UC-KSU Modular UAS Design

Team:

KSU UAS Design Team

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Sponsor Company:

United Consulting

Executive Summary

The objective of this project was to design and build a modular unmanned aerial system (UAS) that satisfies the requirements established by United Consulting. United Consulting provides expert consulting engineering and geotechnical services for the built environment. They are partnering with Kennesaw State University to develop new technologies that will enhance and innovate the construction environment. One example of these technologies includes a modular drone. The purpose of this drone is to be able to perform four missions. These include surveying, weld inspection, manhole probing, and thermal/infrared imaging. Key requirements were that the drone must maintain a minimum flight endurance of 30 minutes for the heaviest mission, have a connection range of a minimum of 1 mile, and can support modular equipment. The maximum budget for this project is $5000.00.

The design of this modular drone required extensive literature review and benchmarking of existing drones to study and learn from the drones that are currently on the market. In addition, careful research was done on the selection of electronic components to ensure quality, reliability, and compatibility. Calculations for power, weight, flight endurance were performed to ensure the drone would perform as intended. FEA static simulations were performed to ensure structural stability of key parts. Also, connectivity and compatibility between electronic components were ensured. This progress has led to the design of a scaled 3D printed prototype.

Ultimately, the goal is to fabricate and test a real prototype with the proper equipment and modules. Due to the overall expertise of the team and time constraints, this was not possible to meet in the Fall 2021 semester. A final report detailing electronic selections, design of key systems like the main drone, pulley system and mount system, wiring diagram, calculations, simulations, and fabrication procedure are provided.

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Chapter 1: UAS for Surveying, Thermal Imaging, and Air Quality Testing

1.1 Introduction:

The objective of this project is to design and build a UAS system prototype that will replace the human aspect in dangerous and inefficient construction work. This UAS will be designed to meet the functional and physical requirements of United Consulting and their engineers. Despite the many existing drones, this design will fulfill the requirements specific to United Consulting.

The UAS will be required to meet three major design requirements – 30-minute flight endurance, 1,610-meter minimum flight communication range, and the ability to support different modular equipment to perform specific missions. In addition, this UAS is comprised of 3 major systems which are further comprised of sub-systems. The major systems include the UAS, mount system, and pulley system. The UAS system can be divided into two categories: frame components and electrical components. The frame components are components that make up the overall design of the frame of the UAS. These include the main body, boom, landing gear, motor housing, and frame cover. These components will be used to hold all the electrical components as well as the other two major systems. The electrical components are important to make the UAS fly and communicate with the pilot. The weight, structure, and cost of the systems is analyzed, using useful aircraft design and helicopter theory equations, FEA analysis, and literature review. Construction of the final prototype was in the initial schedule, but due to limited time and overall experience of the team, a detailed written report and a 3D printed prototype is used as the submission in this project.

1.2 System Overview:

United Consulting provided a description of the type of system they are expecting as follows: conduct visual inspections of buildings utilizing photo and video functions, ability to carry discrete sampling equipment, support different camera types for potential thermal and infrared uses, size is small for normal vehicle transport, and a minimum 30-minute flight time capability.

1.3 Objective:

The primary objectives of this project are to design, analyze, and 3D print the UAS. To consider this project as successful, the design must meet design requirements stated in section 3.2. A sample of requirements include but are not limited to a minimum flight time of 30 minutes, a minimum transmission range of 1,610 meters, and capability to carry discrete sampling equipment such as multi-RAE PGM-6228 and LandTec GEM 5000.

1.4 Justification:

The motivation behind this project is initially inspired by our client. United Consulting looks forward to partnering with Kennesaw State University in developing new technologies to enhance and innovate the construction, environmental, and inspection industry. These enhancements can increase productivity, save time and money, and enhance clientele experience and the product they receive.

One project believed to accomplish this is a UAS that can conduct multiple modular tasks. Although there are existing drones that can perform certain missions, this UAS will be tailored to complete specific missions to United Consulting. In addition, concerns of propwash affecting data of the sampling equipment leads to a need to design a drone capable of being an improvement to current existing UAS.

1.5 Mission Profile:

The KSU-UC UAS has multiple mission profiles depicting each mission. Each profile consists of takeoff, climb, cruise/observe, descend, and land phases. These phases will depict when the mission is expected to be performed. The mission profile is represented visually in the figures below.

Table 1. Mission 1 UAS Performance Parameters and Information

Parameter	Performance Value
Objective	Surveying
Weight	5666.26g
Endurance	41.3 minutes
Range	1,610 m
Modular Equipment	No additional equipment required

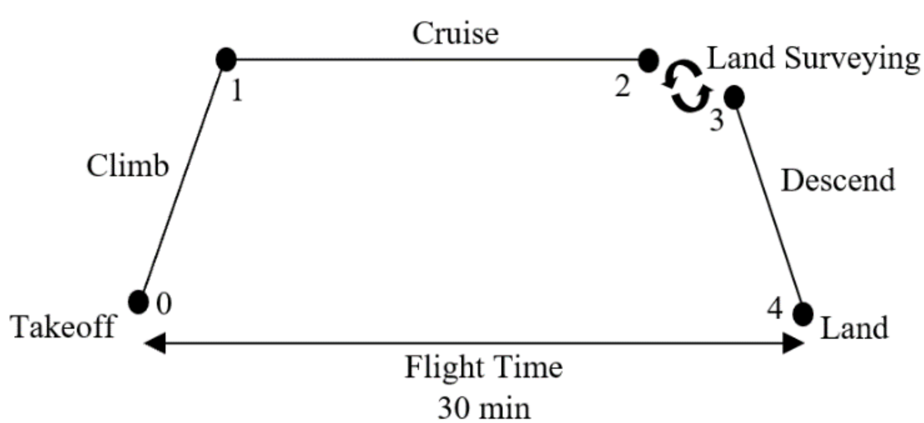

Figure 1. Mission Profile of Proposed UAS for Surveying Mission

The surveying mission will be one of the missions without any added components and can be performed by the baseline drone. The requirements for this mission include the camera view, transmission range, and flight endurance.

Table 2. Mission 2 UAS Performance Parameters and Information

Parameter	Performance Value
Objective	Weld Inspection
Weight	5666.26g
Endurance	41.3 minutes
Range	1,610 m
Modular Equipment	No additional equipment required

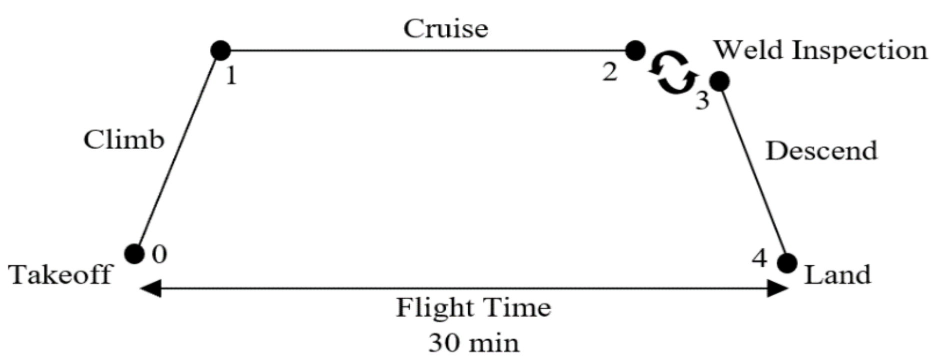

Figure 2. Mission Profile of Proposed UAS for Weld Inspection

The weld inspection mission is the second mission to use only the baseline drone. Similarly, to the surveying mission, this mission needs only a camera for live stream viewing. In addition, the gimbal holding the camera will feature a tilt mechanism that is useful to inspect welds below and above the drone. This feature will be available for all missions.

Table 3. Mission 3 UAS Performance Parameters and Information

Parameter	Performance Value
Objective	Manhole Probing
Weight	LandTec: 7693.85g MultiRAE: 6927.85g
Endurance	LandTec: 26.1 minutes

	MultiRAE: 30.5 minutes
Range	1,610 m
Modular Equipment	Mount System, Pulley System, Sampling Equipment (MultiRAE or LandTec GEM)

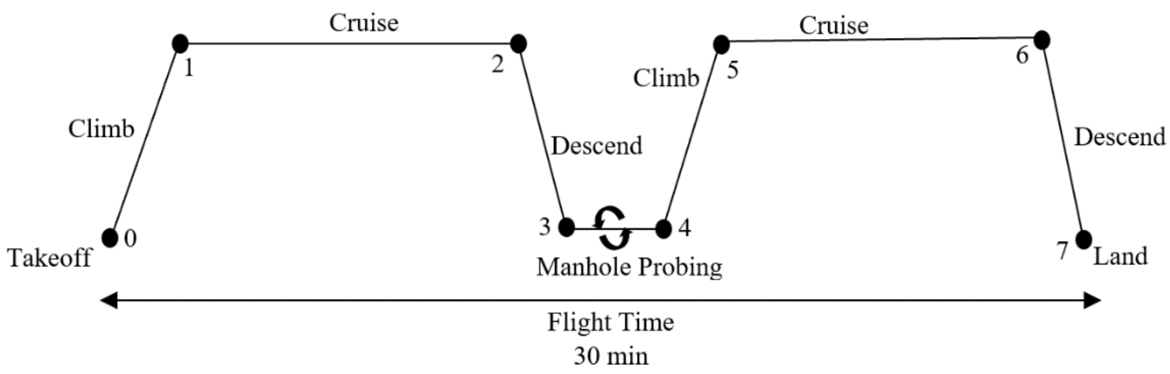

Figure 3. Mission Profile of Proposed UAS for Manhole Probing Mission

The manhole probing mission is the most complex of the four main missions due to the number of equipment needed to perform it. The mounting system will attach one of the two air quality testing devices, the LandTec or the MultiRAE. It will also include the pulley system to lower the probe over the manhole. Due to the significant addition of the modular equipment, this mission will be the heaviest out of all.

Table 4. Mission 4 UAS Performance Parameters and Information

Parameter	**Performance Value**
Objective	Thermal/Infrared Imaging
Weight	5972.8g
Endurance	38.1 minutes
Range	1,610 m
Modular Equipment	Mount System, Thermal/Infrared Camera

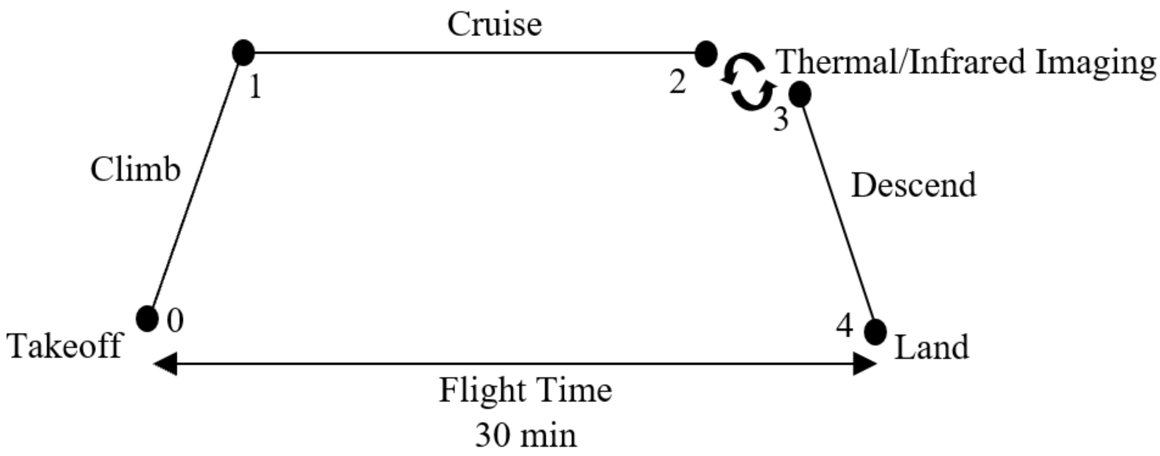

Figure 4. Mission Profile of Proposed UAS for Thermal/Infrared Imaging

The thermal/infrared mission needs only one attachment of a thermal or infrared camera. The camera in use will require its own mounting system detailed in the later chapters.

Chapter 2: Literature Review

2.1 Optimization of quadcopter frame using generative design and comparison with DJI F450 drone frame

One of the initial challenges of this project has been determining an optimal design for the frame of the drone. This research paper written by Bright, Akash, and Giridharan explores designing the frame of the drone utilizing generative design tools [2.1]. This research was beneficial in the design of this project by supplying information on important frame design considerations. These included determining the weight of each individual component, the placement of the components, and material selection.

2.2 A procedure for power consumption estimation of multi-rotor unmanned aerial vehicle

An important consideration during this project is the power consumption required of the quad-copter motors. This is a research paper written by Chan and Kam which explored a procedure to estimate the power consumption of a composite UAV [2.2]. This paper was particularly useful in that it evaluates the propeller system and electric parts which are something the team does not have much experience in. By exploring the methods presented, the team applied similar techniques to the design of this drone and determined the power consumption of the motors. This will help the team design a drone that is most optimal when completed.

2.3 A multipurpose modular drone with adjustable arms produced via the FDM additive manufacturing process

The configurations of the drones presented in this research paper were beneficial in determining an optimal design of this drone. Studies for the number of arms, electronics, and materials for 3D printing were explored. This paper by Brischetto, Ciano, and Ferro introduced material comparison methods, and modular drone arm designs. [2.3] The designs presented, helped optimize the weight of the arms in this design by presenting data for material and configuration.

2.4 Stress and Vibration analysis of a drone

Another challenge in this project was to figure out how to test the design of the drone. There are calculations, simulations, and experiments that can be performed, but figuring out how and what to test is a crucial aspect of this design process. Urdea's paper reviews the FEA analysis of a drone and how to set it up [2.4]. This was useful for the setup of our simulations and helped provide an understanding of some of the assumptions that must be considered when running the FEA analysis.

2.5 "A LiPo Battery Guide"

A difficulty the team faced was lack of electrical expertise. This link helped provide information regarding the different values for batteries and how to make an informed decision. Examples of knowledge learned include the battery capacity, discharge rating, and some material safety data sheets for various configurations.

2.6 Specifications Sheet for senseFly's eBee X Drone

Part of the researching phase included looking at existing drones in the field and we took note of equipment and electronics on these drones to see what they were able to accomplish. SenseFly's eBee X has an endurance of 90 minutes. This is longer than our goal endurance, so we looked into this battery. It uses a 15.2 V 4 cell LiHV battery, with either a mAh of 3700 or 4900 depending on the condition. However, the max takeoff weight is far below what we need, only reaching a weight of 1.6 kg compared to our 5 kg expectation.

2.7 Specifications Sheet for EXO's Blackhawk

The EXO Blackhawk does not carry a payload weight, but it does have an endurance of 85 minutes. When looking at its specifications, the battery was seen to be a 11.4V 5000 mAh which was decided to be far less power than we required but it was helpful information to have a benchmark of what the different batteries could offer in tangible examples.

2.8 Specifications Sheet for Autel Drones' EVO II

Autel's EVO II has an endurance of 40 minutes with a takeoff weight of up to 2 kg. They use a 11.55V 7100 mAh battery. Between the last few drones examined, this would provide the closest accuracy of what the team was looking for, but still falling short in payload ability.

2.9 "Range and Endurance Estimates for Battery-Powered Aircraft"

One of the mission criteria provided by United Consulting was that the proposed UAS should have a range of roughly 1 mile. This article provides guidelines for estimating range and endurance for electric aircraft, specifically a battery powered UAS. The equations and general methodology described in this article by L.W. Traub [2.9] were helpful in performing range calculations and endurance calculations for the KSU-UC UAS.

2.10 "Optimal Mission Path Planning (MPP) For An Air Sampling Unmanned Aerial System"

One of the challenges of designing a modular system is the variability of missions that the system must be adept at. To this end, several mission profiles were required for this project. One mission profile was created for each of the four anticipated missions. This conference paper from Queensland University of Technology served as a reference point for the manhole probing mission. It was a good data point for the typical path of an air sampling UAS mission. The paper was ultimately too specific to maximize applicability to the KSU-UC project, as the focus was on analytical methods that were beyond the scope of the project. While the details of this paper ultimately did not directly affect the UAS design significantly, it was helpful in shaping the way certain problems were approached, particularly when it comes to mission path planning [2.10].

2.11 "MOS SENSORS ARRAY FOR METHANE MONITORING WITH UAS"

This conference paper from the University of Liege provides an insight into some existing methods for air sampling via UAS. Methane monitoring is one of the direct missions of the manhole probing mission, which made it important to familiarize ourselves with the current approaches used in this particular area. [2.11] DOI: 10.1109/ISOEN.2019.8823371

2.12 "Wind Profiling in the Lower Atmosphere from Wind-Induced Perturbations to Multirotor UAS"

In this journal article, researchers from Virginia Tech and the University of Virginia investigate some of the aerodynamic interactions associated with a multirotor UAS, such as propwash. They considered both hovering and steady ascending flight conditions [2.12]. This article was instrumental in informing the team's understanding of the effects of propwash. As a note, mitigating the effects of propwash was one of the primary criteria for the manhole probing mission. This requirement led to the introduction of a flexible probe mechanism.

2.13 "Moving towards a Network of Autonomous UAS Atmospheric Profiling Stations for Observations in the Earth's Lower Atmosphere: The 3D Mesonet Concept"

Journal article from University of Oklahoma. Details the benefits of UAS systems for air sampling from a meteorological standpoint. Provides insight into other uses/considerations for integrating UAS instrumentation. http://dx.doi.org/10.3390/s19122720

2.14 "Power and Endurance Modelling of Battery-Powered Rotorcraft"

This conference paper from University of Bristol details a methodology for modelling the power and endurance of a battery powered (LiPo) UAS. The information in this paper was very useful for providing a more robust method of calculating both the electrical power consumption and the endurance of an electric rotorcraft [2.14]. When compared with the simplified model used in the preliminary power calculations, this model yielded similar results. The similarity in outcomes provides reassurance that the assumptions made in the simplified model were appropriate.

2.15 "3D scanning and printing of airfoils for modular UAS"

Journal article from NASA Ames Research Center. Provides information about 3D printing for small, modular UAS. https://doi.org/10.1117/12.2253068

2.16 "A Modular Unmanned Aerial System For Missions Requiring Distributed Aerial Presence or Payload Delivery"

Conference paper from NASA Langley Research Center, Georgia Tech and Purdue University. Describes a modular UAS system and provides many ideas for successful implementation of such as system. https://doi.org/10.2514/6.2017-0210

2.17 "Challenges in bridge inspection using small unmanned aerial systems: Results and lessons learned"

This conference paper from Utah State University details some of the challenges that can arise in trying to perform bridge/weld inspection with a small UAS. It was very useful for identifying challenges preemptively and designing around them. Additionally, it was helpful in informing the team as to how weld inspections are typically conducted utilizing a UAS. Some of the specific information of use was the type of cameras typically used. Depending on the application, some UAS use 1-2 cameras that were a mixture of integrated cameras, external cameras (i.e. GoPro), thermal cameras, and even LiDAR [2.17].

2.18 "Fatigue Crack Detection Using Unmanned Aerial Systems in Under-Bridge Inspection"

Report from Utah State University to Idaho Transportation Department. Comprehensively details methodology, challenges and results associated with performing a under-bridge inspection with a UAS. This report was also useful as an example of proper formatting. In particular, the literature review was well done [2.18].

2.19 "Survey of thermal infrared remote sensing for Unmanned Aerial Systems"

Conference paper from UC Merced. Details some of the uses of thermal and infrared cameras on a UAS. https://doi.org/10.1109/ICUAS.2014.6842387

Chapter 3: Project Overview

3.1 Requirements:

Table 5 shows the requirements of the UAS expected and provided by the customer. On the left column, REQ ID is a value assigned to each requirement to provide a convenient method of identifying the requirements. The requirements are divided into 2 main categories: Physical and Functional. Physical requirements are used to define the physical boundaries of the system. Functional requirements define the functionalities expected of this system. Typically, the functional requirements are provided by the customer. In addition, three more major categories are considered to successfully meet the customers' requirements – Design, Performance, and Safety. Design requirements are limitations in the UAS design and composition. Performance requirements define how well a mission or task is to be performed. Finally, safety requirements are developed and considered to ensure no harm is caused to an individual.

Table 5. Requirements

REQ ID	Requirement
REQ 01	UAS shall have a flight endurance of a minimum of 30 minutes
REQ 02	UAS shall maintain a transmission range of a minimum of 1610 meters
REQ 03	UAS shall perform surveying mission
REQ 04	UAS shall perform manhole probing mission
REQ 05	UAS shall perform weld inspection mission
REQ 06	UAS shall perform infrared and thermal imaging mission
REQ 07	UAS shall provide telemetry information to ground station
REQ 08	UAS shall not be designed over $5000 budget
REQ 09	UAS shall contain a pulley system for manhole probing mission
REQ 10	UAS shall contain a camera that can tilt up and down
REQ 11	UAS shall be no longer than 0.9 meters wide for effective transportation

REQ 12	UAS shall follow FAA regulations
REQ 13	UAS shall be capable of streaming two cameras simultaneously
REQ 14	UAS shall have a mounting system for modular components
REQ 15	UAS shall lift a minimum of 5000 grams
REQ 16	UAS shall have navigation lights (green and red lights)
REQ 17	UAS shall have beacon lights (flashing red lights)
REQ 18	UAS shall have strobe light (white light)
REQ 19	UAS shall not be used in inclement weather
REQ 20	UAS shall be made of ABS filament

3.2 Minimum Success Criteria:

Success of this project will be measured by the completion of a final report and a prototype. The final report should detail the methods of physical testing and fabrication of the drone. In addition, the electronic components must be finalized and a purchasing plan detailing where to buy and how to wire the components must be presented. The prototype should be at minimum the baseline version of the drone. This means that all the parts and components aside from the off-the-shelf items must be 3D printed and fabricated. The prototype should detail how each part will be connected.

3.3 Gantt Chart:

Figure 5 shows the Gantt Chart detailing the tasks needed to be completed on a weekly basis to complete this project. The completion of each task is highlighted by a dark bar. It is important to note that not all items are completed as scheduled. This is due to revised scheduling because throughout the semester the requirements have changed. Due to limited time, and time spent extensively on literature review and component selections, the final fabrication and testing phase could not be completed. The Gantt Chart is divided into 4 phases: Design Phase, Fabrication Phase, Testing & Revision Phase, and Final Report & Documentation Phase.

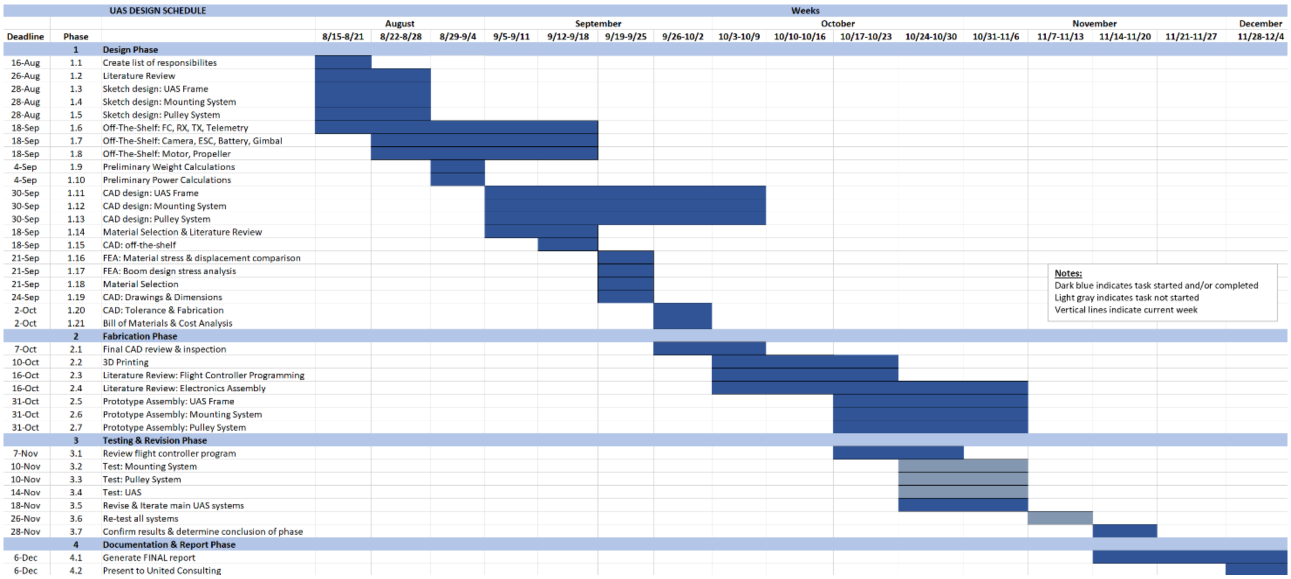

Figure 5. Gantt Chart

3.4 Flow Chart:

Figure 6 shows the system block diagram detailing the functional and physical requirements of the UAS. These are constraints provided by the customer. The functional requirements show the missions that the UAS must be capable of performing as well as the required modular equipment it must hold.

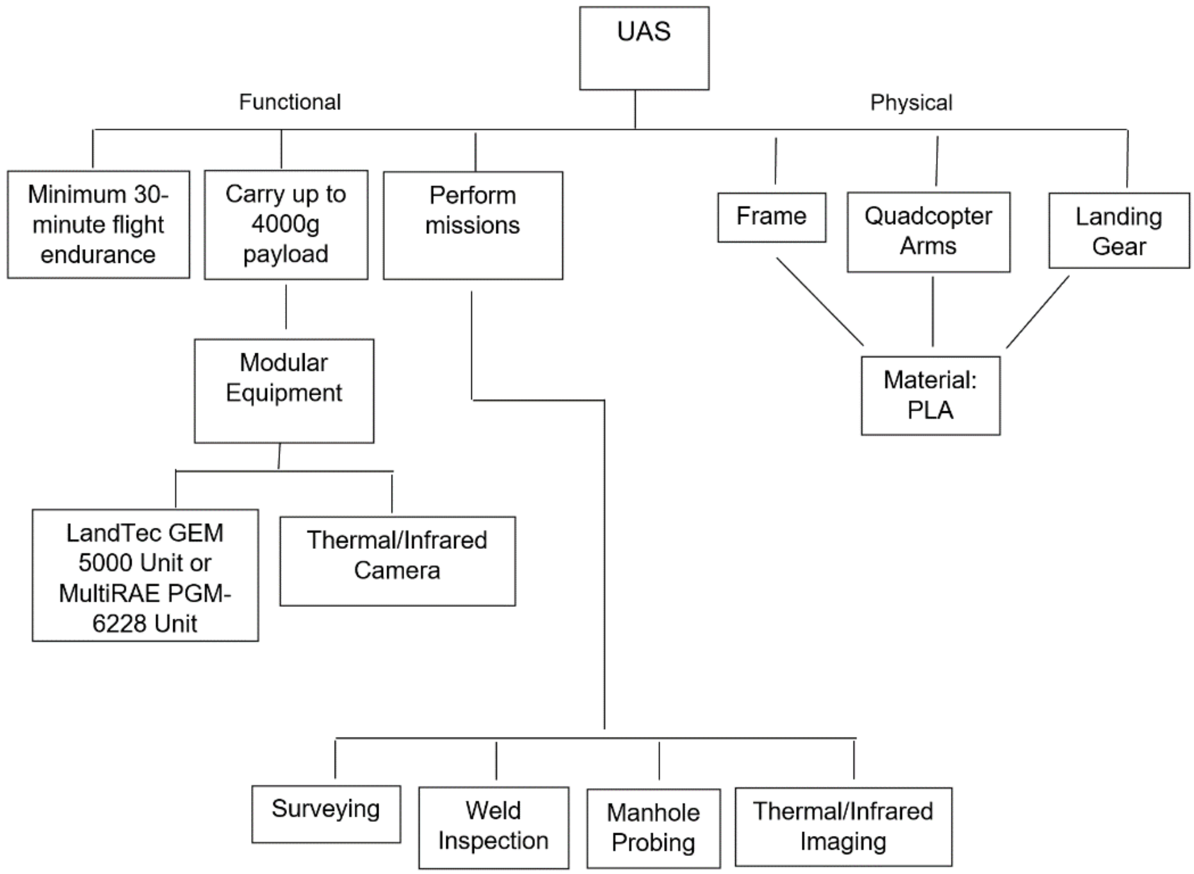

Figure 6. Requirements Block Diagram

Figures 7 and 8 show a block diagram created to show the process of how the UAS is designed. Each arrow in the figure is designated with a "yes" or a "no." This displays which path to follow. The system block diagram begins by asking whether a task has been completed. If the task has not yet been completed, additional sub-tasks must be completed prior to moving onto the next task. This system diagram outlines the design process of this project and concludes with experimental testing tasks the must be performed to determine the completion of this project.

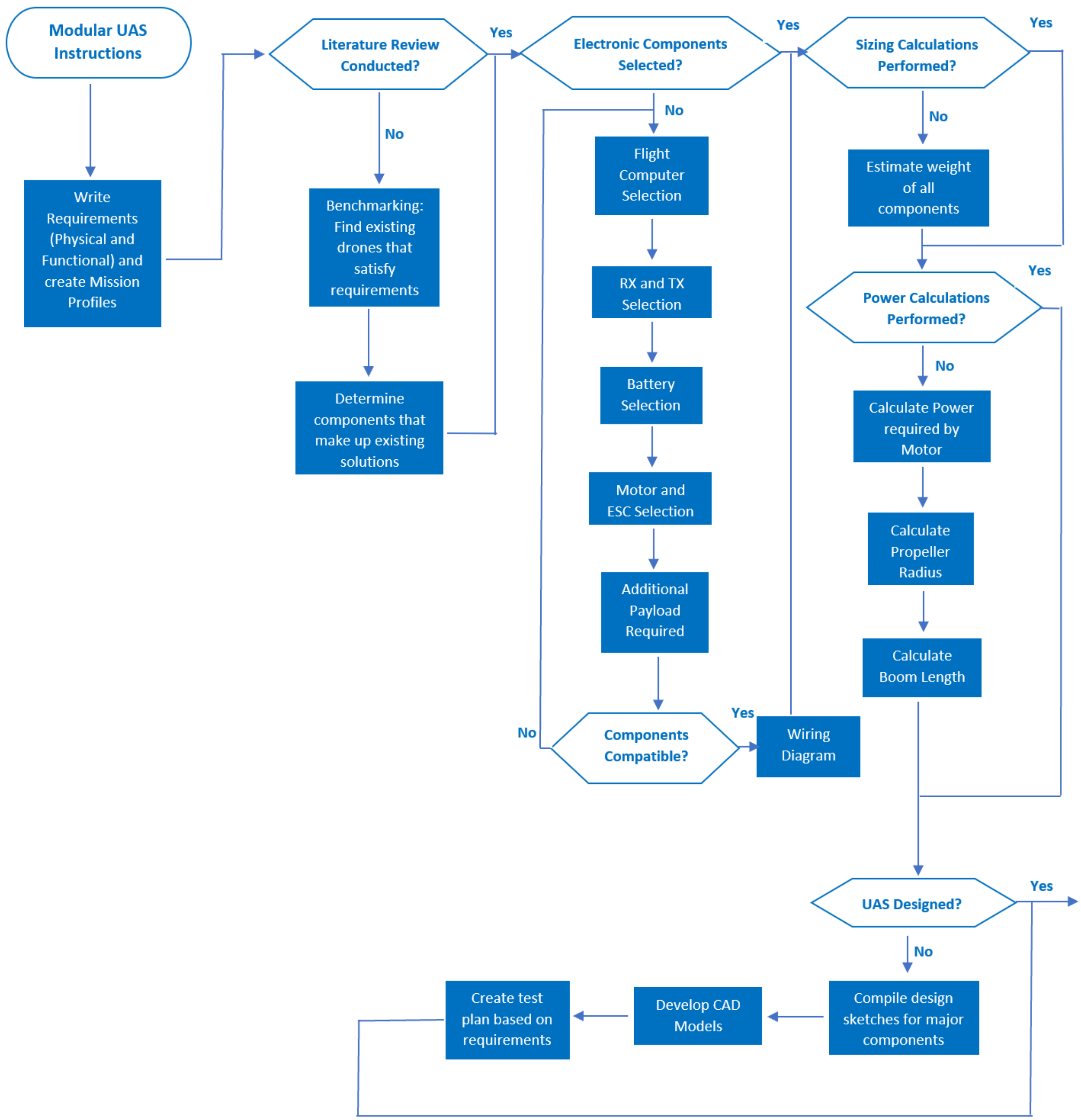

Figure 7. UAS Design Block Diagram Part 1

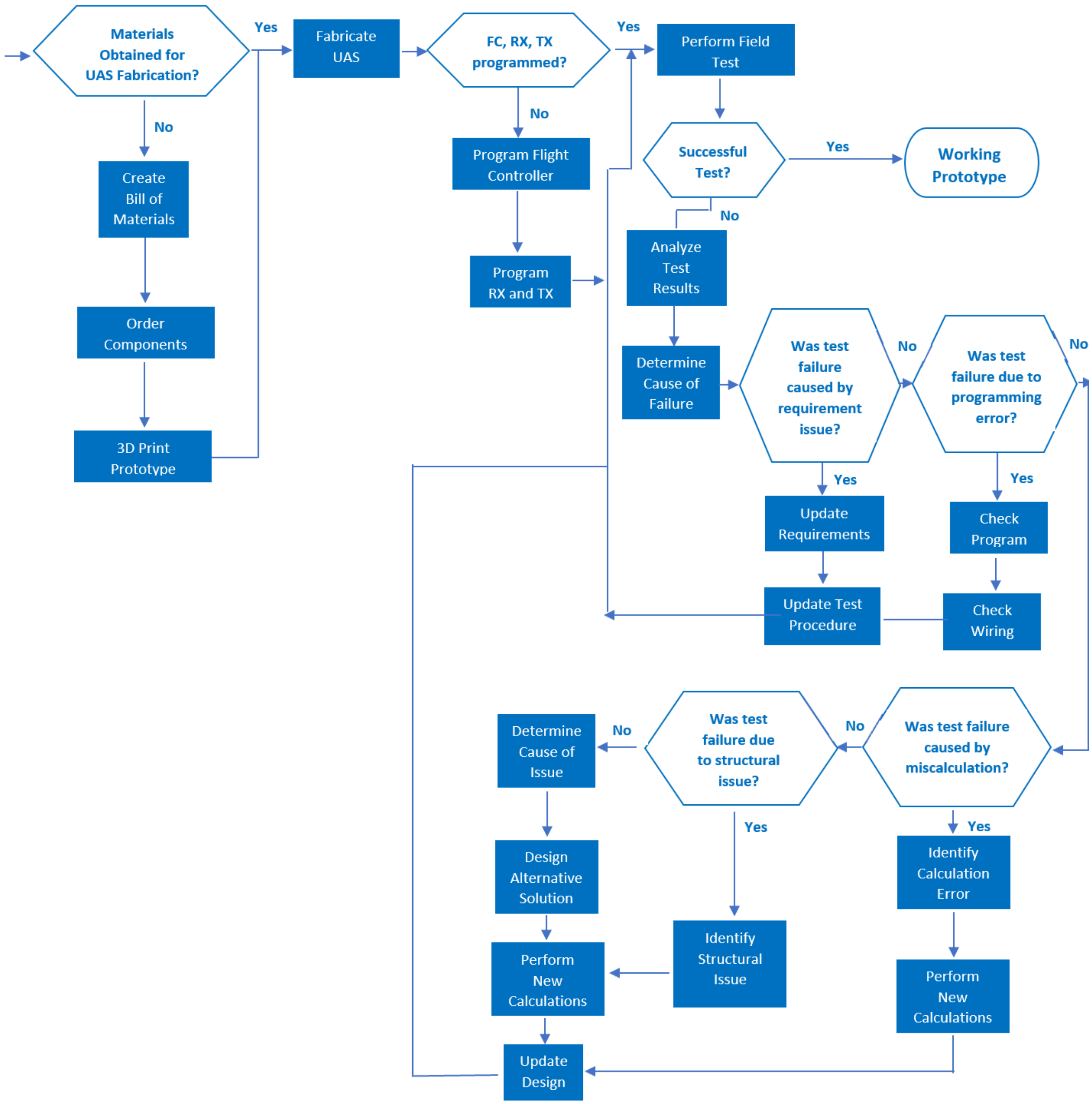

Figure 8. UAS Design Block Diagram Part 2

3.5 Schedule and Responsibilities:

Important deadlines are shown in Table 6. These deadlines are dates that cannot be changed and must be met. Table 7 shows what each member was responsible for.

Table 6. Important Deadlines

Date	Event
August 16, 2021	Group member and topic selection
August 23, 2021	Initial Design Review (IDR)
September 27, 2021	Preliminary Design Review (PDR)
October 25, 2021	In Progress Review (IPR)
November 15, 2021	Critical Design Review (CDR)
November 29, 2021	Final Design Review (FDR)

Table 7. List of Responsibilities

Task	Assigned To	Status	Notes
Obtain Requirements	**Team**	**Complete**	**Due August 16**
Create Gantt Chart	**Vlad**	**Complete**	**Due August 16**
Create Mission Profiles	**Sydney**	**Complete**	**Due August 16**
Perform Benchmarking Analysis	**Team**	**Complete**	**Due August 16**
Find “Off-The-Shelf” FC, RC, TX	**Vlad**	**Complete**	**Due August 30**
Find “Off-The-Shelf” Camera, Battery, ESC	**Sydney**	**Complete**	**Due August 30**
Find “Off-The-Shelf” Motor, Propeller	**Maurice**	**Complete**	**Due August 30**
Determine components compatibility	**Team**	**Complete**	**Due September 3**
Create Bill of Materials	**Sydney**	**Complete**	**Due September 3**
Create Wiring Diagram	**Vlad**	**Complete**	**Due September 6**
Perform Literature Review	**Team**	**Complete**	**Due September 6**
Make Design Sketch for UAS frame	**Vlad**	**Complete**	**Due September 10**
Make Design Sketch for Pulley System	**Maurice**	**Complete**	**Due September 10**
Make Design Sketch for Mounting System	**Sydney**	**Complete**	**Due September 10**
CAD “Off-The-Shelf” components	**Team**	**Complete**	**Due September 10**
CAD UAS	**Vlad**	**Complete**	**Due September 17**
CAD Pulley System	**Maurice**	**Complete**	**Due September 17**
CAD Mounting System	**Sydney**	**Complete**	**Due September 17**
Research Camera Transmission Range	**Sydney**	**Complete**	**Due September 20**
Create an Assembly/Rendering of each Mission	**Sydney**	**Complete**	**Due September 24**
Perform Sizing Calculations	**Team**	**Complete**	**Due September 24**

Calculate Required Power of each Motor	**Maurice**	**Complete**	**Due September 24**
Calculate Required Propeller Diameter	**Maurice**	**Complete**	**Due September 27**
Calculate Boom Length	**Vlad**	**Complete**	**Due September 27**
FEA: Mesh Convergence Analysis	**Vlad**	**Complete**	**Due October 4**
FEA: Static Analysis on boom and landing gear	**Vlad**	**Complete**	**Due October 4**
FEA: Static Analysis for PLA and ABS	**Vlad**	**Complete**	**Due October 8**
FEA: Static Analysis for Mounting System	**Sydney**	**Complete**	**Due October 8**
FEA: Static Analysis for Pulley System	**Maurice**	**Complete**	**Due October 8**
Add Tolerancing and Fabrication to CAD Models	**Vlad**	**Complete**	**Due October 11**
3D Print Components	**Team**	**Complete**	**Due October 18**
Develop Plan to Order "Off-The-Shelf" Components	**Sydney**	**Complete**	**Due October 25**
Assemble UAS	**Team**	**Complete**	**Due October 25**
Create a Plan to Program Flight Controller, RX, and TX	**Vlad**	**Complete**	**Due November 1**
Create Flight Test Procedure for UAS	**Team**	**Complete**	**Due November 8**

3.6 Budget:

United Consulting are sponsoring this project and are providing up to $5000.00 to ensure successful completion of this project. The following is a breakdown of the estimated cost of the UAS, not including equipment provided by United Consulting.

Table 8. Budget

Component	Name	Cost	Purchase Site
FPV Camera	GoPro Hero 8 Black	$224.97	[1]
Data Collection Camera	GoPro Hero 8 Black	$224.97	[1]
Data Collection Camera Lens	QKOO 16X Macro Lens	$29.99	[2]
Flight Controller	Pixhawk 4	$170.00	[3]
Receiver	AR7700	$58.64	[4]
Transmitter	Spektrum iX12	$629.99	[5]
Battery	ZDF 6s 22.2 V Battery	$449.00	[6]
Lights	Firehouse Arc "V" Drone Light	$198.00 ($33.00 each)	[7]
Gimbal	Tarot TL3T05 Brushless Gimbal	$154.99	[8]
ESC	Spektrum Avian 30	$179.96 ($44.99 each)	[9]
Motor	Spektrum FIRMA 4000 kV Brushless	$179.96 (44.99 each)	[10]
Propeller	Hongyi Carbon Fiber Propellers	$42.14 ($10.54 each)	[11]
3D Printing	All components (ABS material)	$494.90 ($10/cu.in.)	[12]
Tablet	iPad Mini	$499.00	[13]
TOTAL		**$3381.52**	

3.7 Required Materials:

The materials required for this project are listed below. The list is divided into three categories. The first category lists the software the team will utilize to design the UAS. The second category lists all the hardware needed. Lastly, any personnel used to help in this project are listed.

Software:

- SolidWorks (FEA Testing)
- MATLAB (Flight Controller Programming)

Hardware:

- Aero LAB (Workspace)
- 3D Printer (Components)
- 3D Printing Filament
- Transmitter
- Receiver
- Propellers
- Motors
- Electronic Speed Controllers (ESC)
- Battery
- Battery Charger
- Telemetry
- Gimbal
- Camera
- Data Collection Camera
- Tablet

Personnel:

- Dr. Adeel Khalid (advisor)
- Dr. Cameron Coates (advisor)
- United Consulting Team (client)

3.8 Resources Available:

Kennesaw State University has an Aero Lab that was used as a workspace to complete this project. In addition, KSU provides 3D printers to print the components of the UAS. Lastly, KSUs library provided access to many journals to help conduct literature review.

Chapter 4: Trade Studies & Benchmarking

4.1 Benchmarking:

To create a design for a product, it is necessary to examine previous and current designs in the field. This gives the designer's an understanding of what is available, and where the need for the new design originates from. During this stage, it is possible that the team discovers a current product that suits the need, but if not, then the process continues. The benchmarking parameters explored consist of the weight of the drone, payload weight, takeoff weight, endurance, range and price. Existing drones that best meet the requirements described in Chapter 1 are selected and further explored. They are shown in Table 9.

4.2 Previous Solutions:

Table 9. Examination of Current Drones

Name	Weight (grams)	Payload (grams)	Takeoff Weight (grams)	Endurance (minutes)	Range/Altitude (meters)	Price ($)
Autel EVO II	1133.98	861.82	1995.81	40	8999.83	1495-1795
FIMI X8SE	762.04	N/A	-	35	7999.78	$400.00
EXO Blackhawk	706.6	-	-	85	999.74	659-899
Yuneec H520	-	-	1860	28-30	2000	$1,999.00
eBee X	800	800	1600	90	3000-8000	N/A
Skydio X2	-	-	1325	35	6000	$10,999.00
Albatross UAV	-	-	10000	60<	25000	N/A
MATRICE 600 PRO	9997.17	5497.54	15499.25	18	4988.97	$6,599.00
MATRICE 300 RTK	6300.4	2698.88	8999.27	55	7999.78	$13,200.00
Freefly ASTRO	3093.5	1501.39	6663.27	38		$7,995.00
DJI Inspire 2	3438.23	811.93	4250.16	27	6920.18	$3,299.00
Autel Robotics EVO	863	-	-	30	7000	$1,049.00
DJI Mavic 2	-	-	907	31	18000	$1,599.00
M6FC Heavy Payload Drone		10000	36000	30	1609	-
Chroma Camera Drone	1300	-	-	30	-	$699.99
Matrice 200 Series	4530	-	6140	24	3000	-

Table 9 shows an evaluation of 16 drones that the team looked at during the research phase of this project. The table's columns contain the main elements we were concerned about to view all important aspects at once to determine if any pre-existing UAS' would fulfil our client's needs.

The easiest one to make eliminations is the Endurance time; we had a strict requirement of 30 minutes or more, so all that fall under a time of less than 30 minutes are not eligible. The next eliminating element is the payload weight. The heaviest equipment that we are attaching to this drone is the LandTec GEM 5000 which weighs 1644 grams alone. That automatically removes any drone with a capacity of less than that. Of the 16 collected, these two eliminations leave us with only the MATRICE 300 RTK and the M6FC Heavy Payload Drone. The Matrice 300 is listed at $13,200, which is far above the desired budget of our client, and the M5FC does not list a price to the public and it is barely over the endurance requirement. From this study, we determined that there was not a currently accessible drone to fit our needs and we needed to continue with the design of our own UAS.

4.3 Baseline Study:

The baseline study is linked to the requirements of the project given by the client which are listed in Section 3.1. This provides the checkmark goals to achieve, such as endurance, payload weight, and doing it within the budget. These values were all explored throughout the rest of the report. Chapter 5,6,7, and 8 detail the weight, performance, and design of the UAS and how it performs.

4.4 Proposed Solution:

By analyzing the currently produced UAS platforms and the client's requirements, the path forward results in the designing and fabrication of a new platform. Even though none of the benchmarking drones can be utilized for our purpose, the information about what electronics and parts are used can help assemble our drone. For example, when looking at the FIMI X8SE and Skydio X2 and how they have an endurance of 35 minutes, we can use the information of their electronics and sizing to help our drone reach that endurance goal.

4.5 Comparison Analysis:

Based off of the estimated material costs and electronics, we believe that we can design a drone to fulfill the needs of our client within their budget. By taking the parts we need from each of the benchmarked drones, we can put together a UAS to compare to all the rest.

Chapter 5: Components

5.1 Sampling Equipment:

The main feature of this drone is that it must be able to support and carry modular equipment provided by the client. This includes discrete air sampling equipment such as the MultiRAE PGM-6228 and LandTec GEM 5000. In addition, a thermal and an infrared camera will be supplied. The air sampling equipment will be modular and can be switched out with each mission. The MultiRAE and LandTec units will be used to perform the manhole probing mission. They will be used independently and not together simultaneously. The following figures show what these units look like.

Figure 9. MultiRae

Figure 10. LandTec

Table 10. Equipment Weights

Component	Name	Mission	Dimension	Weight
Air Sampling Unit	MultiRAE	Manhole Probing	193mm x 96.5mm x 66mm	879g
Air Sampling Unit	LandTec	Manhole Probing	228mm x 165.1mm x 63.5mm	1645g
Thermal Camera		Thermal/Infrared Imaging	57.41mm x 44.45 mm	92.14g
HEAVIEST				**1645g**

5.2 Electronics and Components:

The electronics of this drone are there to help the drone takeoff. They are useful in supplying power to the drone as well as connecting the pilot to the controls. The electronic equipment associated with this drone is listed as follows:

- **Flight Controller x1**

The flight controller is the brain of the drone. It is a circuit board with several sensors that are useful in detecting motion of the drone as well as the inputs of the user. In addition, it also controls the speed of the motors to assure the drone moves as intended.

- **Electronic Speed Controller x4**

The Electronic Speed Controller (ESC) is a device that allows the drone flight controller to monitor and adjust the speed of the electric motors. A signal received from the flight controller causes the ESC to increase or decrease the voltage of the motor. This results in a change in the speed of the propeller.

- **Motor x4**

The purpose of the motors is to spin the propellers of the drone to establish flight. They are connected to both the ESC and propellers. The motors must be carefully selected to ensure they can manage the necessary power to lift the drone.

- **Propeller x4**

The propellers are used to generate lift for the drone by being spun by the motors. The rotational energy of the motors is converted to linear thrust. By being spun, an airflow is created which results in a pressure difference between the top and bottom surfaces of the propeller. This process propels air in a direction providing lift which counteracts the weight of the drone and the force of gravity.

- **Battery x1**

The battery is a critical component when designing a drone. This component supplies and powers all the electrical components. It is crucial to the drone's performance and flight endurance. Careful consideration of the voltage it supplies, and its weight will need to be accounted for.

- **Receiver x1**

The receiver is an electronic device that is used to receive radio signals from the transmitter. It then sends the information to the flight controller of the drone. The receiver is made up of antennas which receive radio signals.

- **Transmitter x1**

The transmitter is an electronic device that is used to send radio signals wirelessly to the receiver via a radio frequency. The radio signals are controls and functions operated by the pilot which control the drone.

- **Power Management Unit x1**

The Power Management Unit (PMU) regulates the power being fed to the flight controller, ESCs, and other components. It features voltage detection and alarming. It is to ensure the electronic components do not overheat and the current is not oversupplied.

- **Inertial Measurement Unit x1**

The Inertial Measurement Unit used built-in inertial sensors to measure the aircraft altitude. This unit uses sensors such as accelerometers and gyroscopes to measure the acceleration and rotation of the drone.

- **GPS Compass x1**

The function of the GPS compass is to determine the position of the drone. In addition, speed and relative position of the drone are determined by the GPS. It is usually the central component of a drone.

- **Camera x2**

The cameras will be for streaming and transmitting live video to the pilot via a radio signal. One camera will provide vision to the pilot and the other will be streaming live data in the manhole probing mission.

5.3 Component Selections:

Flight Controller: Pixhawk 4

Figure 11. Pixhawk Flight Controller

The selected flight controller for the drone is the Pixhawk 4. This FC was selected for its relatively affordable cost, popularity, and usefulness for bigger drones. Since the project is under a $5000.00 budget, it is important to select a flight controller that is both affordable and reliable. In addition, this flight controller comes with the GPS and Power Management Board. This ensures compatibility and reduces the risk of the system failing. With the set, the cost is $230.95. The popularity of this flight controller is an important consideration because that means there are lots of resources and videos to help the team program and set up this controller. This is particularly useful since the team has limited experience in the electrical and programming department. Lastly, this FC is a common choice for heavy drone builds. This drone is expected to be in the 5 kg range, and this makes Pixhawk 4 the optimal choice for this design.

Electronic Speed Controller (ESC): Spektrum Avian 30 ESC

Figure 12. Spektrum Avian 30 ESC

The Spektrum Avian 30 ESC was selected as the ESC for this project. This ESC was compatible with the selected motor and flight controller. The three wires on one side connect with the motor and the two wires on the other side connect with the flight controller. This ESC weighs 50g and costs roughly $44.99. A wiring diagram is shown later in the report to detail the connection between electronic components.

Motor: Spektrum Firma 4000kv Brushless Motor

Figure 13. Spektrum 4000kv Brushless Motor

An important component in designing a drone is the motor. The motor must be able to lift and support the weight of the drone and all modular components. To maintain the same brand and ensure compatibility, the Spektrum Firma 4000kv Brushless motor was selected. This motor was determined to be suitable through power calculations performed later in the report.

Propeller: Hongyi 30cm Carbon Fiber Propeller

Figure 14. Hongyi Carbon Fiber Propellers

Hongyi propellers made of carbon fiber were selected. The 30 cm length was found to be enough to provide the thrust and lift force needed.

Battery: ZDF 6s LiPo 22.2V 22000 mah Battery

Figure 15. ZDF 6s LiPo Battery

The most difficult selection in this project was the battery. The battery is a key factor in determining the flight endurance of each mission. In order to come as close to the 30-minute flight endurance requirement as possible, the battery had to have a capacity of 22,000 mAh, a 100% battery discharge, and a voltage of 22.2. Finding a battery with these requirements was not as tough as accounting for the weight. Ultimately, it was found that the ZDF 6s LiPo Battery was the best choice for this project.

Receiver: Spektrum AR7700 Receiver

Figure 16: Spektrum AR7700 Receiver

The Spektrum AR7700 Receiver was selected for its compatibility with both the Pixhawk 4 flight controller and Spektrum iX12-Channel transmitter. In addition, its lightweight and ability to support 12 channels makes it an optimal choice. The receiver also includes extra ports which is useful for running additional functions like a retractable landing gear, lights, or gimbal control. In this project, a pulley system, lights, and gimbal will benefit from this receiver selection.

Transmitter: Spektrum iX12 Radio 12-Channel Transmitter

Figure 17. Spektrum iX12 Transmitter

The factors in selecting a transmitter for the project were based on the number channels the transmitter could support and its compatibility with the receiver and flight controller. The number of channels this project required was 12, so the transmitter had to support 12 or more channels. Next, since the flight controller was the first selected component, the transmitter had to be compatible with it first. The Spektrum iX12 transmitter was selected because it supports the 12 channels required and is compatible with the Pixhawk 4. The Spektrum iX12 also provides information on telemetry and is within a reasonable price.

Camera: GoPro Hero 8

Figure 18. GoPro 8

For the front sight and data collection in the UAS, the GoPro 8 was decided upon. They are easy systems to work with and are compatible with existing processes.

GPS Compass: Pixhawk 4 GPS Module

Figure 19. Pixhawk 4 GPS Module

The Pixhawk 4 GPS Module was selected for its compatibility and capability. This module is included in the Pixhawk 4 module ensuring its compatibility with the flight controller.

PMU: Pixhawk 4 Power Module (PM07)

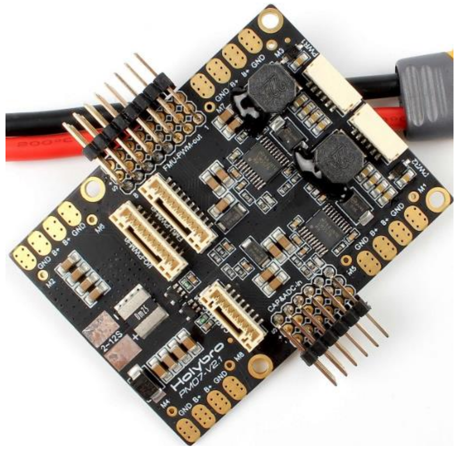

Figure 20. Pixhawk 4 Power Module (PM07)

The Pixhawk 4 Power Module comes included with the Pixhawk 4 bundle. This also ensures compatibility and reduces the overall cost of the components. This board connects to the Pixhawk 4 flight controller and the speed controllers that the motors are connected to.

5.4 Compatibility:

The compatibility of each electric component was reviewed through literature review. The components must be compatible regarding their wiring connection and the amount of power and voltage the components can handle. The following is a table listing each component and their connection type and voltage they support.

Table 11. Electronic Components Compatibility

Component	Connection Type	Voltage Range
Flight Controller	Can Bus, I2C Port, SPI Bus, DSM	4.9-5.5 V
Receiver	PPM, DSM, DSMX	3.5-9.6 V
Transmitter	DSM2, DSMX	-------------------
Battery	AS150/XT90/XT60	22.2 V
ESC	IC3 with 14AWG 3.5mm Female Bullet with 14AWG	11.1-22.2 V
Motor	4mm Bullet	6-8.4 V
Power Management Board	XT60 connector	4.75-5.25 V

This table was useful in creating the wiring diagram to represent the compatibility of the components in a figure. This was one of the most crucial aspects of the project, because components would not be purchased or selected in the design unless it was known for certain they are compatible with each other. As previously mentioned, compatibility was only one criterion in the selection of the components. The others included performance and cost described in other chapters.

5.5 Wiring Diagram:

The wiring diagram is created to assist the next team in connecting and programming the electronics for this drone. This is to ensure and prove compatibility between each component. The wiring diagram displays the connection between the flight controller, receiver, transmitter, ESC, motor, and battery.

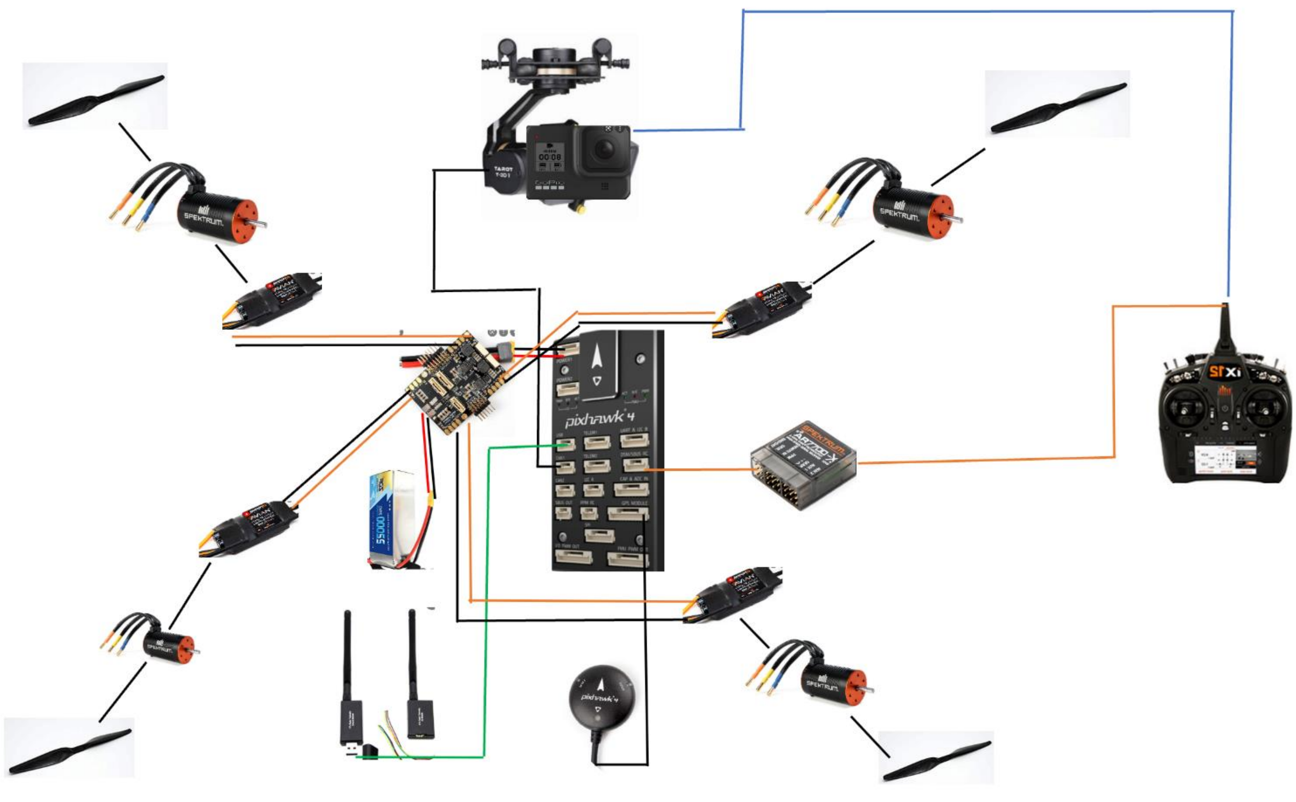

Figure 21. UAS Wiring Diagram

Chapter 6: Design Concepts

6.1 UAS Concept:

After reviewing existing drones and selecting the electronics, a final concept of the baseline drone was developed using SolidWorks. This concept consists of four motors to make this design a quadcopter. The booms holding the motor housing are angled at 2 degrees to improve the hover stability of the drone. The two landing gears are added to ensure structural stability when the drone lands. Figures 18-22 display the CAD model of the assembly to be 3D printed. This 3D printed model will serve as a prototype to build off when the electronics are purchased.

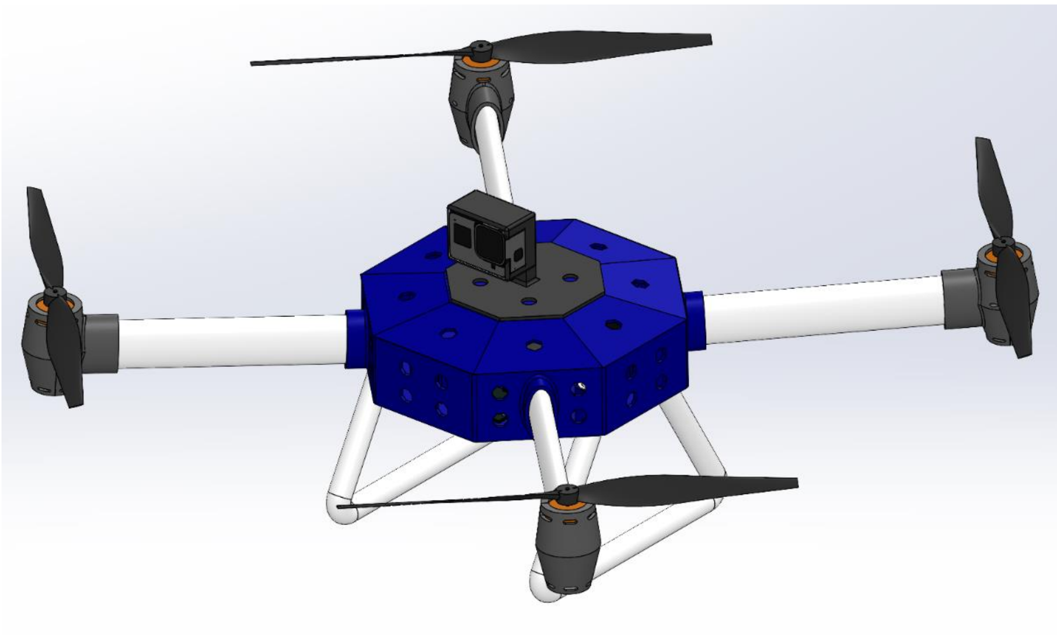

Figure 22. Isometric View of Proposed Modular Drone Concept

Figure 22 shows the isometric view of the baseline drone. The drone is made up of four arms, four motor housing parts, a main frame, a cover, and two landing gears. This adds up to 18 total parts that are to be 3D printed and fabricated. Each motor housing part is made up of two separate parts to ensure the motor can fit inside. Tolerancing and fitting is further discussed in Section 9.1.

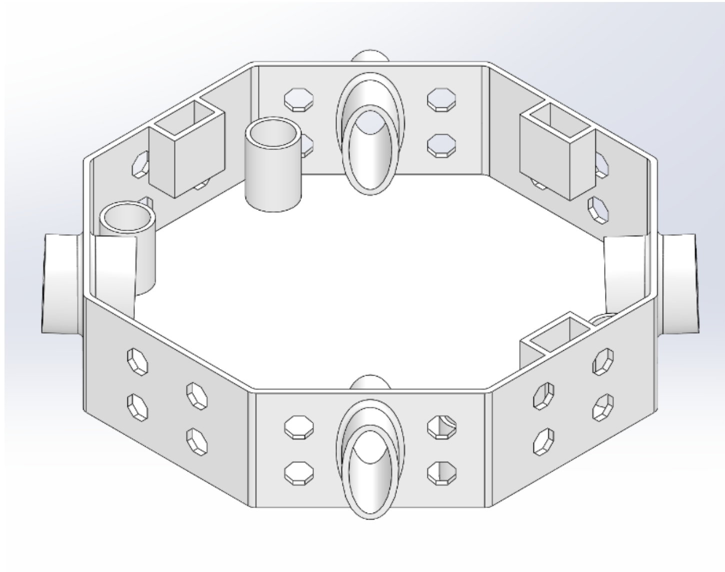

Figure 23. Frame of Modular Drone

A crucial part of the UAS is the frame. The frame holds all the electronic equipment and keeps the entire drone together. This part not only has to be lightweight, but structurally sound to not break apart midflight. There are three main parts in the main frame to prevent structural failure. This includes the boom, frame, and landing gear supports where each system will be mounted. Figure 19 displays these supports and where they are located. Next, hexagonal holes were added on the sides of the frame to reduce the total takeoff weight of the drone. Sizing studies are conducted in Chapter 7 to determine the total weight of the drone.

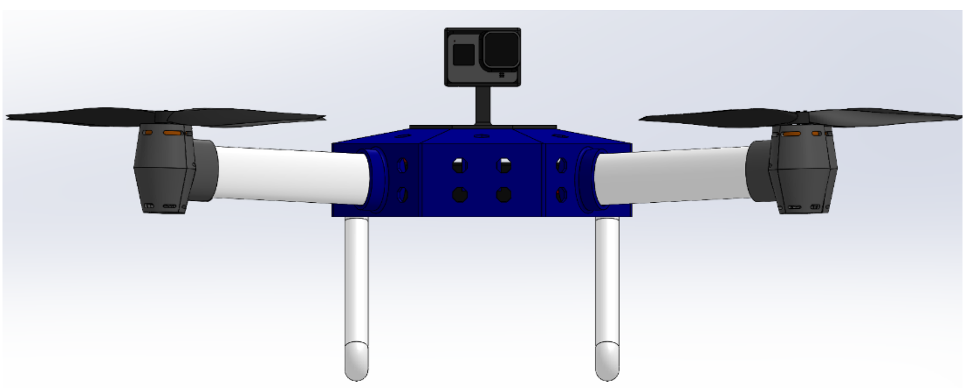

Figure 24. Front View of Baseline Drone

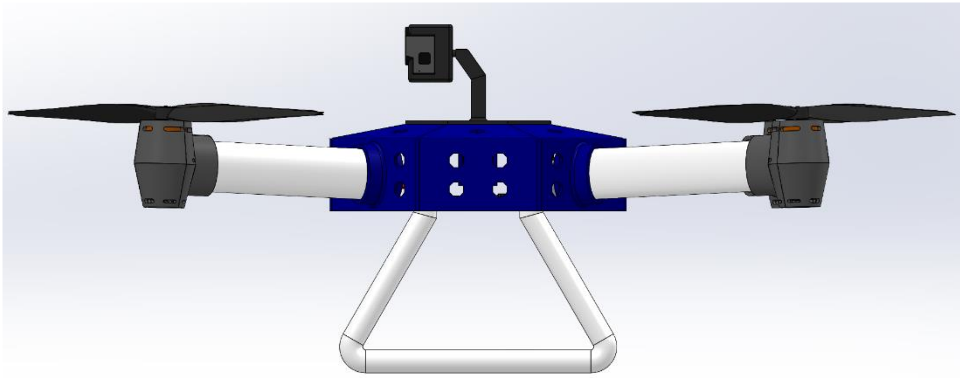

Figure 25. Side View of Baseline

The previous two figures display the front and side views of the baseline drone. Here, the angled booms can be observed as well as the landing gear configuration. Figure 20 shows the landing gears distanced roughly 8.5 inches from each other to allow ample space for the modular equipment below. Dimensions and engineering drawings are found in the appendix.

The proposed concepts for the modular drone were designed with weight, safety, and stability considered. The oval shape of the booms makes them more durable and less likely to fail due to bending. This landing gear was also designed to be safer. They are safer because each landing gear has two connection points to the main frame. This will divide the load between those connection points. This was important because this drone will be slightly heavier than average. As such, the landing gear must be able to support such weight. Lastly, the main frame was decided on a hexagonal shape to create room on the bottom for the modular components that will be added. In addition, there is sufficient space for electronics on the inside of the frame. The only concern with this current design is the added structural weight. There are slight adjustments in terms of size to reduce weight where it was possible. One way was to add hex slots across the frame to allow airflow inside the frame and reduce weight.

6.2 Mount System Concept:

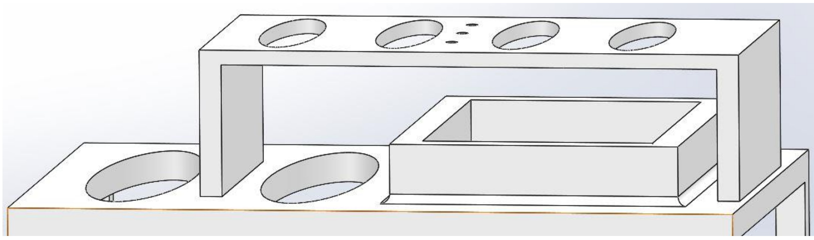

Figure 26. Top Mount

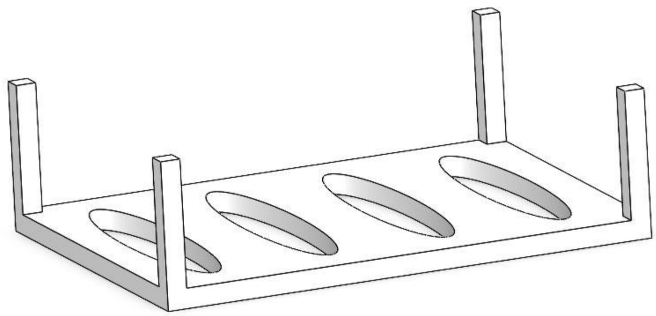

Figure 27. Bottom Mount

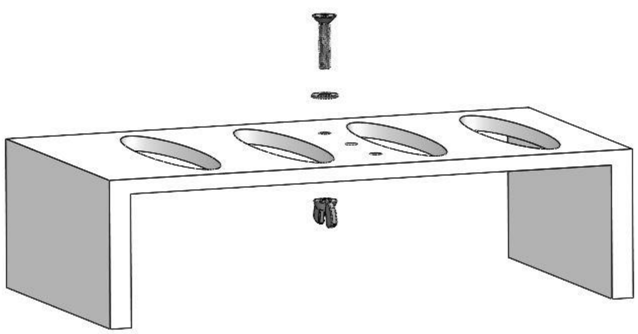

Figure 28. Mount with Hardware

The main goal of this projected design was to be a modular system, easily able to switch between missions on the field. Figure 26 shows the top plate of the mounting system and Figure 27 shows the bottom part. There is a slot along the poles of the bottom for the top plate to slide into. The top portion also has the part of the system that will connect directly to the drone base. They will be printed in two pieces and joined together for the full system.

It was designed for ease of access, thus the only tool needed will be a hex key and a hand. Later in the Mission Concepts, there is an example of an assembly attached to the drone base to give the full picture of use. The mounting system will be aligned with the base, the bolts will be placed in, a washer on either side of the mount, followed by the wing nut to fasten it all together. The bracket will be 3D printed, and the hardware will be outsourced from McMaster Carr.

6.3 Pulley System Concepts:

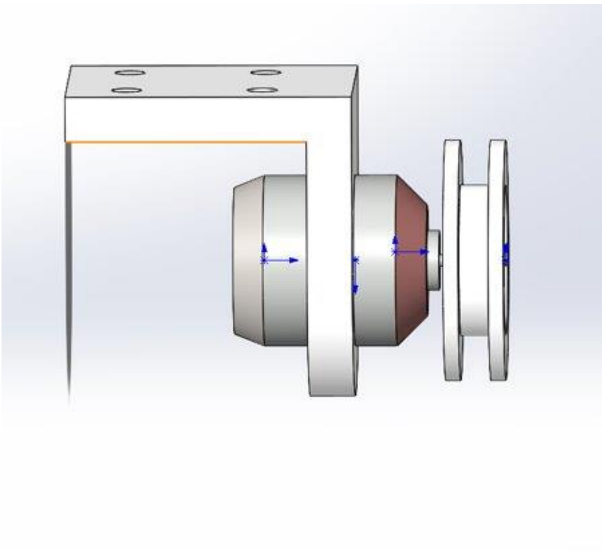

Figure 29. Pulley and Motor

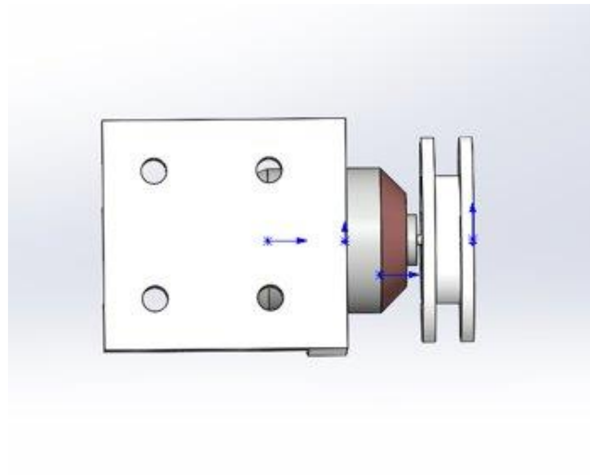

Figure 30. Pulley and Motor (Top View

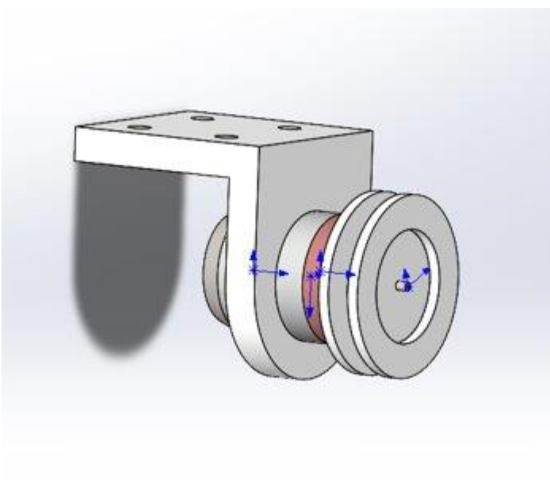

Figure 31. Pulley and Motor (Isometric View)

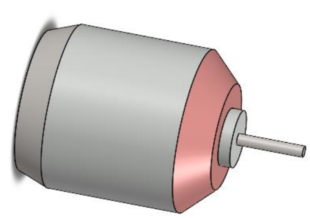

Figure 32: Brushless DC Motor

The manhole probing mission proved to be the most complex and involved of the four missions specified by United Consulting. One of the key aspects that resulted in this enhanced complexity was the introduction of specialized (and heavy) equipment. The purpose of the mission is the use a UAS system as a way to avoid exposing human workers to potentially toxic gases inside manholes. To perform the manhole probing mission, we are required to make use of handheld air sampling equipment (in the form of the LandTec and MultiRAE devices). However, United Consulting wanted to avoid lowering the UAS completely into the manhole, which means that the UAS needs to be capable of testing the air from a (vertical) distance. To this end, it was decided that the use of a flexible probe that could extend down into the manhole would be the best solution. To lower and raise the flexible probe, a pulley system has been designed.

There were several iterations of the pulley system subassembly. The model above (Fig. 31-33), was one of the earlier designs that proposed to bolt a mount holding the motor to the underside of the instrument box that the device would be held in. The mount held the motor, and the motor was attached to the pulley wheel. The motor could spin in either direction to turn the pulley wheel, which would either lower or raise the probe which would be wrapped around the wheel.

While this model had the benefit of simplicity, concerns quickly developed surrounding both the durability and stability of such a model. For one thing, being located directly under the modular attachment housing, and thus in between the landing gear, there was concern that the system could be damage if a hard landing was sustained. Additionally, there was not much in place to prevent the flexible probe tubing from swaying in the wind. In the end, we moved on to more developed designs.

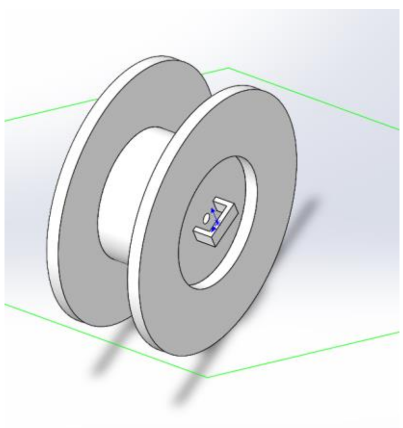

Figure 33: Pulley Wheel

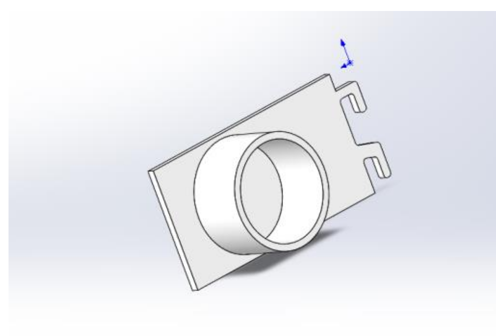

Figure 34: Pulley-Frame Arm (Motor)

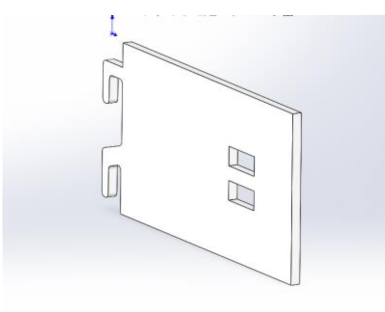

Figure 35: Pulley-Frame Arm (Spring)

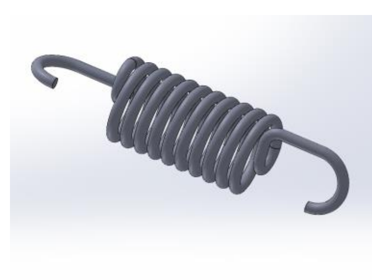

Figure 36: Pulley System Spring

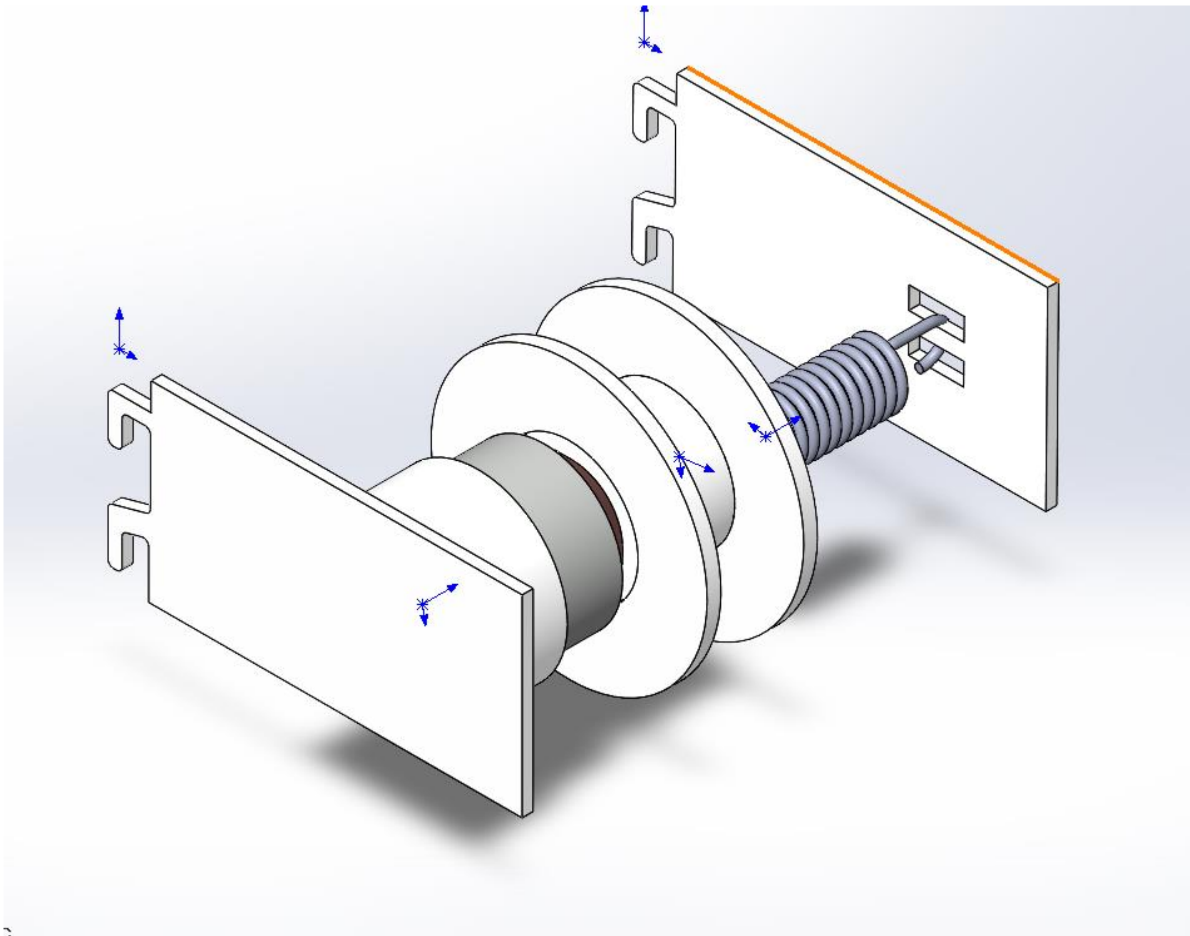

Figure 37: Final Pulley System Subassembly (Isometric View)

The final iteration of the pulley system subassembly is pictured above (as are all of the components). This iteration aimed to address some of the shortcomings of the previous design, primarily durability and stability. Rather than bolting onto the bottom of the modular attachment system, this version is designed to attach to the front of the UAS frame itself. There are two arms, 3D printed from ABS material. The arms are attached via hooks that will serve as a self-locking mechanism. This allows for the system to be secure without the need for excessive moving parts. The left arm serves as a built-in motor mount, while the right arm holds the tension spring in place. The purpose of the tension spring is largely to help the system maintain balance and reduce the amount to which the probe, or even the entire pulley system, will sway during movement. Should the pulley start to change position in the horizontal position, the spring will serve to pull the components back into their original positions. In addition, there will also be a counterweight on one end of the flexible plastic tubing to further increasing stability. The larger pulley wheel is able to accommodate more tubing length (over 12 feet), which should more than meet United Consulting’s goal of 6 feet down into the manhole. Overall, this design proved to be an overall more balanced system for the manhole probing application.

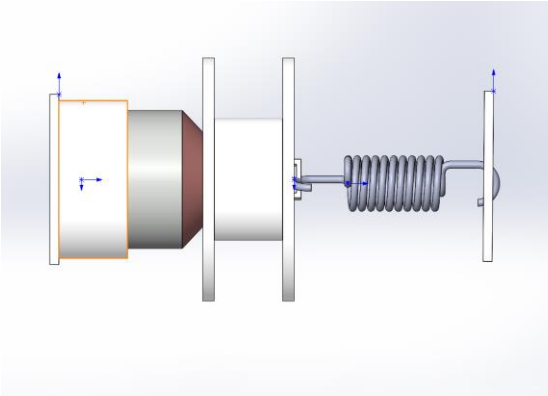

Figure 38: Final Pulley System Subassembly (Front View)

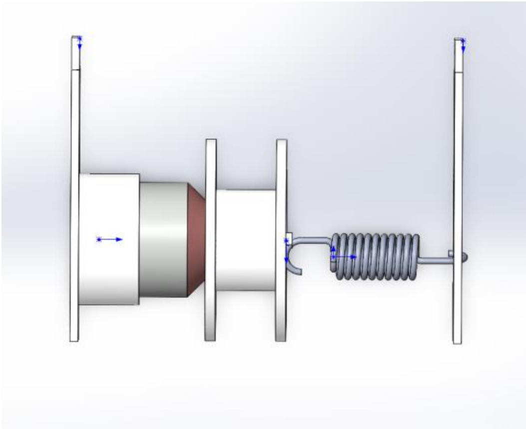

Figure 39: Final Pulley System Subassembly (Top View)

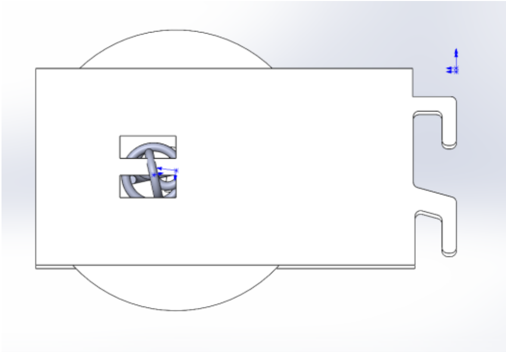

Figure 40: Final Pulley System Subassembly (Right View)

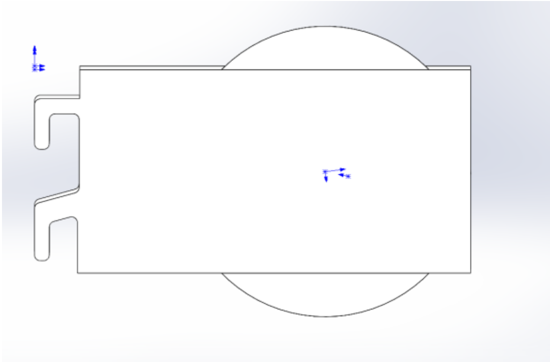

Figure 41: Final Pulley System Subassembly (Left View)

6.4 Mission Concepts:

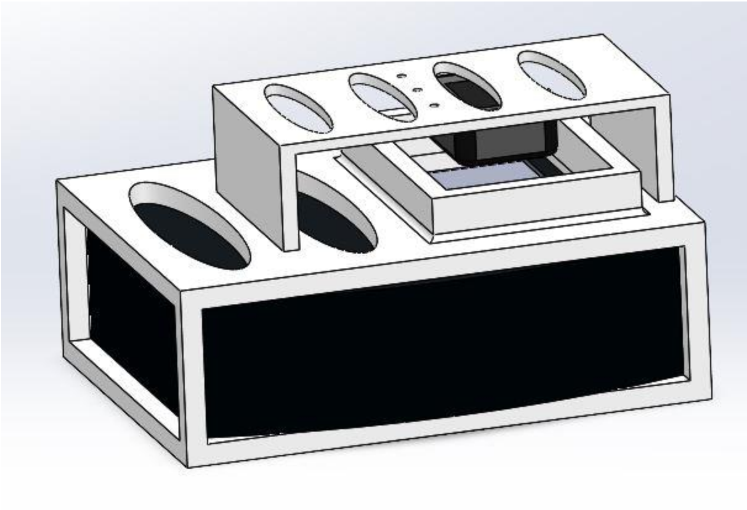

Figure 42. Mounting System with MultiRAE

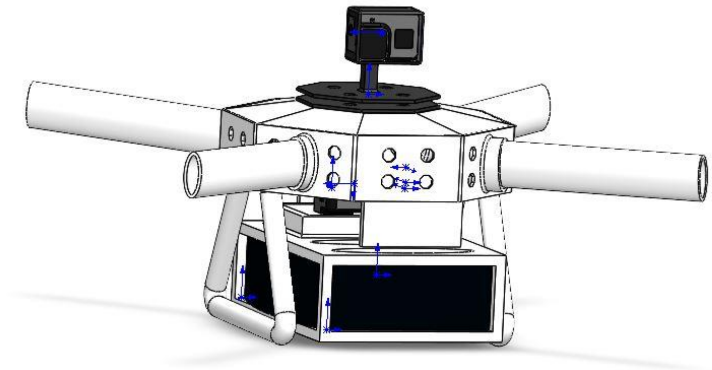

Figure 43. MultiRAE Mounted on Drone Body

The manhole probing mission has the most components. It will utilize either the LandTec GEM 5000 or the MultiRAE PGM-6228 as the air quality probing device and sitting just above it will be another camera to live view the screen. The top of the drone cover will come off, and the hardware will be attached through the bottom to secure the mounting equipment in place.

6.5 Layout Configuration:

The layout configuration consists of laying out all the electronic components, as well as the modular equipment and components. To ensure stability, the components' weight must be evenly and symmetrically distributed. The figure for this is still in progress and will include the layout of all components including the gimbal and modular equipment. The figure below is an example of the current progress made.

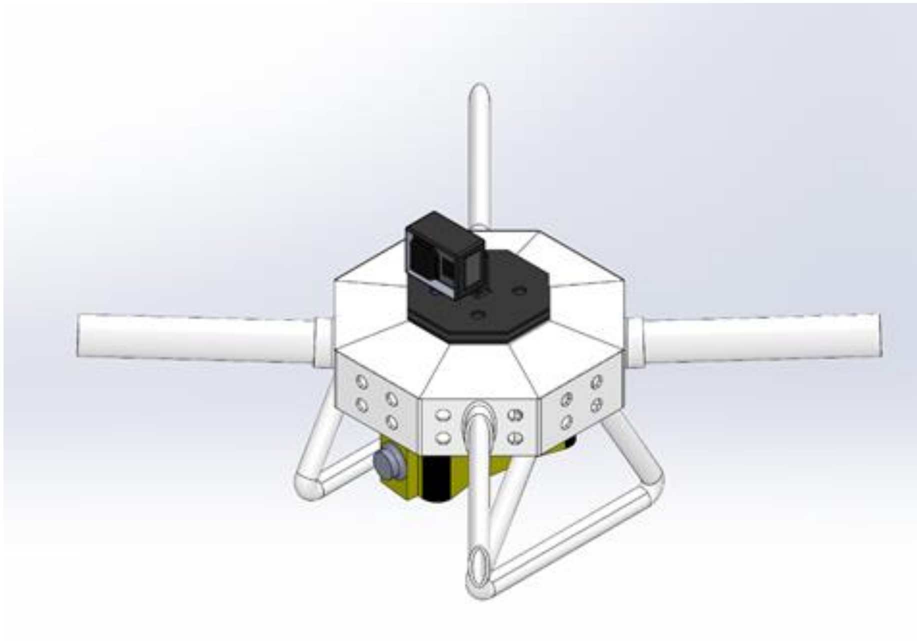

Figure 44. UAS with Gimbal Placement

Additional figures for the layout of the electronic components are shown below. In addition, it can be observed that the drone was able to maintain its center of gravity at the center for the baseline drone. This is important for stability during flight.

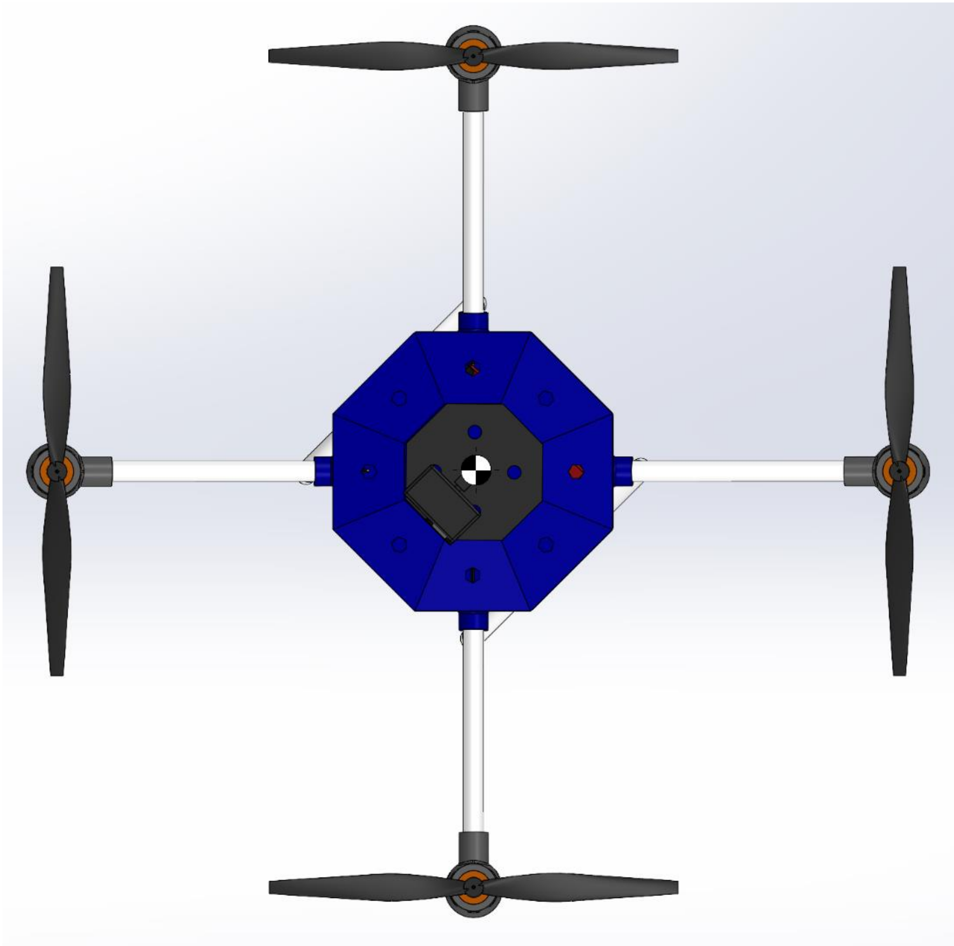

Figure 45. Top View of Drone with center of gravity

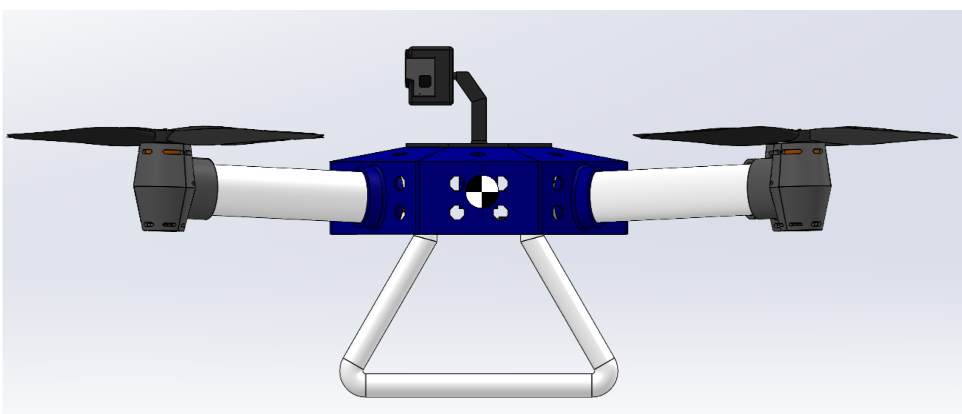

Figure 46. Side view of drone with center of gravity

The next figure shows the component layout of the drone. The GPS module and telemetry units are not included. The layout configuration is important because it determines how each component will fit and if the weight is equally and properly distributed. This layout is the latest iteration but will still have to be updated in the future. It is important to note that the flight controller must face the forward direction and be placed in the center. The GPS module also must be placed in the center for accurate telemetry data.

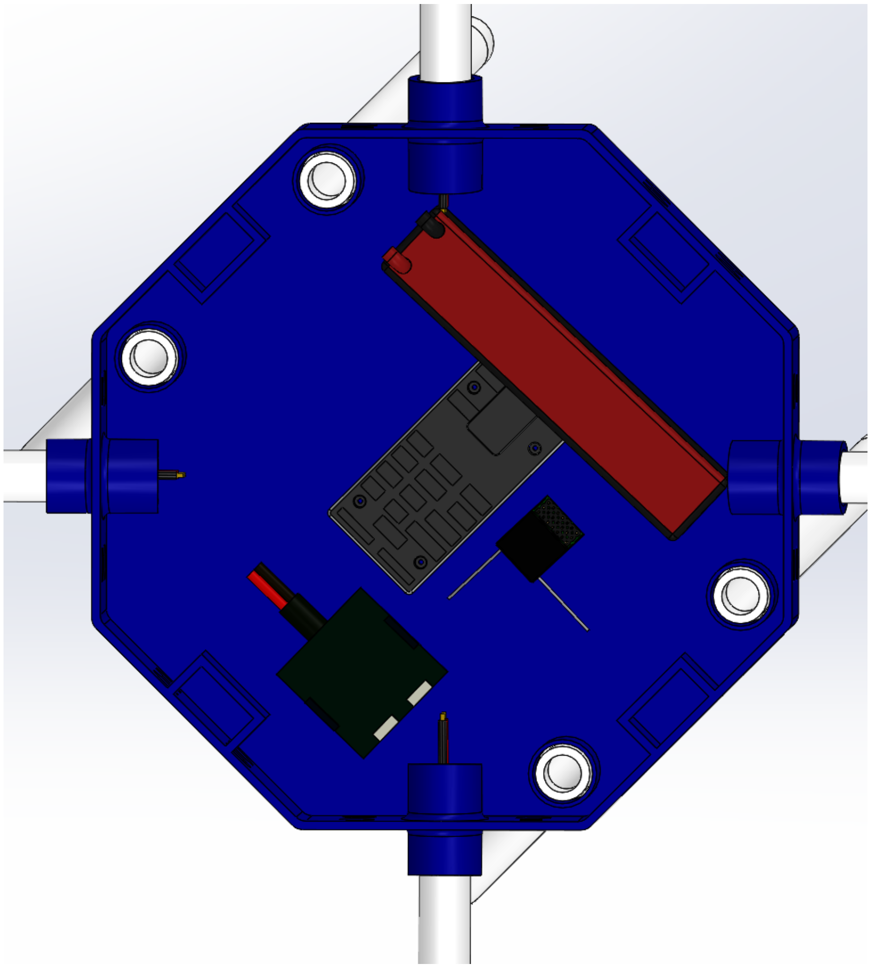

Figure 47. In-Progress Electronic Layout

Chapter 7: Calculations

7.1 Baseline UAS Sizing:

The weight of the baseline drone was calculated using Tables 12 and 13. This included totaling the total weight between the electronic components and the 3D printed components. Adding both weights will give the total takeoff weight of the baseline version of the drone. This will be useful in power calculations, simulation studies, and flight endurance calculations. The heaviest component on the baseline drone is the Venom Power LiPo 6s battery. This weighs a total of 770g and weighs more than twice the next heaviest electronic component.

Table 12. UAS Components Weight

Component	Name	Dimension	Weight	Quantity	Total Weight
Camera	GoPro Hero 8 Black	62mm x 45mm x 32mm (lwt)	116g	x1	116g
DC Lens	QKOO Macro Lens		108.9g	x1	108.9g
Flight Controller	Pixhawk 4 (SKU20034)	84mm x 44mm x 12mm (lwt)	15.8g	x1	15.8g
GPS	Pixhawk 4 GPS module	50mm diameter	32g	x1	32g
Telemetry	30R Telemetry Radio Set	-----	67g	x1	67g
Receiver	AR7700	29.8mm x 29.3 mm x 11.5 mm	13.75g	x1	13.75
Battery	ZDF 6s 22.2V 22,000 mAh Battery	160mm x 48.5mm x 46.5mm	2570g	x1	2570g
Lights	Firehouse Arc “V” Drone Light	38.1mm x 25.4 mm x 12.7 mm	13g	x6	78g
Gimbal	Tarot TL3T05 Brushless Gimbal	100mm x 75mm x 60mm	153g	x1	153g
ESC	Spektrum Avian 30 ESC	56mm x 27mm x 13mm	50g	x4	200g
Motor	Spektrum Firma 4000kv	36mm motor length, 52mm motor diameter	210g	x4	840g
Propeller	Hongyi Carbon Fiber	30 cm length	30g	x4	120 g
TOTAL					**4350.45g**

Table 13 displays the weight distribution by each 3D printed component. This included 3D printed components used in the missions utilizing modular equipment such as the mount system and pulley system components. The main frame of the drone was the heaviest part at 430.15g. All the parts are made of ABS plastic.

Table 13. UAS 3D Printing Costs

Component	Material	Weight	Quantity	Total Weight
Boom	ABS	77.14g	x4	308.56g
Landing Gear	ABS	102.49g	x2	204.98g
Frame	ABS	430.15g	x1	430.15g
Cover	ABS	165.96g	x1	165.96g
Motor Housing 1	ABS	29.44g	x4	117.76g
Motor Housing 2	ABS	22.10g	x4	88.40g
Pulley System 1	ABS	24.73g	x1	24.73g
Pulley System 2	ABS	6.39g	x1	6.39g
Mount System	ABS	92.78g	x1	92.78g
Mount System Box	ABS	5.69g	x1	5.69g
TOTAL				**1445.40g**

7.2 Mission Sizing:

It is useful to determine the weight of the drone at each mission it will perform. This is due to each mission utilizing different modular equipment. The heavier the mission, the lower the flight endurance will be. It is a requirement that the heaviest mission will fly a minimum of 30 minutes. As such, the main point of focus will be the manhole probing mission which going to be the heaviest mission. Table 14 displays the weight of the drone at each mission.

Table 14. Total Weight by Mission

Mission	**Weight (g)**
Mission 1: Surveying	5666.26 g
Mission 2: Weld Inspection	5666.26 g
Mission 3: Manhole Probing (with LandTec)	6927.85 g
Mission 3: Manhole Probing (with MultiRAE)	7693.85 g
Mission 4: Thermal/Infrared Imaging	5972.87 g

7.3 Power:

Utilizing the calculated weight, the power required of each motor is determined. This is found by utilizing the power equation shown below.

$$\text{Ideal Power} = W \times \sqrt{\frac{W}{2\rho A}}$$

The following table displays the parameters used to calculate the power. The biggest factors that affected the power were the areas of the four rotors and the mass of the drone. The mass used was the mass of the manhole probing mission since it was the heaviest at which the drone will be.

Table 15. Power Calculation

Mass (kg)	7.693kg
Weight (N)	75.468N
Rotor Diameter (cm)	30.0 cm
Rotor Radius of each blade (m)	0.15 m
Area per rotor (m^2)	0.0707 m^2
Area of 4 rotors (m^2)	0.2823 m^2
Density of air (kg/m^3)	1.225 kg/m^3
Ideal Power (W)	787.71W
F.M.	0.7
Actual Power for 4 rotors (W)	1125.3W
Power per motor (W)	281.33W

It was determined that each motor will have to supply at least 281.33 W to support the drone at its heaviest phase. This also considers 30 cm diameter propeller blades. The motors selected are presented in Chapter 5.

7.4 Flight Endurance:

A flight endurance of a minimum of 30 minutes is one of the requirements presented in Chapter 1. Using the information of the weight of the drone and the selected battery, it is possible to provide an estimate of what the flight endurance may be. In addition, the flight endurance is subject to change for each mission as each mission carries a different payload. The equations and assumptions below will be used to determine the flight endurance of each mission. Some assumptions include that there is minimal drone movement and that it mainly hovers. This is to give an initial estimate of how the drone will perform. During each mission, additional movement and functions can reduce the calculated flight endurance to roughly 70% and even 50% of the estimated time.

t: flight endurance or flight time of the drone [min]

C: battery capacity [mAh]

Bd: battery discharge [%]

AAD: average amp draw

Wt: take-off weight [g]

P: power required to lift one kg of equipment [W/kg]

V: battery voltage [V]

I: current [A]

EQ.7.4.1

$$t = (C \times Bd) / (AAD)$$

EQ.7.4.2

$$AAD = (Wt \times P) / (V)$$

EQ.7.4.3

$$AAD = Wt \times I$$

As stated, it will assume that the drone will spend most of its time hovering. If there is significant movement or other functions increasing the current usage, the flight time will decrease. The battery discharge weight is 100%. This comes from the ZDF battery that was selected. The power required to lift one kilogram was calculated to be 140 W/kg. This is a conservative estimate for less efficient systems. With this assumption, the flight endurances calculated will provide an estimate and not an exact time for how long the drone will fly for.

Mission 1 & 2: Weld Inspection and Surveying

Flight Endurance: **41.3 minutes**

This meets the requirement. Since these missions were the lightest, it makes sense for them to have the highest flight endurance. This flight endurance is higher than the average drone, so this can be considered a success.

Mission 3: Manhole Probing with LandTec

Flight Endurance: **26.1 minutes**

This mission failed to meet the requirement. Additional weight savings need to be made to increase the flight endurance. The LandTec is the heaviest module, so it aided in making the flight endurance below 30 minutes.

Mission 3: Manhole Probing with MultiRAE

Flight Endurance: **30.5 minutes**

The manhole probing mission with the MultiRAE unit successfully met the 30 minutes flight requirement. This means that the manhole probing mission can be conducted with the necessary time if the modular equipment is the MultiRAE unit.

Mission 4: Thermal/Infrared Imaging

Flight Endurance: **38.1 minutes**

The thermal imaging mission was also successful in meeting the minimum flight endurance requirement. The flight endurance for this mission is 38.1 minutes which is still a significant flight time for a drone.

Chapter 8: FEA Analysis

8.1 Mesh Convergence Analysis:

Mesh convergence analysis was conducted to determine at which number of blade elements the results converge. In the following figure, as the number of blade elements increased, the displacement decreased. At first the change in displacement was large, but then became smaller. This means that the data tends to be more accurate between 20-30 blade elements. As such, all the FEA studies performed were done with a mesh set in that range to ensure consistent and accurate results. This analysis was performed for the boom component. The figure is an example of mesh convergence analysis performed for one of the drone components.

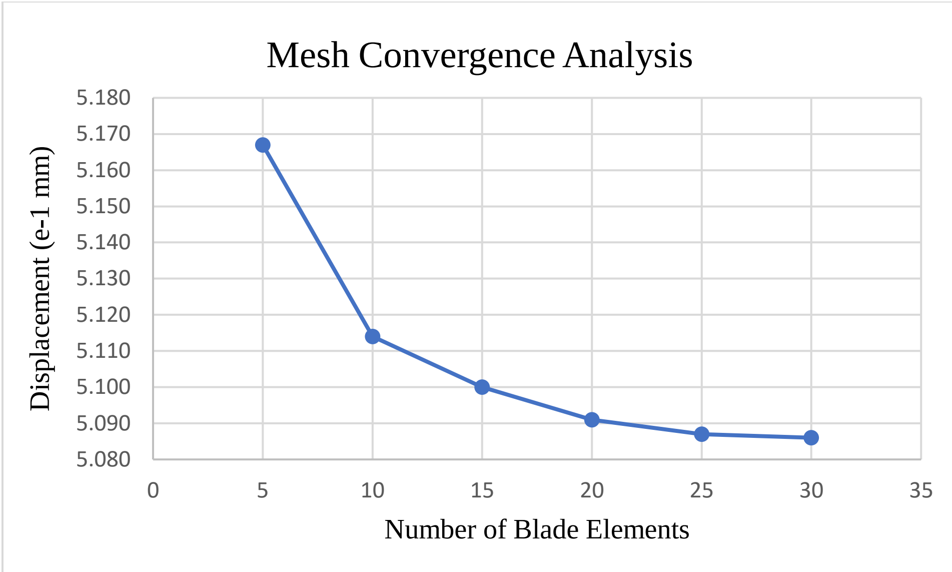

Figure 48. Mesh Convergence Analysis

8.2 Boom Design:

An important component is the boom of the drone. The boom not only supports the weight of the drone, but also holds the motor housing which contains the motor. The static study is conducted to compare the maximum stress and displacement that occurs at varying boom lengths. In addition, the shape of the boom and material it is made of is also analyzed. The results obtained will be useful in determining an optimal design. The goal is to find which properties will make the boom the lightest, strongest, and one with the lowest deflection. Tables 15 and 16 show the results of these simulations.

To conduct this study, a force had to be determined. This was done by multiplying the total weight of the drone by a factor of safety and dividing that by 4. This gives the force experienced per arm. Because the weight is known and will remain constant during flight, a factor of safety of 1.25 was chosen. This is a relatively low safety factor but is included to consider possible forces experienced due to wind. As mentioned, minimizing the weight is a big driving factor in the design of the drone. That is why the factor of safety is 1.25.

Force: weight x F.O.S. = 7500g x 1.25 = 9375g = 9.38kg / 4 arms = 2.34kg/boom

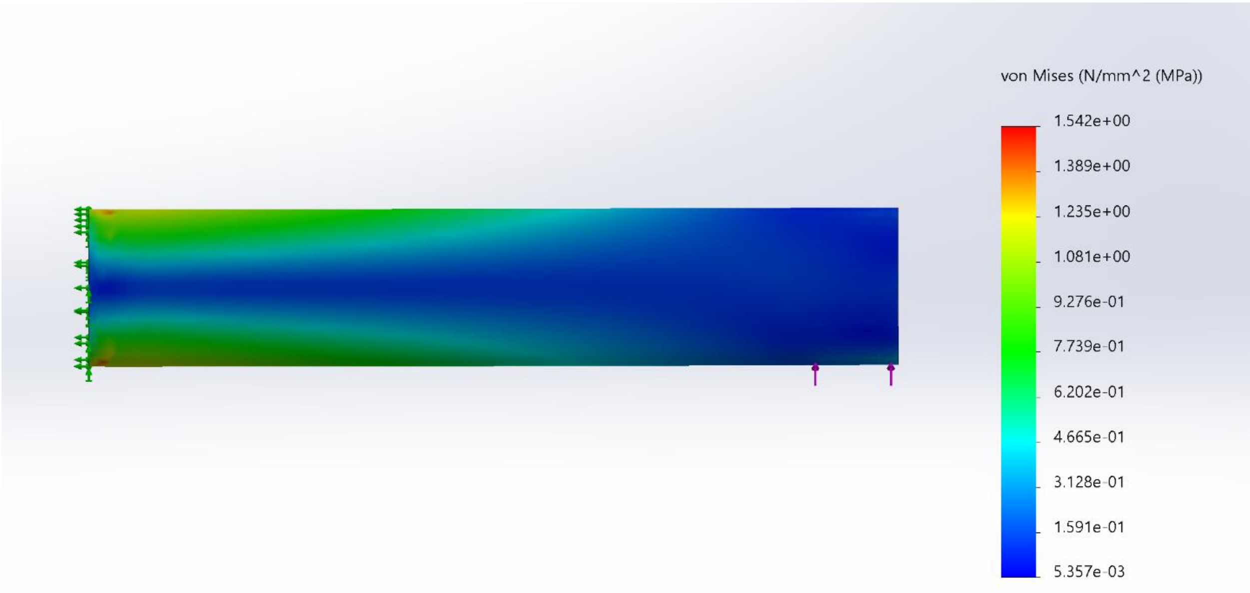

Figure 49. FEA Stress Results for ABS Oval Boom

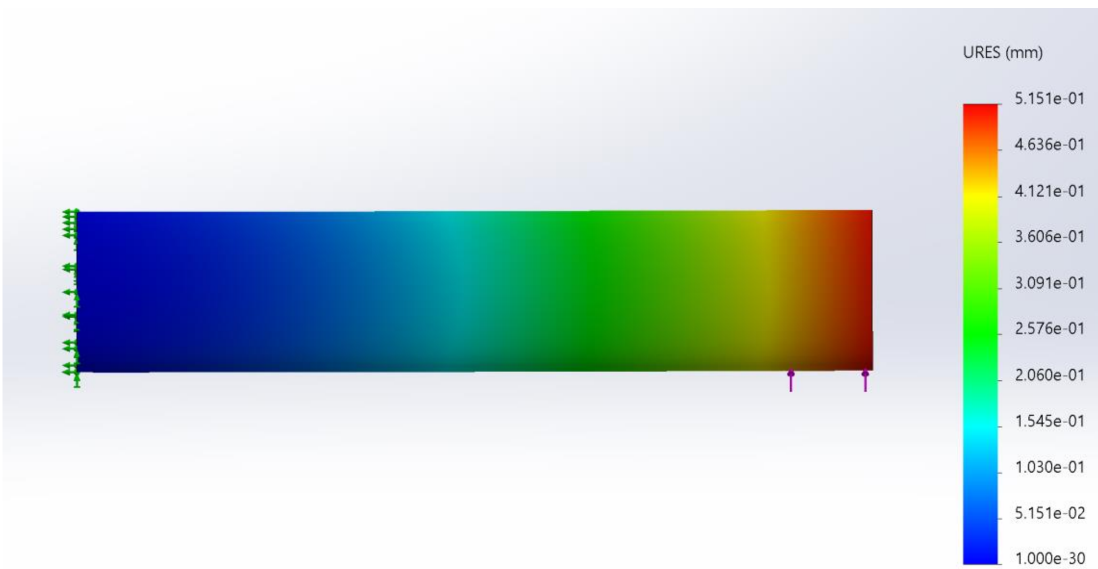

Figure 50. FEA Displacement for ABS Oval Boom

Table 16. Boom Design

Boom Length	Weight	Max Stress	Displacement
8in.	61.71g	1.361 N/mm^2 (MPa)	0.363 mm
9 in.	69.42g	1.542 N/mm^2 (MPa)	0.515 mm
10 in.	77.13g	1.710 N/mm^2 (MPa)	0.706 mm

As the boom length increased, the weight, stress, and displacement all increased. This study was performed for the oval shaped boom made of abs plastic. In addition to this data, power calculations will help determine the optimal length of the boom.

Table 17. Continued Boom Design

	Weight	Max Stress	Displacement
Circular ABS	47.26g	3.719 N/mm^2 (MPa)	3.247 mm
Circular PLA	60.23g	3.642 N/mm^2 (MPa)	1.850 mm
Circular Carbon Fiber	83.40g	3.686 N/mm^2 (MPa)	0.028 mm
Oval ABS	77.13g	1.786 N/mm^2 (MPa)	0.827 mm
Oval PLA	98.31g	1.788 N/mm^2 (MPa)	0.417 mm
Oval Carbon Fiber	136.12g	1.798 N/mm^2 (MPa)	0.007 mm

Based on Table 16, the boom displacement is less for the oval shaped boom. Also, since abs is the lightest material, the displacement was higher for it. It can also be observed the maximum stress experienced by the boom is lowest for the oval shaped boom made of abs. Due to its lightweight and strength, this design was selected.

8.3 Static Test Landing Gear:

Table 17 depicts the stress and displacement results from the static simulation for the landing gear component. This was an important area of study to determine whether the landing gear can withstand heavy loads. This FEA test was conducted for various loads including the weight of the drone and more than twice the weight of the drone. The results reveal that even at 12.5 kgf, the displacement of the landing gear was still less than 1 mm. This reveals that the addition of a second connection point to the frame made the landing gear more structurally safe despite the addition of some weight.

The next figure displays the setup of the static FEA analysis for the landing gear. The landing gear is fixed at the top portion. This is where the landing gear would be fixed to the main frame of the drone. The forces on the bottom are there to replicate the impact that the landing gear would feel upon landing.

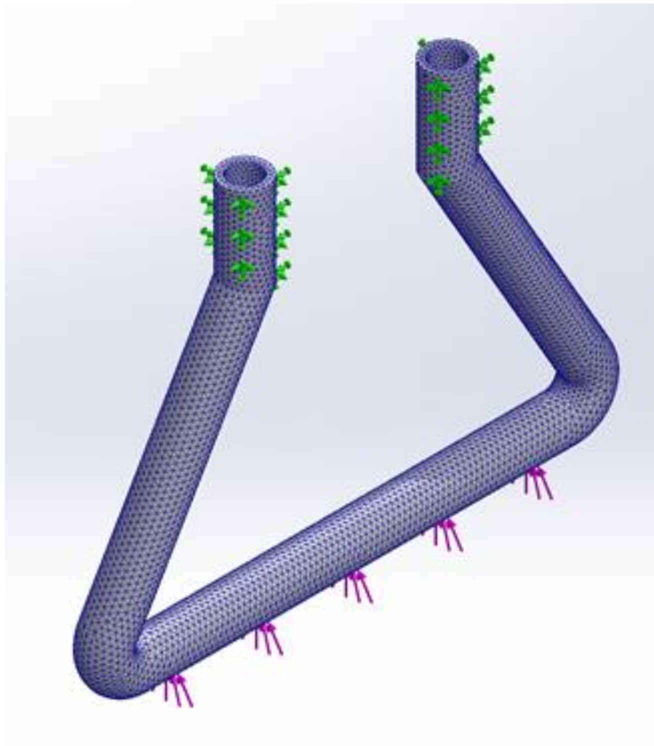

Figure 51. FEA Setup for Landing Gear

Table 18. Stress and Displacement Data for Landing Gear

Force	2.5 kgf	5kgf	7.5kgf	10kgf	12.5kgf
Max Stress N/mm^2 (MPa)	1.702	3.405	5.107	6.810	8.512
Displacement (mm)	0.162	0.323	0.485	0.647	0.809

The following figures display the FEA results for the landing gear at 12.5 kgf. It is important to observe the critical stress locations in the landing gear, because if the landing gear was to fail, it would be there. These locations are at the bottom where the landing gear bends and at the curve towards the top of the landing gear.

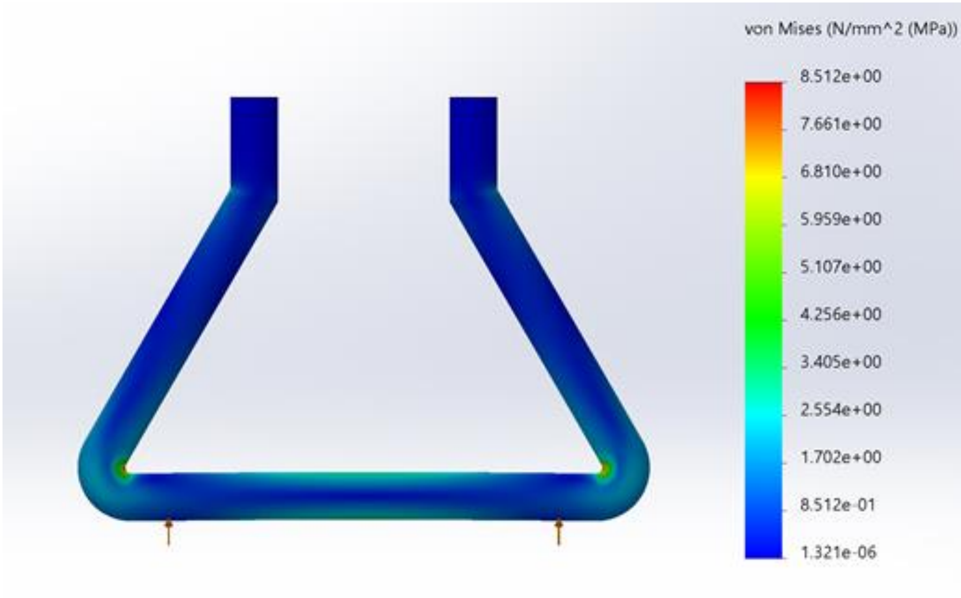

Figure 52. FEA Stress Results of Landing Gear at 12.5 kgf

The next figure shows the displacement of the landing gear. It is successful to see the landing gear displaced at the bottom middle, because the critical areas will not be affected. This ensures that the landing gear is safe and can withstand a high impact landing.

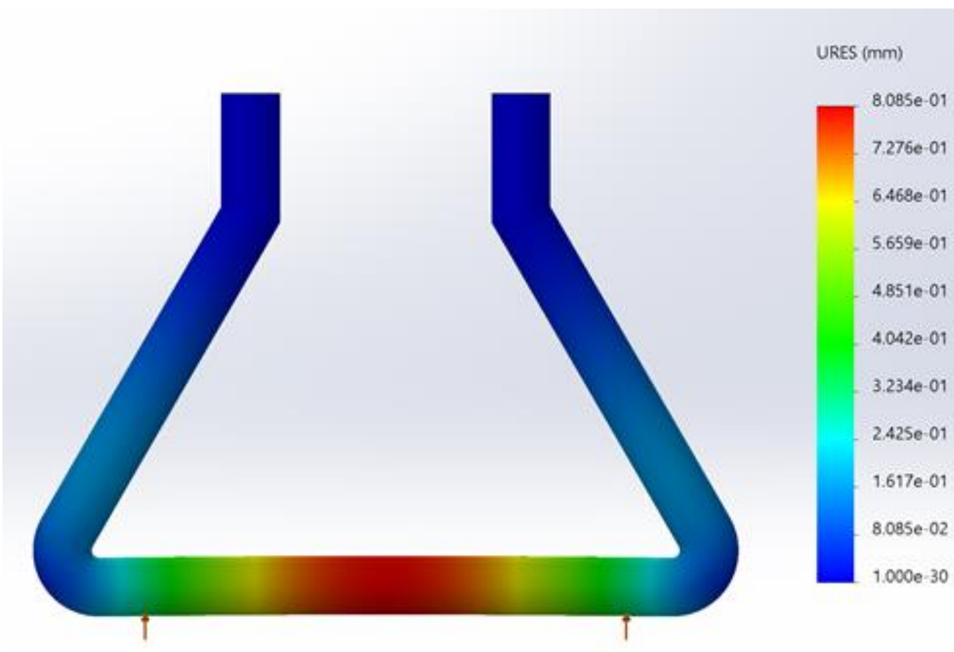

Figure 53. FEA Displacement Results of Landing Gear at 12.5 kgf

8.4 Mounting System Static Analysis:

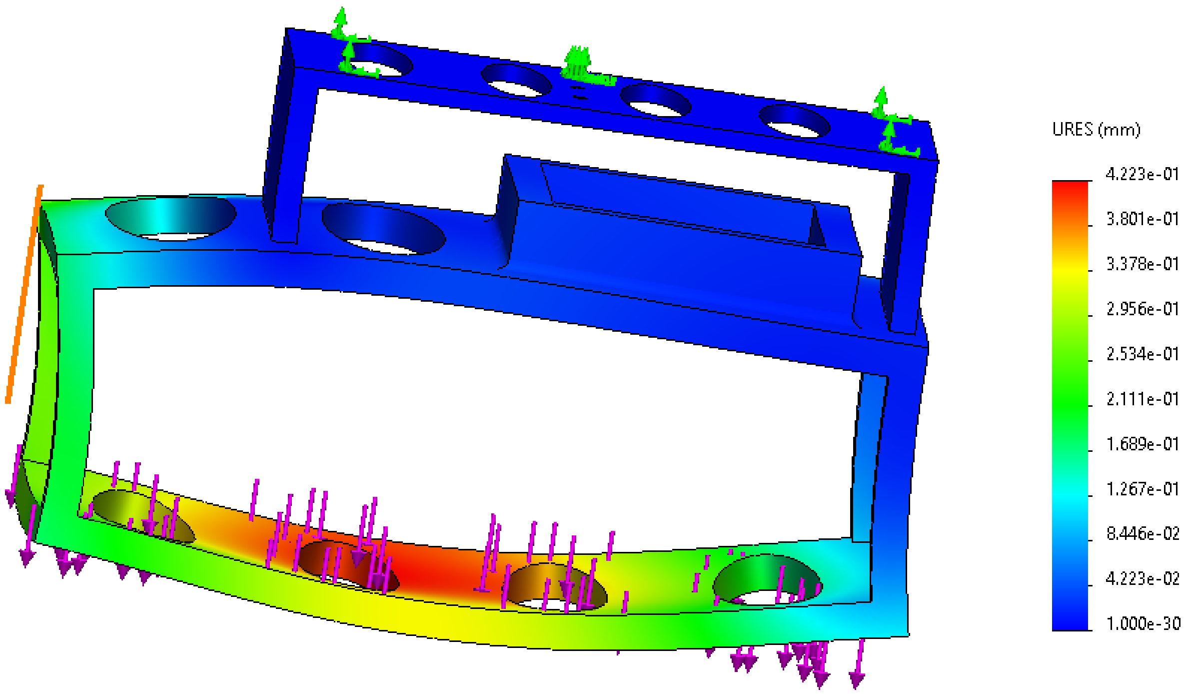

Figure 54. Static Study Displacement

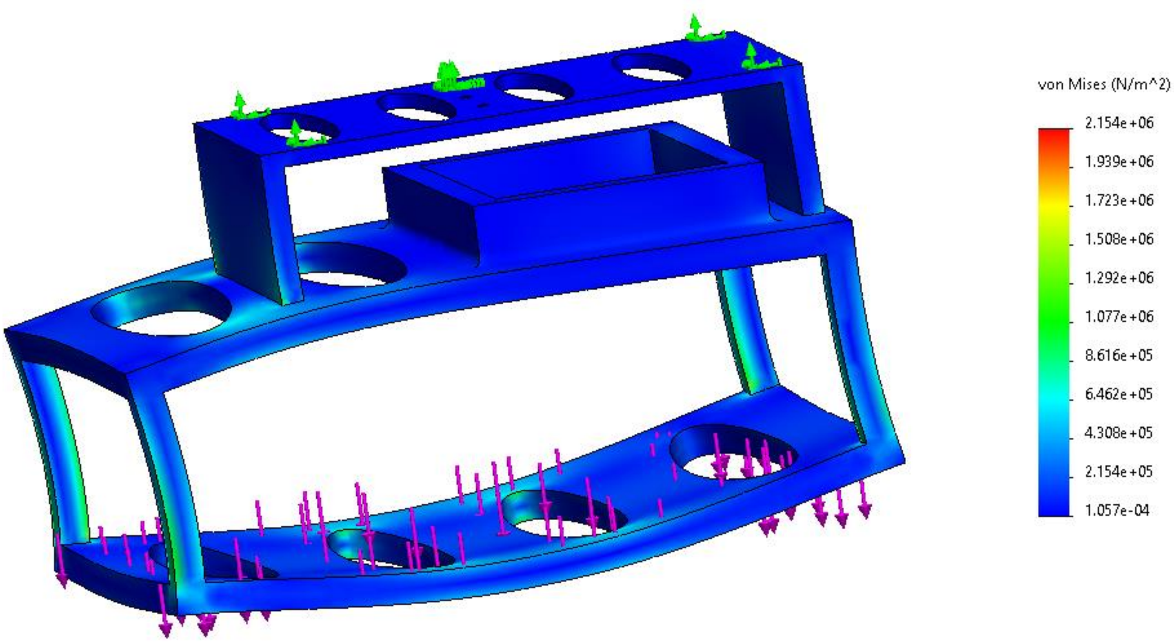

Figure 55. Static Study Stress

FEA was performed on the mounting bracket to aid in the process of the design. The static study was set up by having the top bracket be fixed and the bottom plate experience a 6 lbf load to simulate the

LandTec weight. The LandTec weights 1645 g, so 3.6lbs and I increased the load to get a higher factor of safety. In Figure 56, the maximum displacement is 0.422mm and in Figure 57, we see very low stress concentrations on the part.

8.5 Pulley System Static Analysis:

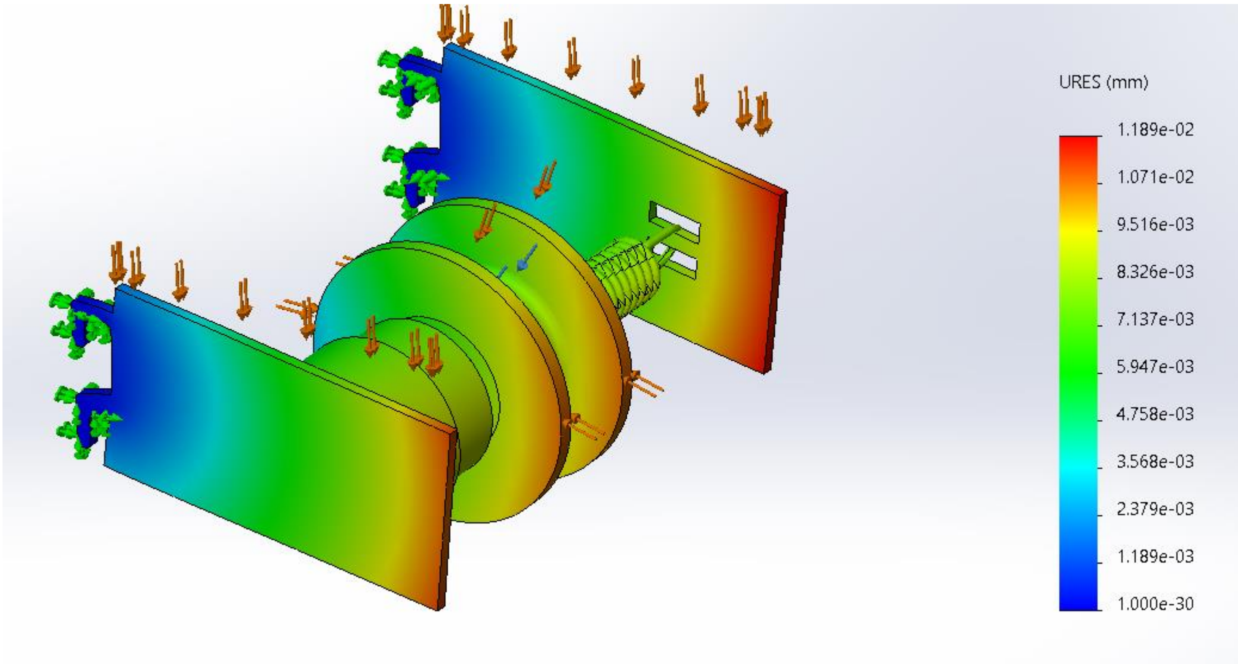

Figure 56: Pulley System Static Study Displacement

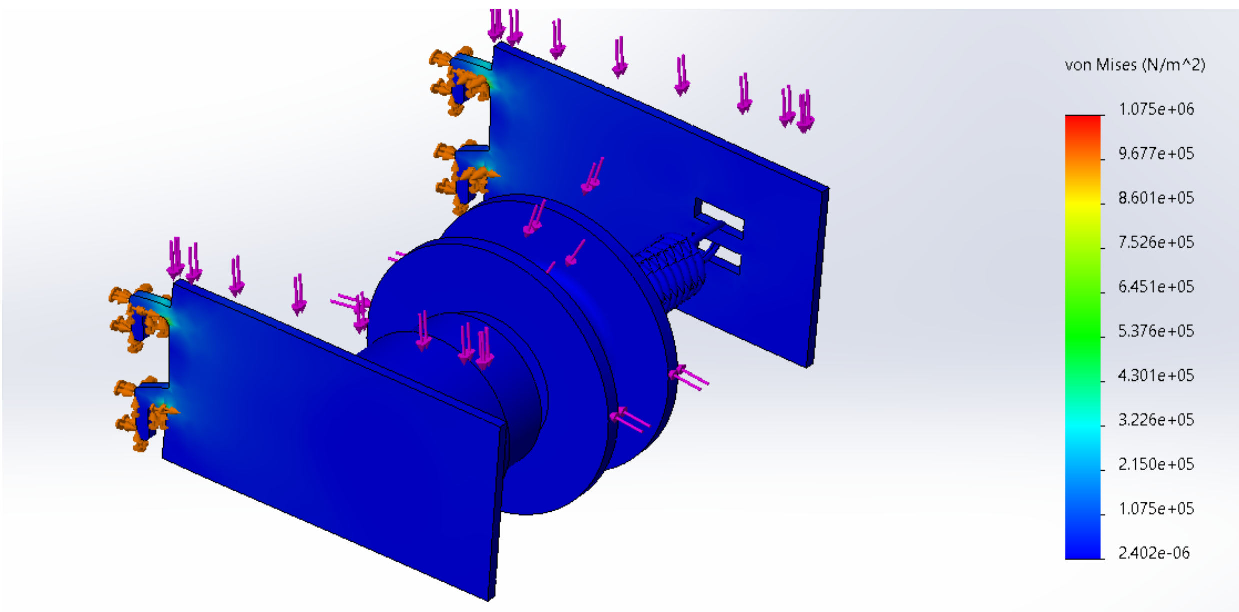

Figure 57: Pulley System Static Study Stress

As part of the iterative design process, the pulley system subassembly also underwent FEA analysis. In particular, a static study was conducted on the entire subassembly in SolidWorks. In terms of the study constraints, the hooked portion of the arms that connect to the frame was considered to be fixed.

This is because the arms would ideally move in unison with the frame. In terms of external loads, various values between 1-10 N were applied, based on the weight that 12 feet of ¼ inch PVC tubing would exert on the pulley system (roughly 1 N). Further allowances were made for factors of safety, the weight of the probe and counterweight, which are not presently known. Given the 5 N condition, the subassembly experienced a maximum deflection of 0.01189 mm in the downward direction, which is practically negligible. The stress is also negligible across most of the subassembly, except for the corner of the hook mechanisms. Sharp corners are known to be areas of stress concentration. It may be possible to reduce the stress in these areas by further rounding those interior corners.

8.6 Material Selection:

Material selection was another critical design choice that needed to be studied. The choice of material can impact the weight and structural safety of the drone. The density, ultimate tensile strength, and modulus of elasticity were some of the material properties explored when determining the best material for this project. Table 18 shows these properties for ABS, PLA, and Carbon Fiber materials. These three were explored due to their availability in the 3D printing center at Kennesaw State University. By working with the 3D printing center, a prototype can be developed efficiently.

Table 19. Material Properties

	Material Type		
Material Properties	ABS	PLA	Carbon Fiber
Density	1.06g/cm^3	1.24g/cm^3	1.6g/cm^3
Ultimate Tensile Strength	29.6 MPa	26.4 MPa	4000 MPa
Modulus of Elasticity	2.24 GPa	2.3 GPa	228 GPa

To compare the material selections, the weight was explored for each crucial component of the drone when made from each material. Table 19 reveals that ABS material was the lightest and that carbon fiber was the heaviest. Section 8.2 explored the resulting stress effects and displacement when using each material.

Table 20. Material Mass Evaluation

3D Printed Component	Volume (cm^3)	100% PLA (g)	100% ABS (g)	100% Carbon Fiber (g)
Boom	68.07	88.49	69.43	122.52
Landing Gear	100.48	130.63	102.49	180.87
Frame	415.06	539.58	423.36	747.11
Cover	155.81	202.55	158.92	280.45
Motor Housing	69.19	89.95	70.58	124.55

Chapter 9: Fabrication

9.1 Tolerance:

Due to the many different components and how they fit together, tolerancing was an important consideration when making a CAD model in SolidWorks. The biggest areas of concern regarding tolerancing involved the connections between the motor housing and the boom, the frame and the boom, the cover and the frame, and the landing gear and the frame.

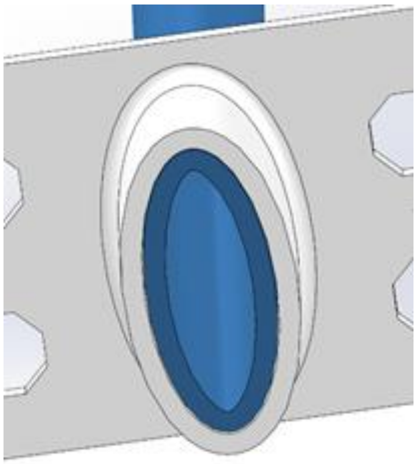

Figure 58. Boom and Main Frame Connection

The previous figure illustrated the connection between the boom and the main frame of the drone. The boom was 0.75 in. wide and 1.75 in. tall. A tolerance of 0.08 in. (2 mm) was used. The same tolerance was used for the landing gear and main frame connection and the boom and motor housing connections. These tolerances are also shown in the table to be uploaded.

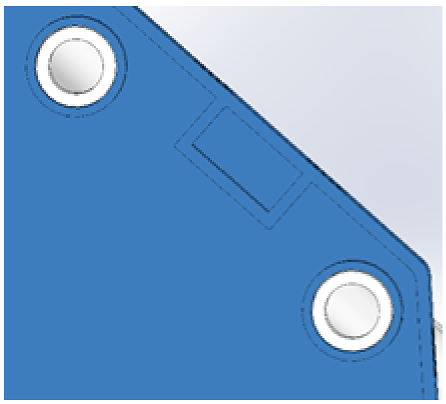

Figure 59. Landing Gear and Main Frame Connection

Figure 45 shows the connection between the landing gear and main frame assembly. A 2 mm tolerance was also applied to the main frame. The diameter of the landing gear is 0.8 in, and the diameter in the main frame is 0.879 in. This will ensure a tight fit between both components.

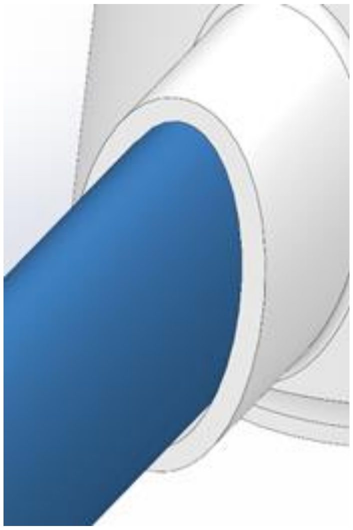

Figure 60. Boom and Motor Housing Connection

The connection and tolerance between the boom and motor housing is the same as shown in Figure 44.

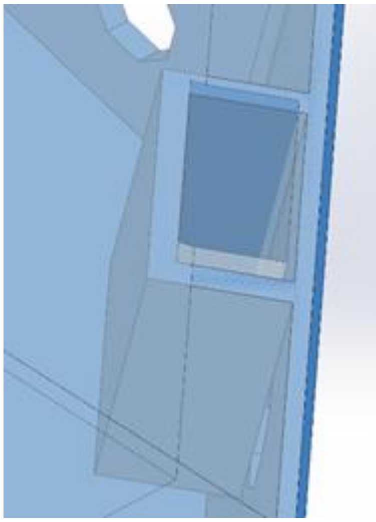

Figure 61. Cover and Main Frame Connection

The last important tolerance to consider was the connection between the cover and main frame. The tolerance in this situation is also 2 mm. An assembly in SolidWorks was used to determine the proper fit and dimensioning for this connection.

9.2 Assembly:

One beneficial factor from this design is that the assembly process is not complex. In the following figure an exploded view of the motor housing is shown. This assembly is only made up of five components. The motor fits between both halves of the motor housing before sliding into the boom. These parts will all be fastened with screws.

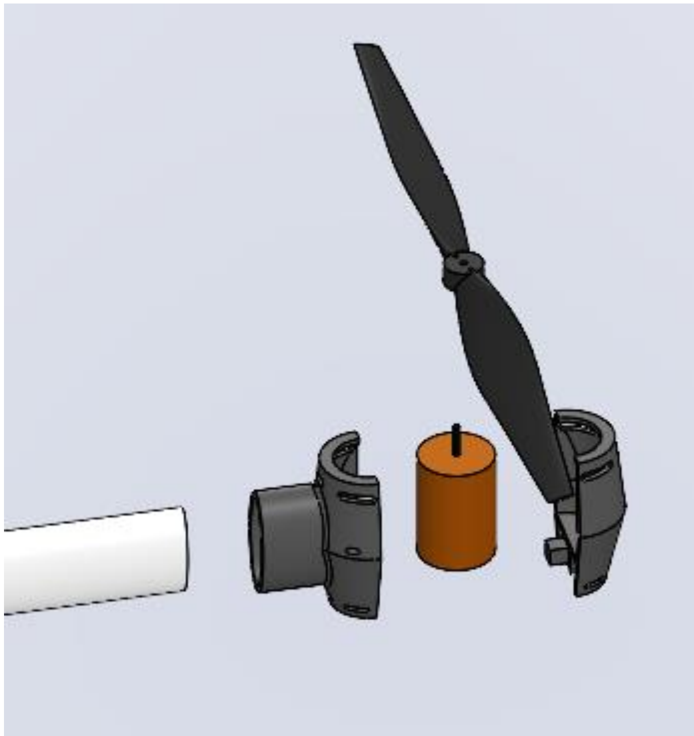

Figure 62. Motor Housing Assembly

The exploded view of the entire drone shows how the booms, landing gear, and cover fit with the main frame. All these components will also be screwed in.

9.3 Fabrication Procedure:

As stated, the drone will be 3D printed of ABS material. This drone consists of 16 parts. These parts include the booms (x4), motor housing (x8), cover (x1), main frame (x1), and landing gears (x2). The following figure shows an exploded view of the components and how they will fit and be fabricated together. They will be fastened with screws. A small tolerance of 2mm was used to ensure a tight and sturdy fit. The figure below shows how each part is connected.

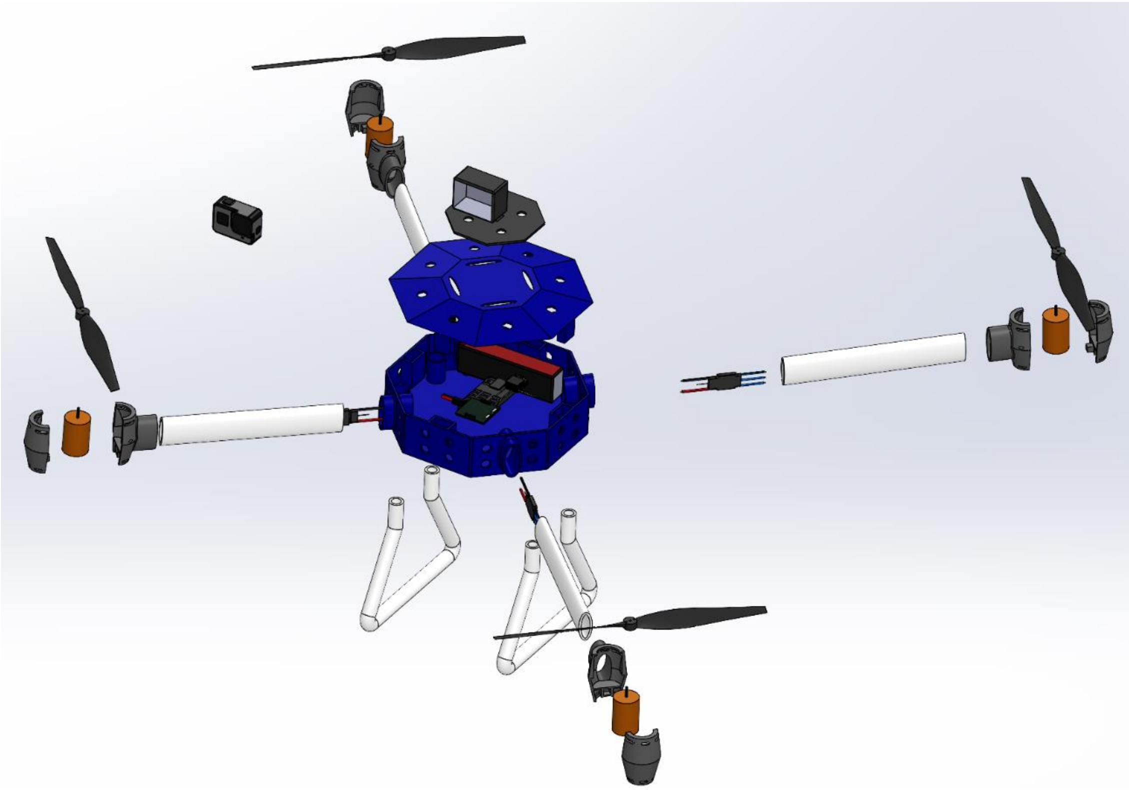

Figure 63. UAS Exploded View

Chapter 10: Results & Discussion

10.1 Results:

After creating a design and performing calculations and simulations, a final design has been developed. This drone consists of components that were strategically designed for optimal performance and structural stability. The booms were designed in a hollow oval shape made of ABS material. The oval shape provided better structural stability and safety to the booms. The material was chosen specially for its good strength to weight ratio when compared to PLA and Carbon Fiber. The booms were also made hollow for light weight purposes and to hold the ESC and wires that connect the motor to the flight controller. The landing gear was designed with two connections to the main frame to reduce the load felt by the landing gears. These designs have been 3D printed and assembled. The final prototype was a half-scale model that details the parts of the drone and how they all connect.

Ultimately, the objective was to design this drone to perform the specified missions. Weights and flight endurances were determined for each mission. Mission 1 and 2 the surveying and weld inspection missions had weights of 5666.26g respectively. Their calculated flight endurance was 41.3 minutes. They were the same because each mission comprised of baseline components. They did not have additional modular equipment that was needed to be able to perform the missions. Next, for mission 3, the manhole probing mission weighed 6927.85g and 7693.85g for the MultiRAE and LandTec units. The flight endurance was calculated to be 26.1 minutes and 30.5 minutes respectively. Lastly, for mission 4, the thermal imaging mission, the weight was calculated to be 5972.8g. This led to a flight endurance of 38.1 minutes.

Based on these results, all the missions satisfied the flight endurance requirement of a minimum of 30 minutes except for the manhole probing mission utilizing the LandTec air sampling unit.

10.2 Discussion:

A half-scale prototype was developed. Even though the goal was for a flying prototype, progress on the electronic component selections, UAS design, pulley system design, and mounting system has been made. A report detailing and defending each selection has been made and can be used to progress this project. The design ended up being a quadcopter with oval booms and triangular landing gear. All decisions have the engineering process behind it, and it is ready to continue into a next phase to finalize everything.

Chapter 11: Conclusion & Recommendations

11.1 Conclusion:

The primary objective of this project was to design an unmanned aerial system (UAS) that would satisfy the requirements presented by United Consulting. These requirements included endurance limits, size constraints, equipment requirements, and cost considerations. In this report, each requirement is examined, and we find that the current design successfully meets each requirement. The only mission that did not fulfill the given requirements was the manhole probing mission, which only reached an endurance limit of 26 minutes rather than the desired 30 minutes.

11.2 Recommendations:

Looking back over the past two semesters shows a lot of what the team was able to accomplish, but also the sections that are lacking and would need more attention to bring this project to full fruition. First, this team has a lack of knowledge or experience with electronic components and that caused several slowdowns during this project. For this project to be fully successful, it would be beneficial to add a team member with expertise in electronics and programming. A team with a larger diversity of skillsets should prove well equipped to handle the design of such a complex system.

This report gives a foundation for what an idea for the mounting and pulley systems could be, but they can still be explored further and improved. One point specifically to focus on is the attachment of the pulley to the mounting system. In general, joints between distinct components tend to be the most susceptible to stress-related failures. As such, the project will benefit from a more comprehensive structural analysis of these connections (i.e., landing gear to frame, mounting system to frame, boom to motor housing, etc.) Other analysis methods, including buckling and fatigue will be useful for examining various parts of the UAS.

Concerning calculations, the next team should do continue to perform endurance limit calculations and refine the range of flight times the user can expect to experience. The overall design should continue to be examined, with the goal of optimizing the endurance limit for each mission, but particularly the manhole probing mission. Consider design configurations that result in higher endurance limits. Exploring further weight saving methods is a strong place to start. It may also be advisable to research alternative electronic components. As always, comprehensive literature review into how other groups are solving similar challenges should be constantly ongoing.

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Chapter 5

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[5.5] **Spektrum iX12 Transmitter, description, specifications, purchase**

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[5.6] **LiPo 6s Venom Battery, specs, description, purchase**

"22.2V 5000mAh 6s 50c fly Lipo Battery: Uni 2.0 plug," *Venom 22.2V 5000mAh 6S 50C FLY LiPo Battery: UNI 2.0 Plug | Horizon Hobby*. [Online]. Available: https://www.horizonhobby.com/product/22.2v-5000mah-6s-50c-fly-lipo-battery-uni-2.0-plug/VNR25048.html. [Accessed: 10-Nov-2021].

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Chapter 7

[7.1] **Flight Endurance Calculation**

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[7.2**] KSU 3D Printing Center, price, material**

"3D printing materials," *3D Center*. [Online]. Available: https://centers.kennesaw.edu/3dcenter/3d-printing-services/3d-printing-materials.php. [Accessed: 10-Nov-2021].

Appendix

A.1 Acknowledgments:

The team would like to extend its gratitude to Dr. Adeel Khalid for advising the team throughout the project by lending his experience and knowledge. In addition, special thanks to United Consulting and their engineers for providing the opportunity to work on this project.

A.2 Contact Information:

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Role: UAS Mount Design Engineer

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A.3 Reflections:

Maurice Boone:

The famed artist and inventor, Leonardo Da Vinci, once said that "art is never finished, only abandoned." A good engineering project is much the same, never truly finished, only finished for now. There is always further to go. I am extremely grateful to have had the opportunity to be a part of this challenge. Even though we did not accomplish all of our goals, we learned a tremendous amount in the process. As a collective, we learned about teamwork, communication, and the importance of organization. As an individual, I was able to further develop my knowledge of 3D printing, mechanical design and system optimization. I look forward to seeing this project continue to evolve into a viable asset that will benefit United Consulting. I would like to thank my teammates, Vlad Mandzyuk and Sydney Crandall, for their hard work and friendship. I would like to thank Dr. Adeel Khalid for his guidance and leadership. Finally, I would like to thank United Consulting for not only giving us chance to complete this project, but also for granting us the creative license to make the solution our own.

Sydney Crandall:

This project has been an incredible learning experience. It truly required the culmination of all our knowledge and was still extremely challenging. This was a big project for three people with all the same backgrounds, but we were able to come together and make progress on most of the requirements. As always, looking backwards makes one hyperaware of issues and regrets of not doing more, but overall, this was a satisfying project to work on. This was the first time I had a product 3D printed, so it was extremely gratifying to physically hold something you designed from scratch. I want to thank United Consulting for this opportunity and Dr. Khalid for presenting me with this project to work on and his continuing guidance.

Vlad Mandzyuk:

This project has provided an invaluable learning experience of what it requires to make it as an engineer. Ultimately, it is disappointing to not produce a working and flying prototype before the semester ends, but the work that was done should not be taken for granted. I've gained valuable experience in performing literature review over subjects not originally in my field of expertise, creating and following a schedule, communication skills, and following the engineering design process to create a design. In addition, I have learned to use the 3D printer where my team and I were able to build a half-scale prototype. I want to thank Dr. Khalid for lending us his experience and helping us along the way. Lastly, I would like to thank United Consulting for believing in me and giving me the opportunity to help their company.

A.4 Challenges:

Taking on this project has provided many challenges for the team. The biggest challenges involved electronics and programming. With only mechanical engineers on the team, it proved to be a challenge to find compatible components and determine how to wire them together within a semester's time. The pulley system and mount system also proved to be challenging. These systems had to function to meet United Consulting's requirements. It was a challenge to make the modular systems convenient to take on and off the drone while also maintaining the structural safety of these parts. Overall, these challenges are not an excuse, but obstacles the team had to face throughout the semester.

A.5 Contributions:

Table 21. Member Contributions by Chapter

Chapter	**Contributor**
Executive Summary	Vlad Mandzyuk Maurice Boone
Chapter 1: UAS for Surveying, Thermal Imaging, and Air Quality Testing	Vlad Mandzyuk Sydney Crandall Maurice Boone
Chapter 2: Literature Review	Vlad Mandzyuk Sydney Crandall Maurice Boone
Chapter 3: Project Overview	Vlad Mandzyuk Maurice Boone
Chapter 4: Trade Studies & Benchmarking	Sydney Crandall
Chapter 5: Components	Vlad Mandzyuk Sydney Crandall Maurice Boone
Chapter 6: Design Concepts	Vlad Mandzyuk Sydney Crandall Maurice Boone
Chapter 7: Calculation	Vlad Mandzyuk Sydney Crandall Maurice Boone
Chapter 8: FEA Analysis	Vlad Mandzyuk Sydney Crandall Maurice Boone
Chapter 9: Fabrication	Vlad Mandzyuk
Chapter 10: Results & Discussion	Sydney Crandall Vlad Mandzyuk Maurice Boone
Chapter 11: Conclusion & Recommendations	Sydney Crandall Vlad Mandzyuk

	Maurice Boone
References:	Vlad Mandzyuk Sydney Crandall Maurice Boone
Appendices:	Vlad Mandzyuk Sydney Crandall Maurice Boone

Table 22. Member Contributions Specific

Contributor	Specific Contribution
Vlad Mandzyuk	**Report:** Created the report outline, updated the table of contents, list of figures, and list of tables. **Chapter 1:** Wrote the introduction, system overview, objective, and justification. Corrected the mission profiles. Created Tables 1-4. **Chapter 2:** Reviewed and referenced sources 2.1-2.4. **Chapter 3:** Wrote the requirements including making Table 5, the minimum success criteria, the Gantt chart. Created Figures 6-8. **Chapter 4:** Outlined and reviewed chapter. Selected and review 10 existing drones for benchmarking. **Chapter 5:** Described the sampling equipment and made Table 10. Wrote entire Electronics and Components section. Selected the flight controller, receiver, transmitter, lights, battery and sensors. Created CAD placeholders for each part in assembly. **Chapter 6:** Created the baseline UAS. Made a CAD for the drone frame, cover, boom, landing gear, and motor housing. Generated an assembly of UAS. **Chapter 7:** Created Tables 12-14. Filled out based on information present at the time. Researched flight endurance calculation and performed them for each mission. Performed sizing calculations for each mission of the UAS. **Chapter 8:** Created Tables 15-17. Performed a mesh convergence analysis and did FEA boom study. Performed static analysis on boom and landing gear. Material and shape study. **Chapter 9:** Researched and made tolerance for CAD models to ready for 3D printing. Developed CAD models to show layout and exploded view. **Chapter 10:** Wrote results and discussion.

	Chapter 11: Wrote the conclusion. **References:** Wrote the references for literature review 2.1-2.4. Cited electronic selections, and calculation methods. **Overall Project:** Scheduled meetings at least 1-2 times a week to review progress. Created a list of tasks. Spent significant time on drone CAD models making up to five iterations of the drone, researched components, performed calculations and simulations. Wrote a significant portion of report. **Presentation:** Prepared most of the presentation for all presentations. **Video:** Wrote the script, recorded the shots, and edited the video. **3D Printing:** 3D printed all the components and fabricated the scaled prototype.
Sydney Crandall	**Report:** Formatted all tables and figures, ensured overall formatting of the report for smooth flow and proper report standards **Chapter 1:** Wrote Mission profile synopses, made mission profile figures **Chapter 2:** Reviewed and referenced sources 2.5-2.8 **Chapter 4:** Primary author of chapter, made Table 9, reviewed and referenced drones **Chapter 5:** Selected the battery, camera, and gimbal; wrote corresponding sections for the components **Chapter 6:** Designed and created the mount systems and assembly and parts. Created CAD models for demonstration and exploded views for ease of viewing. Wrote section for explanation of system. Created figures **Chapter 7:** Filled out Tables for the battery, gimbal, camera, and mounting systems **Chapter 8:** Performed FEA on mounting system, created figures, wrote explanation sections **Chapter 10:** Wrote results **Chapter 11:** Wrote conclusion and recommendations **Presentation:** Prepared slides for all class presentations, Primary contributor of final presentation
Maurice Boone	**Report:** Formatting for tables and figures, editing for grammar as well as content **Chapter 1:** Wrote portions of introduction, system overview and justification **Chapter 2:** Reviewed and referenced sources 2.9-2.19 **Chapter 3:** Wrote portions of budget, minimum success criteria **Chapter 5:** Component selection (motors, ESCs, propellers, etc.) **Chapter 6:** Designed pulley system subassembly (multiple iterations). Created CAD models. **Chapter 7:** Performed Power Calculations, Sizing Calculations **Chapter 8:** Performed FEA analyses of pulley system subassembly **Chapter 10:** Wrote results **Chapter 11:** Wrote conclusion and recommendations

	Presentation: Prepared slides for class presentations **Poster:** Prepared significant portions of poster **3D Printing:** Printed or assisted with printing of all 3D printed components