
SANTA CLARA UNIVERSITY
Initial Design
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
Category | Our Selection | Reason
Power source | Electric battery (LiPo) | Easy to refill, suits size of drone
Propulsion Type | Brushless motors w/ propellers | Chosen in conjunction w/ battery
Airframe configuration | Tiltrotor/flying wing, Y6 | Satisfy speed, take off location, sufficient lift
Materials | 3D printed plastic, foam | Weight, enables complex design, ease of manufacturing
Controller | Pixhawk PX4 | Out of the box control system, allows video streaming
Phoenix Y6 tilt rotor mechanism from intermediate design stage
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Detailed Design
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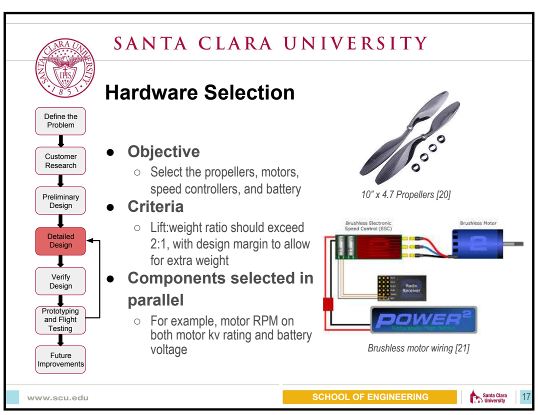
SANTA CLARA UNIVERSITY
Hardware Selection
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
Objective
Select the propellers, motors, speed controllers, and battery
Criteria
Lift:weight ratio should exceed 2:1, with design margin to allow for extra weight
Components selected in parallel
For example, motor RPM on both motor kv rating and battery voltage
10" x 4.7 Propellers [20]
Brushless motor wiring [21]
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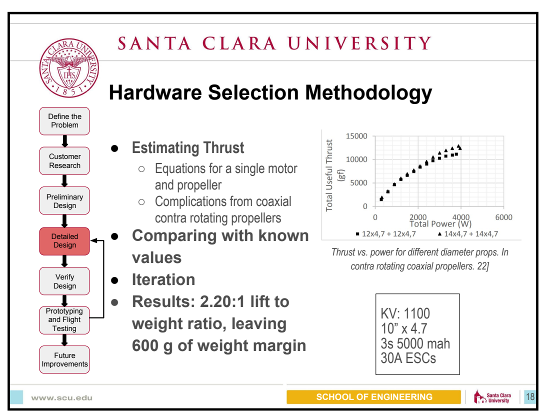
SANTA CLARA UNIVERSITY
Hardware Selection Methodology
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
Estimating Thrust
Equations for a single motor and propeller
Complications from coaxial contra rotating propellers
Comparing with known values
Iteration
Results: 2.20:1 lift to weight ratio, leaving 600 g of weight margin
Total Useful Thrust (gf)
Total Power (W)
Thrust vs. power for different diameter props. In contra rotating coaxial propellers. 22]
KV: 1100
10" x 4.7
3s 5000 mah
30A ESCs
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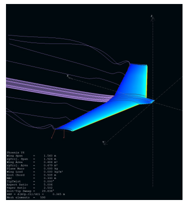
Computational Fluid Dynamics (CFD)

Define the Problem → Customer Research → Preliminary Design → Detailed Design → Verify Design → Prototyping and Flight Testing → Future Improvements

- Objective
  - Aerodynamic coefficients for FEA and controls theory
- Test matrix
  - Understanding how lift and weight change with span and sweep
  - How position of center of lift changes with sweep
  - 60", 30 deg
- Validation of results
  - Well within an order of magnitude


XFLR 5 CFD Model of the Body with Streamlines

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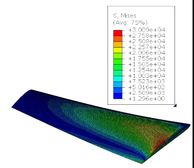
Structural Finite Element Analysis Stress

Define the Problem → Customer Research → Preliminary Design → Detailed Design → Verify Design → Prototyping and Flight Testing → Future Improvements

- Intention: Verify Strength
- Results:

Von Mises Stress [Kpa]	Flexural Strength [Kpa]
30	207

- Assumptions: Fixed wing base


Von Mises Stress in Phoenix Y6 Wing

Design result: Energy transfer spars

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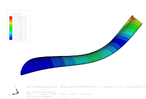
Natural Frequencies

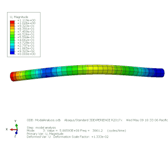
Define the Problem → Customer Research → Preliminary Design → Detailed Design → Verify Design → Prototyping and Flight Testing → Future Improvements

- Intention: Avoid Resonance from motors (12,000 RPM → <200Hz)
- Results: Mode Shapes

Wing [Hz]	Rod [Hz]
6	632
24	632
39	3861
45	3861
55	8923

- Fn Rod >> Motor Excitation
- Fn Wing ~ Motor Excitation


Second Mode Shape Of Wing


Second Mode Shape Of Rod

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Final Design

Define the Problem → Customer Research → Preliminary Design → Detailed Design → Verify Design → Prototyping and Flight Testing → Future Improvements


Rendering of final design produced in Fusion 360 modeling software.

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Verify Design

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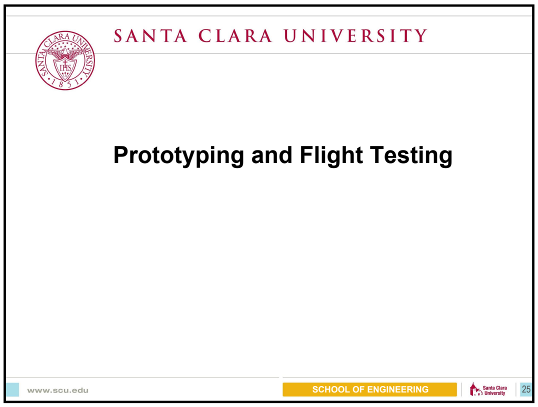
Theoretical Evaluation of Design

Define the Problem → Customer Research → Preliminary Design → Detailed Design → Verify Design → Prototyping and Flight Testing → Future Improvements

Design Criteria	Objective	Estimated value
Take off in small area	Multirotor mode satisfies this	
As fast a response as possible	> 45 mph	60 mph using plane mode.
Transportable	Can fit in a large suitcase	60'', detachable wings
Multirotor flight time	20 min	24 min
Maximum flight distance	25 miles, leave margin	50 miles
Ease of use	Semi autonomy through QGroundControl	
Video Streaming	Streams actively stabilized video directly into QGroundControl	


Phoenix Y6 Model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Prototyping and Flight Testing
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Materials and Manufacturing Techniques
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
Wings
Laser cutting (Naca 4412)
Hot wire cutting
Fuselage Base
3D Printing, ABS
Fuselage Cover
Vacuum Forming
Vacuum Former
Ultimaker 3D Printer
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Control System Overview
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
Pixhawk controller
PX4 (VTOL tiltrotor)
QGroundControl
Yaw
Roll
Pitch
Q Ground Control [17]
Rotational Axes on Body-Fixed Frame of Phoenix Y6
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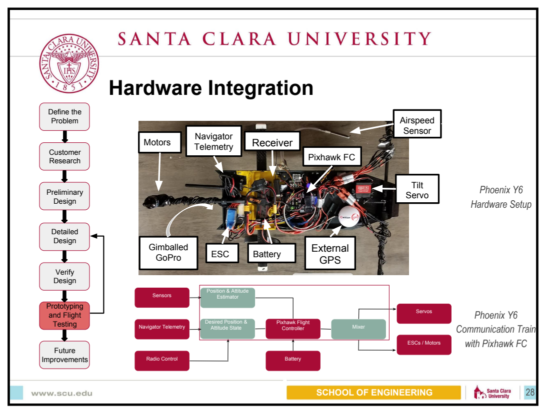
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Hardware Integration
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
Motors
Navigator Telemetry
Receiver
Pixhawk FC
Airspeed Sensor
Tilt Servo
Gimballed GoPro
ESC
Battery
External GPS
Phoenix Y6 Hardware Setup
Sensors
Navigator Telemetry
Radio Control
Pixhawk Flight Controller
Mixer
Servos
ESCs / Motors
Battery
Phoenix Y6 Communication Train with Pixhawk FC
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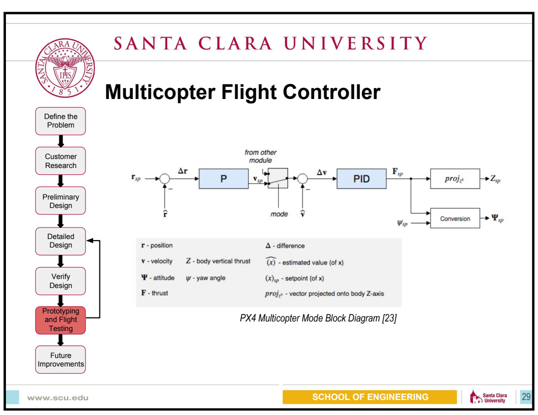
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Multicopter Flight Controller
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
P
PID
Conversion
from other module
mode
r - position
v - velocity
Z - body vertical thrust
Ψ - attitude
ψ - yaw angle
F - thrust
Δ - difference
estimated value (of x)
setpoint (of x)
vector projected onto body Z-axis
PX4 Multicopter Mode Block Diagram [23]
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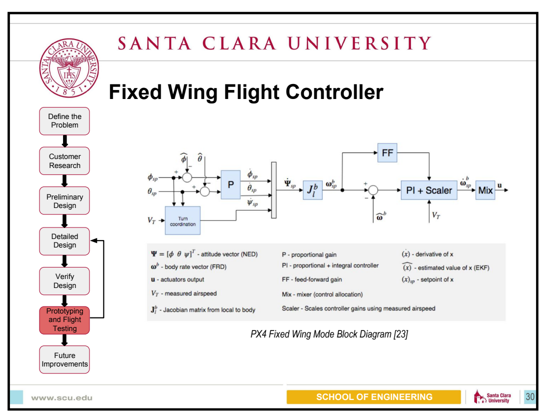
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Fixed Wing Flight Controller
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
FF
P
PI + Scaler
Mix
P - proportional gain
PI - proportional + integral controller
FF - feed-forward gain
Mix - mixer (control allocation)
Scaler - Scales controller gains using measured airspeed
PX4 Fixed Wing Mode Block Diagram [23]
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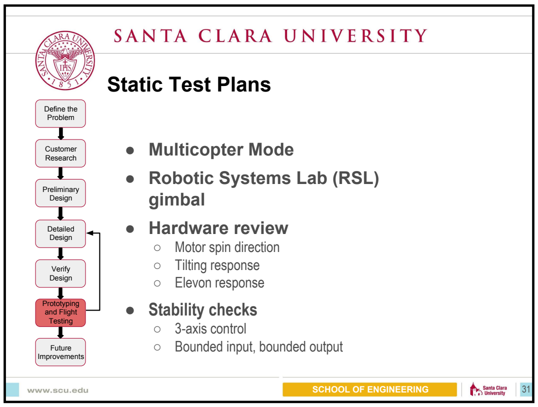
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Static Test Plans
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
● Multicopter Mode
● Robotic Systems Lab (RSL) gimbal
● Hardware review
○ Motor spin direction
○ Tilting response
○ Elevon response
● Stability checks
○ 3-axis control
○ Bounded input, bounded output
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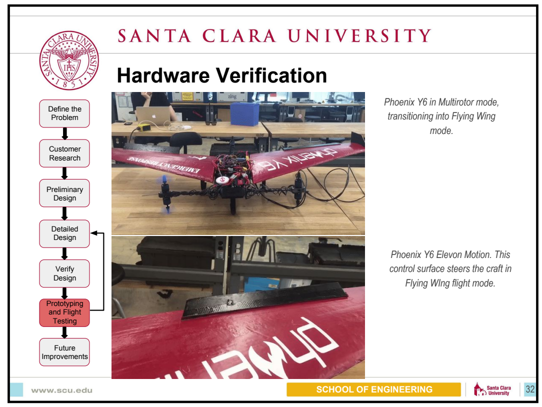
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Hardware Verification
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
Phoenix Y6 in Multirotor mode, transitioning into Flying Wing mode.
Phoenix Y6 Elevon Motion. This control surface steers the craft in Flying Wing flight mode.
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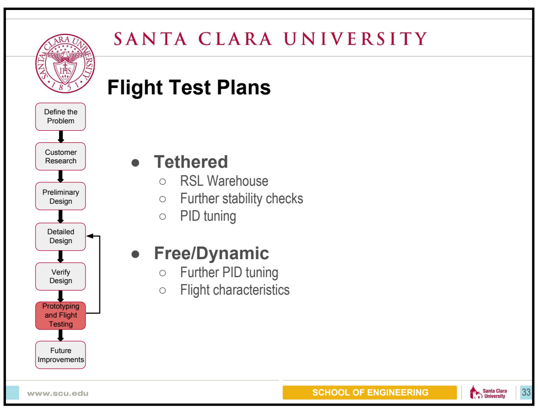
SANTA CLARA UNIVERSITY
Flight Test Plans
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
● Tethered
○ RSL Warehouse
○ Further stability checks
○ PID tuning
● Free/Dynamic
○ Further PID tuning
○ Flight characteristics
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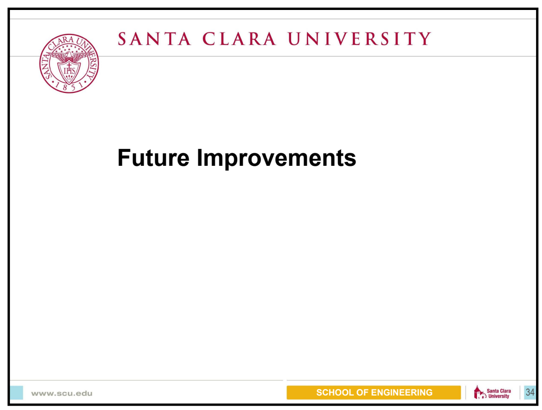
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Future Improvements
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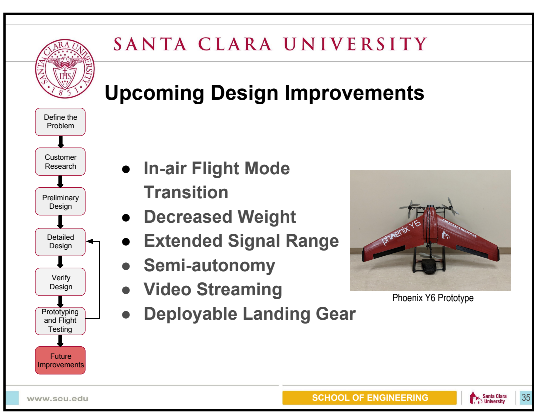
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Upcoming Design Improvements
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
● In-air Flight Mode Transition
● Decreased Weight
● Extended Signal Range
● Semi-autonomy
● Video Streaming
● Deployable Landing Gear
Phoenix Y6 Prototype
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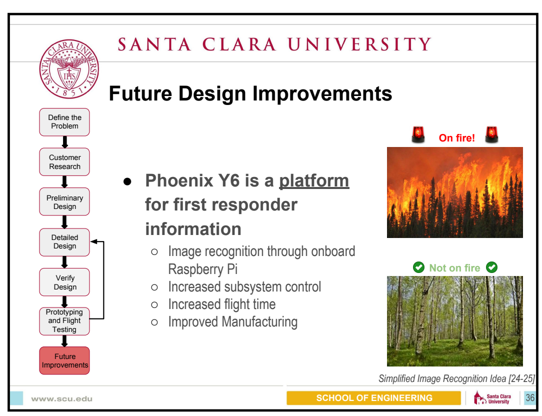
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Future Design Improvements
Define the Problem
Customer Research
Preliminary Design
Detailed Design
Verify Design
Prototyping and Flight Testing
Future Improvements
● Phoenix Y6 is a platform for first responder information
○ Image recognition through onboard Raspberry Pi
○ Increased subsystem control
○ Increased flight time
○ Improved Manufacturing
On fire!
Not on fire
Simplified Image Recognition Idea [24-25]
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Summary

- Designed and fabricated a VTOL fixed wing drone for emergency response
- Relays situational information
- Semi-autonomous
- Maximum speed: 60 mph
- Maximum range: 25 mi (.5 flight distance)
- Portability through detachable wings

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Acknowledgements

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- Dr. Michael Taylor
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- Sean and Pat Lanthier
- Palo Alto Fire Department
- SCU Undergraduate School of Engineering
- Xilinx

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Questions?

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Images Sourced

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Thank you!

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Controls Theory

$$M\dot{x} = Fx + Gu \quad (4.1)$$

$$\begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{r} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} Y_v & Y_p & Y_r & g\cos\Theta_0 \\ L_v & L_p & L_r & 0 \\ N_v & N_p & N_r & 0 \\ 0 & 1 & \tan\Theta_0 & 0 \end{bmatrix} \begin{bmatrix} v \\ p \\ r \\ \phi \end{bmatrix} + \begin{bmatrix} Y_{\delta_a} & Y_{\delta_r} \\ L_{\delta_a} & L_{\delta_r} \\ N_{\delta_a} & N_{\delta_r} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix} \quad (4.2)$$

$$\begin{bmatrix} v \\ p \\ r \\ \phi \\ a_y \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ Y_v & Y_p & Y_r & 0 \end{bmatrix} \begin{bmatrix} v \\ p \\ r \\ \phi \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ Y_{\delta_a} & Y_{\delta_r} \end{bmatrix} \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix} \quad (4.3)$$

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Video Streaming

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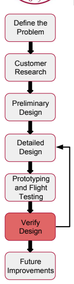
Budget



- $2500 from Santa Clara University
- $500 Xilinx

Electronics Hardware	$1,240
Body	$120

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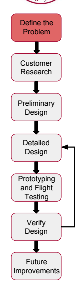
Objective Statement



Our mission is to design and fabricate a vertical take-off and landing (VTOL) fixed-wing drone for use by firefighters and emergency services. Our goal is to develop a working prototype that will be able to collect and relay important information such as live video and thermal images in addition to measurements of air velocity and humidity.

(**need to update**)

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