Spring 5-16-2014

Adding Vision to a Quadrotor: A Design-Build-Test Adventure

Darren Tinker
Western Kentucky University, darren.tinker542@topper.wku.edu

Recommended Citation

Tinker, Darren, "Adding Vision to a Quadrotor: A Design-Build-Test Adventure" (2014). *Honors College Capstone Experience/Thesis Projects.* Paper 479.
http://digitalcommons.wku.edu/stu_hon_theses/479

ADDING VISION TO A QUADROTOR: A DESIGN–BUILD–TEST ADVENTURE

A Capstone Experience / Thesis Project

Presented in Partial Fulfillment of the Requirements for

the Degree Bachelor of Science with

Honors College Graduate Distinction at Western Kentucky University

By

Darren C. Tinker

*****

Western Kentucky University
2014

CE/T Committee:

Dr. Julie Ellis, Advisor

Dr. Joel Lenoir

Trudy-Ann Crossbourne

Approved by

____
Advisor
Department of Engineering

ABSTRACT

Quadrotors are small and exceptionally agile vehicles with maneuverability that permits both indoor and outdoor flight. The vast majority of quadrotors are flown autonomously as drones or remotely by a human-operator. Applications of quadrotors range from commercial deliveries, to military and law reconnaissance as well as research tools for various fields. Our lab at Western Kentucky University built a quadrotor in 2013, and we have been exploring various modifications to refine its performance and various applications in which it could be productively employed. Recently, research has focused on the addition of a camera to add capabilities for first person view (FPV) piloting, photogrammetry, and real-time visual inspection.

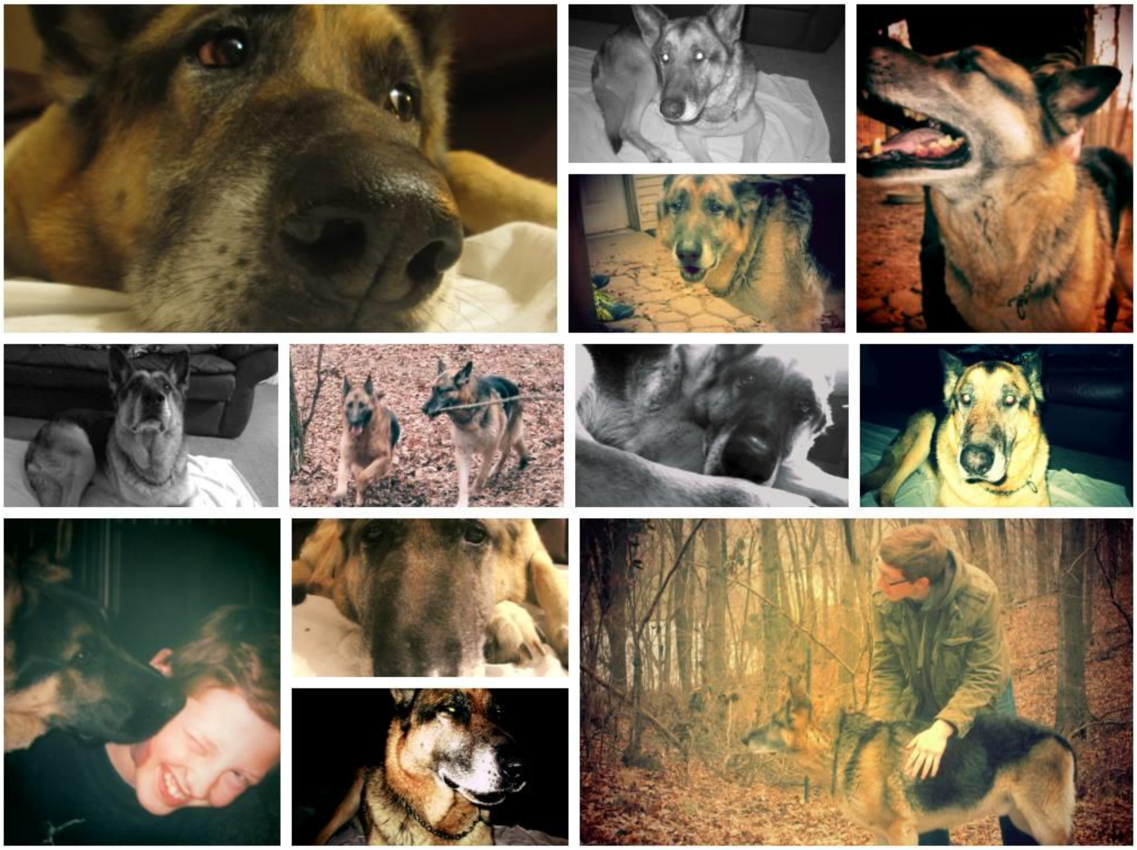
The new camera system was to be designed, built, and tested as part of a Faculty-Undergraduate Student Engagement (FUSE) grant. The system consists of a gimbal with pan/tilt capabilities has been designed and built via a Stratasys rapid prototyping machine

The camera mount has met not only sizing and weight requirements, but also video transmission, recording, and live-viewing requirements. The design process has been successful in developing a pan/tilt camera mount for our lab's quadrotor, and in creating countless learning outcomes as it produced multiple areas of research involving a variety of students with differing interests.

Keywords: quadrotor, engineering, photogrammetry, FPV, drones

DEDICATION

I dedicate this to Jake. Rest easy boy.



ACKNOWLEDGEMENTS

The research presented in this paper and the experiences made possible would not have been possible with contributions from the Faculty-Undergraduate Student Engagement (FUSE) Grant, the Layne Professorship, Western Kentucky University's Engineering Department, the Ogden Scholar Program, and the Ogden College of Science and Engineering. Thank you and all those associated for you aid.

On a personal note, I thank Professors Christopher Byrne, Robert Choate, Joel Lenoir, and Kevin Schmaltz for everything you have done for me. I appreciate the constant availability you provided when I searched for guidance and for a helping hand. I am grateful for the advice, mentorship, and encouragement each of you have given during my time at Western. Regardless if the form was a wry smile and the shake of your head, silent approval, a witty anecdote, or a pat on the back, your encouragement and enthusiasm has made my time here entirely worthwhile. You have all been great encouragement over the past four years. I have greatly appreciated all you have done to help me improve and mature (though the latter may be stretching it). I would not be here without you, and for that I am grateful.

I thank my department head, Dr. Julie Ellis, for encouraging and guiding me. I have seen a glimpse of the work that you are required to do and sincerely appreciate how you have made time for me and all others who need a moment for help. I appreciate how you have made the engineering department Western Kentucky University a welcoming community where we, the students, can thrive. I do not believe I am able to express the gratitude I have for all you have done. With utmost sincerity, thank you.

Similarly, I appreciate the efforts of Troy Robertson, Kathleen Angerbauer, Timothy (Pun-Master) Bucklew Caitlyn Clark, Zachary Lancaster, Jesse Reesor, Will Johnson, and Josh Prince throughout the project. You all have been of great help in the efforts that made this project possible. In addition, I would like to thank the Honors College, particularly Ami Carter, for supporting my academic career as an Honors student and helping me achieve my goals thus far.

As a final point, I thank my Mom and Dad for their continual support and encouragement throughout my life. I know you had one hell of a time raising me as a kid and getting me to where I am now. Your care was the catalyst that started my desire to understand and improve myself as well as the world around me. I hope that you know how much it has meant to me. I love you. Thank you.

VITA

October 15, 1991	Born – Bowling Green, Kentucky
2009	Kentucky Governor’s Scholar Program Graduate
2010	Valedictorian – Edmonson County High School, Brownsville, Kentucky
2010 – 2014	Ogden Research Scholar
2010 – 2014	Award of Excellence Scholarship, Western Kentucky University
2011	University of Virginia - Semester at Sea Study Abroad Program in Central America
2012	Owensboro Sister Cities Summer Study Abroad Program in Central Europe
2012	Research Assistant, Applied Physics Institute, Western Kentucky University
2012 – 2013	Tutor, Kelly Autism Program
2012 – 2014	Thermal Fluids Lab Assistant, Western Kentucky University
2013	Research Assistant, NSF REU at Florida State University
2013 – 2014	Boyce D. Tate Scholar

FIELDS OF STUDY

Major Field: Mechanical Engineering

Minor Field 1: Mathematics

Minor Field 2: Systems Engineering

TABLE OF CONTENTS

Page

Chapter 1 Foreward

Chapter 2 Introduction

Chapter 3 Background

Chapter 5 Results

Chapter 6 Conclusions

Chapter 7 Future Applications

LIST OF FIGURES

CHAPTER 1

FOREWORD

YOU ARE READING AN ADVENTURE

Research and design are adventures. A goal is created and a plan is formed to meet the objective. Throughout the process of following the plan, unexpected events occur; new discoveries are made; deviations from the path are taken. Eventually, the goal is reached or changed. Again, research and design are adventures. Reading an adventure should not be a monotonous process where one is left bored and unentertained. While certain aspects of research and design may not be glamorous to all people, there is need to include it for those curious. I have written this paper so that each chapter may standalone to deliver a message, and ideally have made it necessary to only read chapters of interest. To help build interest and allow the reader to bite into the juiciest parts of this paper, the format is similar to a Choose Your Own Adventure book. In each chapter, the reader will have the option to dive immediately into the information ahead, or jump to a different section of interest. The first decision begins here. Choose to read the conclusion now or start with origins of the project.

(*FOR THE CONCLUSION, GO TO PAGE: 45)*

(*FOR THE INTRODUCTION, GO TO PAGE: 2*

CHAPTER 2

INTRODUCTION

AN OVERVIEW

The Mechanical Engineering Lab at Western Kentucky University (WKU) recently designed and built a quadrotor. Given the direction of research and hobbyist communities, our next priority was to add a camera for reconnaissance, first-person-view (FPV) flight, and photogrammetry purposes. The primary project goals were to create a camera mount with pan/tilt capabilities and the ability to broadcast a live video feed. Over the past two semesters, a camera mount with said features was designed, built, and tested.

As with any design, an iterative approach is necessary to optimize the results. Depending on the part, assembly, or system level view, factors affecting design are subject to significant variation. The most notable of these factors include the method of approach, the problem criteria and constraints, and the design objectives. The design process and these variations are often unnoticed by those outside the field. They will be explained and used to show how the design process is a learning experience in itself.

Before delving further, a general knowledge of relevant topics is required to better understand the impact, creation, and application of the project. This can be found on the following page. Should you feel comfortable with the subjects mentioned, feel free to skip ahead to Chapter 4.

(*FOR THE METHODOLOGY OF THE PROJECT, GO TO PAGE: 14)*

CHAPTER 3

BACKGROUND

THE FUNDAMENTALS

This research project has covered a vast amount of information beyond what is necessary to design a camera system for a quadrotor. Relevant subjects vary from what a quadrotor is and why people choose to building them, to additive manufacturing and the allure of 3D printers, to the Federal Aviation Administration and the implications of unmanned aerial vehicles on legislation.

(*FOR MORE INFORMATION ON QUADROTORS, GO TO PAGE: 4)*

(*FOR MORE INFORMATION ON ADDITIVE MANUFACTURING, GO TO PAGE: 9)*

(*FOR MORE INFORMATION ON FAA REGULATIONS, GO TO PAGE: 11)*

(*IF NONE OF THESE INTEREST YOU, GO TO PAGE: 37)*

QUADROTORS: HISTORY AND GENERAL PERFORMANCE

As early as the 1920s, quadrotors had been designed and flown as manned experimental rotorcraft [1]. An early example is shown in Figure 1. However, despite the successes of the prototypes, the disadvantages of these complex rotorcraft left the devices grounded for years to come. In recent decades, fixed-wing unmanned aerial vehicles (UAVs) have become popular for civil, military, and research applications that vary from search and rescue to aerial reconnaissance to collecting weather data. While fixed-wing UAVs have advantages of longer flight times, higher speeds, and simpler construction, there is growing interest for rotorcraft with higher agility, increased precision for payload delivery, and the ability to hover, as well as land and take off vertically. For these reasons and more, rotorcraft are becoming increasingly popular.

One of the more common rotorcraft, the quadrotor has taken the spotlight due to

Figure 1: Dr. George de Bothezat and Ivan Jerome developed the manned quadrotor shown above in 1922 [1]

its stability, reliability, and increased payload capabilities when compared to helicopters of equivalent size. The key difference between a quadrotor and helicopter is that a helicopter uses a single centralized rotor for propulsion and lift as well as a tail rotor to control yaw (rotation). A quadrotor uses two pairs of counter-rotating props to perform the same functions.

The use of four rotors substantially improves maneuverability as compared to traditional helicopters. The advantages in maneuverability and other perks have been quite influential for the growth of research with quadrotors and their applications. While some hobbyists have found entertainment through the addition of paintball guns and other accessories [2], a significant portion of research has revolved around the addition of camera systems. For those using camera systems, the increased payload capabilities and the higher maneuverability are critical for maintaining flight time, capturing high-quality video, and avoiding risk while performing close-range flights with obstacles.

A brief note is needed to explain the difference between a propeller and a rotor. A propeller is a wing twisted along its length. The twist is to ensure a constant angle of attack into the fluid as the blade rotates. In contrast, a rotor is truly a wing that rotates. The rotary-wing typically has little twist relative to its total length. General differences are listed below.

1. Propellers have a small aspect ratio (the ratio of width to length) and large relative twist as shown **Figure 2**

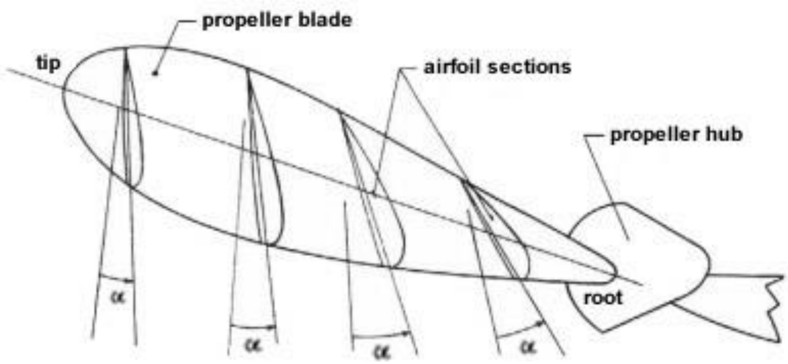


Figure 2: Propellers have a large relative twist along the length of the blade. Alpha (α) represents the changing pitch along the length of the blade [11].

2. Rotors have a large aspect ratio, a small relative twist, and a non-equivalent pitch (angle of attack) given to the angle of the swashplate as shown in **Figure 3**

3. The pitch of each propeller blade is equivalent, with respect to the plane of rotation

4. The pitch of each rotor blade varies independently, with respect to the plane of rotation

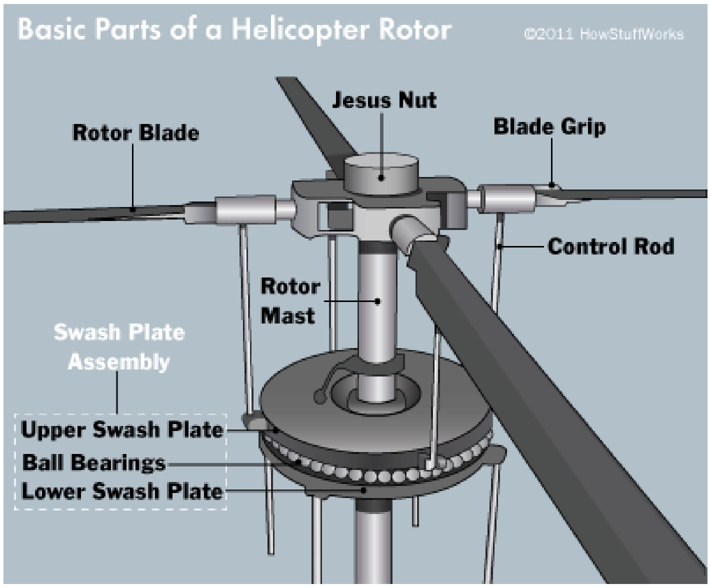


Figure 3: Pilot controls are transmitted through the lower swashplate to the upper swashplate. The rotor blades will vary in pitch based upon the angle of the upper swashplate [11].

Exceptions to these rules are "fixed-pitch rotors" and "variable-pitch props." Both exceptions maintain equivalent pitch between the blades. Variable-pitch props simultaneously rotate along their length to alter the angle of attack, similar to the rotors of a helicopter.

In this paper, the terms propeller, prop, and rotor will all be used for the fixed-pitch rotors found on a standard quadrotor such as ours.

QUADROTOR MANEUVERS

Quadrotors use a complicated method to control and maintain flight. Helicopters use a tail rotor to counteract torque, whereas quadrotors offset torque by using two pairs of counter-rotating props. By varying the speeds of two or more of the props, quadrotors are capable of the same movements of traditional helicopters.

A total of nine basic maneuvers are achieved by varying the rotational velocity of two or more props:

⬆ Ascend
○ Hover
⬇ Descend
↺ ↻ Yaw (Rotation)
⬆ Forward
⬇ Reverse
⬅ ➡ Strafe

The simplest movements to understand are hovering, ascension, and descent, as shown in **Figure 4.** To hover, all props will maintain the speed equivalent to the downward force of gravity. To ascend, the prop speed will increase to overcome gravity. To descend, the prop speed will decrease and gravity will lower the quadrotor’s altitude.

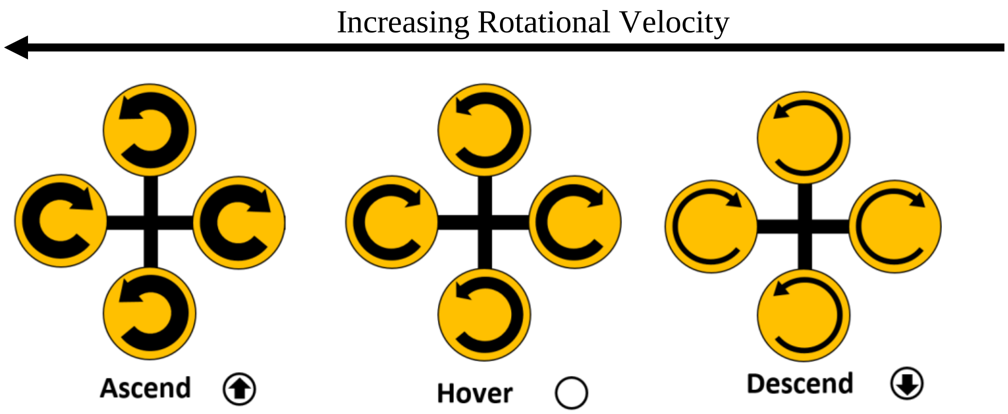


Figure 4: Quadrotors vary the speed of all props to move in the vertical axis

Yaw (rotational) control is achieved as shown in **Figure 5**. As with vertical movements, all props vary in speed. To turn counter-clockwise, the two props rotating counter-clockwise will increase speed. The two props rotating clockwise will decrease speed. To turn clockwise, the two props rotating clockwise will increase speed. The two props rotating counter-clockwise will decrease speed. The net difference in torque causes rotation of the quadrotor. It is necessary to alter the speed of both the props rotating in the direction of the turn as well as those rotating against. By lowering the speed of one pair and increasing the speed of the other, the quadrotor maintains the same altitude while

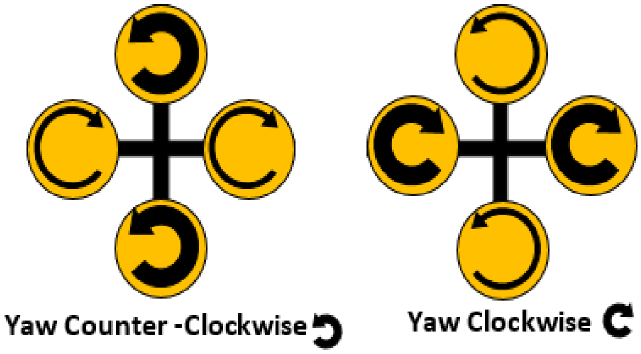


Figure 5: Yaw (rotational) control of quadrotors is achieved by increasing the props rotating in the matching direction of the desired turn and decreasing the speed of the non-matching props to maintain the constant altitude.

turning.

The remaining movements are translational in the horizontal plane. Unlike the previous maneuvers, two props remain at their original speeds, while the other two vary. These actions are shown in **Figure 6**. Combinations of these basic maneuvers allow for a collection of acrobatic feats.

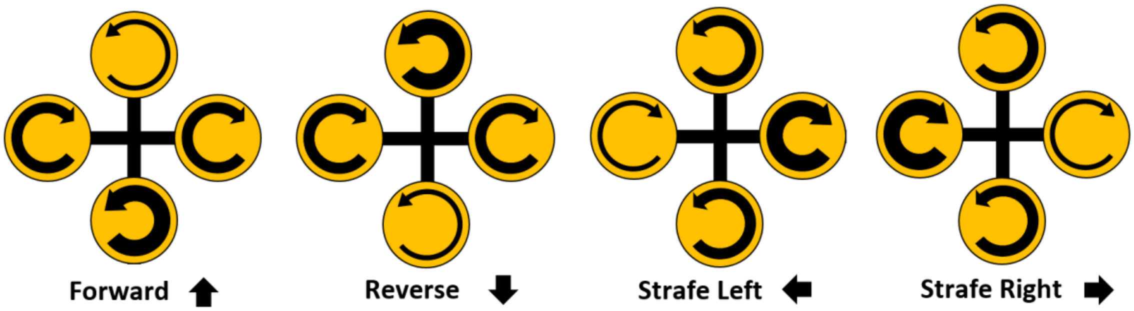


Figure 6: Horizontal movement of quadrotors given the rotational speed of the props

3D PRINTING (ADDITIVE MANUFACTURING)

A rapid prototyping machine, or 3D printer, is capable of creating virtually any object using additive manufacturing, the process of creating an object by laying down successive layers of materials. The most common 3D printers available generate parts using a variety of thermoplastic materials. While more expensive, some existing models are able to utilize metals, ceramics, and even food for the manufacturing process [3]. Additive manufacturing differs from the more common method of subtractive manufacturing in a variety of ways. In short, the major benefit of additive manufacturing is that there is little, if any waste material produced when creating parts. Additive manufacturing only requires the amount of material equal to that used in the part, whereas in subtractive manufacturing, one must start with excess material, then bore, mill, and grind away superfluous material. An exception to this statement does occur with some 3D printers that use multiple thermoplastics. One plastic is used for the model, while another, which is chemically dissolved after completion, is used as support material to buttress overhangs or fill holes temporarily.

Minimizing waste is only one of the benefits of additive manufacturing. 3D printers eliminate geometric restrictions when fabricating parts. As a result, the difficulty of fabricating a sphere versus a helix is virtually equal. Tooling paths are no longer a concern as parts are created layer by layer. As the complexity involved with the understanding and restriction of manufacturing tool paths and machining set-ups are practically eliminated, nearly anyone can use a 3D printer to create objects in a matter of hours.

The manufacturing freedoms, ease of complex part fabrication, and simplicity of distributing and modifying parts are highly encouraging when creating prototypes and/or single-use parts. Such abilities are extremely important due to the variety of quadrotor designs available today. To best create an interchangeable platform between quadrotors and other land or air vehicles, the weight-bearing components of the camera mount were manufactured from extruded ABS via our lab’s Stratasys Dimension Elite (3D Printer) as shown in **Figure 7**.

Figure 7: The Mechanical Engineering Lab at WKU uses a Stratasys Dimension Elite 3D Printer as shown above

Understanding the material properties of the extruded thermoplastic is paramount for efficiently printing safe and reliable parts. Estimates of the tensile strength of said plastic were found to be 4500 psi. However, no readily available data existed regarding the testing procedures or how the samples were prepared. A secondary research project by our lab was therefore necessary to collect data to determine the material properties of our printer's thermoplastic. Detailed explanations of the testing procedure and sample creation are explained later in the methodology section.

FEDERAL AVIATION ADMINISTRATION (FAA) RULES AND REGULATIONS

The addition of cameras on quadrotors and other aerial vehicles has become increasingly popular. Subsequently, there have been concerns regarding privacy, safety, and the regulation of UAVs. The FAA has safety of persons both in the air and on the ground as the primary focus when UAVs, such as our quadrotor, enter the airspace. The growth of UAVs in recreational, industrial, and research uses has far exceeded the FAA's ability to properly address and regulate the matter. Despite the challenges associated with creating appropriate and fair laws, the FAA has acted as best possible to keep up with the rapid development and use of UAVs.

As of February 2007, those seeking to fly UAVs for non-recreational purposes in national airspace are required to complete a FAA Certificate of Waiver or Authorization (COA) [4]. At this current time (April 2014), only government agencies have been recipients and only one commercial flight has been approved. With the new standard, many hobbyists responded that they had previously justified commercial operations under Advisory Circular (AC) 91-57, a document originally intended for recreational use of model aircraft in sites advised [5].

The advisory was created well before the formation of the modern definition of a UAV, which is now inclusive of model aircraft, and using it as justification was questionable at the least. To clarify the matter, the FAA published a Federal Register notice in 2012 to clarify that AC 91-57 applied solely to modelers and thus prohibited the use of UAVs for commercial use [4]. It is worth noting that the Advisory Circular 91-57 was not a law (consequently unenforceable) and acted as more of a voluntary guideline for model aircraft use.

Even with the immense number of hobbyists and commercial entities using UAVs to capture aerial footage, there was only a single prosecution regarding commercial flights. The FAA filed charges against Raphael Pirker in October 2011 for flying over and filming the University of Virginia's medical school campus. The allegations were made prior to the Federal Register notice stating that UAV flights were not subject to the previous rules for model aircraft (AC 91-57).

Regardless of the timestamp, the FAA's case did not end in their favor. The judge presiding over the case ruled that there was no clear definition of a UAV and that the Federal Register notice is not enforceable [6]. Despite the ruling, the FAA has announced their intent to appeal the case and continue to enforce their policy regarding commercial UAV flights [7].

CHAPTER 4

METHODOLOGY

THE ENGINEERING DESIGN PROCESS

Despite the presentation of the engineering design process given in many explanations of engineering, the actual process is far from linear. It is iterative, multi-level, and logical. Design is a cyclic process, helical truly. Often one will return to the same point in the design process. However, upon return, new information has been acquired, criteria and constraints may have changed, and the problem being addressed may be entirely different.

To translate the design process in a linear manner is difficult, as several aspects can be left out if one is not careful. Fundamentally, the same steps are followed in each iteration, but one must remember at each iteration, there is new information to be analyzed. The basic design process as a whole is universal across many disciplines and applications. A circular diagram representing the design process can be seen in **Figure 8.**

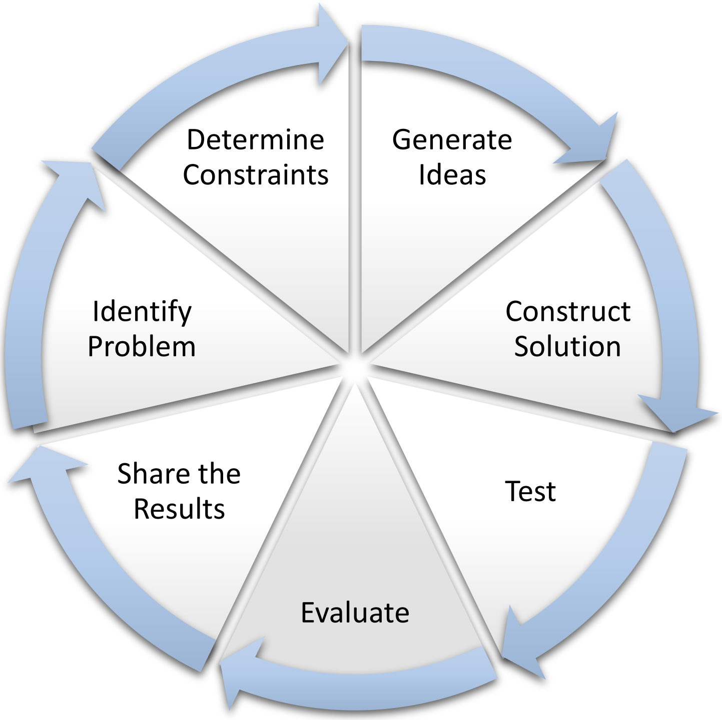


Figure 8: An outline of a generic version of the design process

Similar to linguistic accents, there are certain characteristics of the design process that differ in complexity depending on where one learned the associated formalities. The design process is flexible and easily modified. Depending on the scenario, one may find themselves in the middle of the process, which is entirely acceptable. The design process is a science, but equally an art.

One must use a systematic approach to master both the science and art of design. Though the process appears to be broken into bite-sized steps, each step is made from multiple perspectives. On the smallest scale, the part level, one must consider the strengths of the material, the associated costs, the fabrication process, and other similar factors. Expanding to the assembly level, the designer must now take into consideration the interaction between individual components and understand how altering the size and shapes of parts can add or remove degrees of freedom, weight, ease of assembly, etc. The difficulties of design expand further when system integration occurs. A simplification on the part level may lead to assembly difficulties or hamper the ability for the design compatibility with the system as a whole. Success, failures, and changes all ripple throughout the design and on each level at which it is examined. While the idea of a camera mount is a relatively simple system, a variety of factors must be considered during its creation.

What must also be taken into consideration is the depth of the design process needed. Not all steps are required to create a solution and every step may not require a significant level of detail. For example, in our system, the initial concern was system integration with the quadrotor.

The first problem encountered was the placement of a camera. A GoPro was purchased and temporarily attached to the quadrotor. As the stock landing gear were too short, the camera was attached to the top of the quad. Our first flight with a camera was not ideal. The placement of the camera shifted the already high center-of-gravity further upward. The quadrotor was difficult to fly in a stable manner and flipped over on landing.

As simple as camera placement may seem, many questions spawned from our experiment. Should we lower the center of gravity? Can we raise the height of the quadrotor? Would a different camera suffice? Due to these questions and many more unmentioned, our first design process began. The first step was to choose the problem that we would be able to address most efficiently. Due to our project goals and progress to this point, the landing gear would be the first problem to address.

As mentioned, understanding the depth of the design process one should go is critical to be an effective engineer. Given enough time, an engineer will polish until the product has been reduced to nothingness. Good engineers ship. An example of the design process follows with the exit point being a product that meets the necessary criteria.

[Identify the problem clearly]

Physically, the height of the quadrotor was low due to the stock landing gear available.

[Determine Criteria and Constraints]

The new landing gear height will leave six inches between the lowest plate and the ground

The total length of the legs cannot exceed 11 inches due to the size of the 3D printing tray

[Select and Construct a Solution]

To accommodate the camera system, extended-proportional landing gear will be built

[Test and Evaluate]

While the new landing gear solved the height concern, they were prone to breaking at the attachment point, due to strength differences between the original composite landing gear

Figure 9: Landing gear design iterations from left to right: Aeroquad stock gear, first design iteration, second and current design iteration

and the new plastic design.

[Refine the design]

The points of attachment were redesigned improving both the height and strength concerns of the landing gear. These design iterations can be seen in **Figure 9.**

Here, there was minimal effort needed to generate a solution for the first iteration. The simplest, fastest, and lowest-risk solution is to create new landing gear proportionally larger. The old design had succeeded and was an acceptable template, given the parameters of the quadrotor's use. While the first iteration failed, there was no need to repeat the entire process. Given the low risk associated with refining the old design, a simple reinforcement and testing was all that was required for success. While one could study methods to create "the perfect landing gear," our project requires only a landing gear that works. We do not need "the" answer. We need "an" answer.

Throughout this paper, the design process will be outlined for each system, assembly, and part used. Understanding how the design process varies in itself is necessary to truly understand and appreciate how a system is created. I advise the reader to read each section in this chapter by order of their personal interest. Start from the point where curiosity is greatest and travel from there.

(*FOR THE ELECTRONICS SYSTEM, GO TO PAGE: 19)*

(*FOR THE VISION SYSTEM SCHEMATICS, GO TO PAGE: 22)*

(*FOR THE PHYSICAL DESIGN, GO TO PAGE: 25)*

(*FOR THE PAYLOAD TESTING, GO TO PAGE: 29)*

(*FOR THE MATERIAL TESTING, GO TO PAGE: 31)*

Electronics System

Once a height ceiling was established by the landing gear, the next step was designing a platform that produced desired video quality while remaining small enough to fit within the space available. Several existing pan/tilt systems had been created such as by FatShark shown in **Figure 10** [8]. The system shown has been used primarily for FPV and co-axial images when recording flights. While an excellent design, it did not sufficiently meet our goals and acted more as a guideline for minimization of our design.

Figure 10: A premade pan/tilt camera used for FPV and co-axial camera views. The official title for the camera system is “600TVL FPV Tuned CMOS” (TVL: Television Line, FPV: First Person View, CMOS: Complementary metal–oxide–semiconductor [8]

After extended research, the best available components found within our budget consisted of high-torque analog servos; a video system consisting of GoPro®, Fat Shark©, and Immersion RC© transmitting and receiving components. The design process associated with the vision system is below.

[Identify the problem clearly]

There is need for a vision system for FPV, reconnaissance, and photogrammetry uses.

[Determine criteria and constraints]

The vision system must provide high quality video.

The vision system will have live video feed.

The vision system will have no noticeable latency.

The vision system will not interfere with quadrotor flight control.

The vision system will internally store recordings on-board.

[Select and construct a solution]

The GoPro Hero 3 Black was chosen as our camera due to its durability, ability to store video on-board, image quality, battery life, and the company's reputable support staff. The most significant factor listed was durability, because of the experimental nature of our research and expected hardships. Proving the value of our investment, the camera has since been subject to two major quadrotor crashes and only received aesthetic damage. The use of the camera is highly advised for similar platforms that have not yet been perfected.

A Fat Shark© headset and compatible Immersion RC© transmitting and receiving components were used as they were the highest quality system given monetary constraints. The Immersion RC© components communicated through radio frequency waves and would allow multiple stations to receive the signal. More importantly, the same components transmitted farther than the stock components by Fat Shark©. The Fat Shark© headset system also offered the capability to use a head-tracking device. The head-tracker offers a more realistic perspective when using the vision system as it follows the motion of the user's head.

[Test and evaluate the solution]

Testing is discussed in a later section (see page 36), and was an extensive process. The evaluation results were that the transmitting and receiving units could be improved to reduce interference due to distance and obstacles between the two components.

The vision system meets all of the original criteria and can be considered complete. However, design is a continuous process and therefore no design is ever complete. Aspects considered a failure or simply insufficient will be corrected in future designs. For our system, given our point in development, the proof of concept is first priority. There is no need to redesign the wheel, especially when other priorities exist. The camera system does not need to be perfect, similar to the design involved with the landing gear. The camera system needs to function. A system meeting all original criteria has been created and the system can be considered complete, for now.

(*TO LEARN MORE ABOUT THE VISION SYSTEM SCHEMATICS, GO TO PAGE: 22)*

(*FOR THE PHYSICAL DESIGN, GO TO PAGE: 25)*

VISION SYSTEM SCHEMATICS

The camera system is divided into two sections: On-board and Base. Two communication conduits for video transmission and servo control exist between the subsystems. A bill of materials can be found on page 51 of the appendix.

On-Board Subsystems

A subsystem schematic of the on-board servo control is shown in **Figure 11.** One *Hitec HS-645MG* servo is used for panning the camera and two are required for tilt movement. An electric model servo reverser is used between the two tilt servos to cause the rotation of each servo to occur in the same direction at the same rate. Often, the same device is used on model aircraft to control flaps.

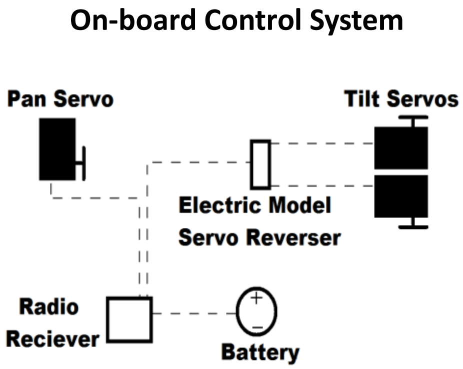


Figure 11: Subsystem schematic of the pan/tilt servo control

In **Figure 12**, the on-board video system is shown. The camera used is a *GoPro Hero 3 Black* and contains its own power supply. Furthermore, it is encased with an impact resistant housing and is capable of recording and storing a variety of quality videos. The video is simultaneously fed through an *ImmersionRC 600mW 5.8GHz transmitter* on an open (unprotected)

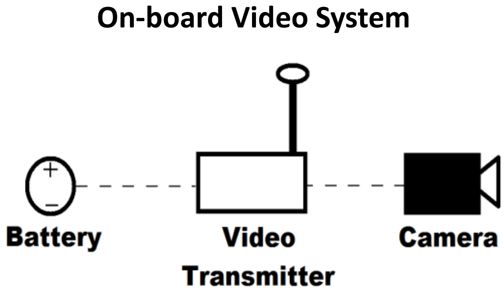


Figure 12: Subsystem schematic of the on-board video transmission system

frequency. As the transmitter, receiver, and servos do not require large quantities of electricity to operate, each subsystem is connected to the quadrotor's main power supply.

Base (Ground) Subsystems

Shown in **Figure 13** is the base station. As the video is transmitted on an open frequency, anyone with a matching receiver can view the live footage. Our team uses a *Uno5800 v2 5.8GHz A/V* receiver for displaying live feed to spectators during our flights.

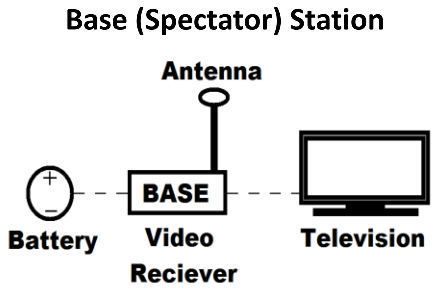


Figure 13: Subsystem schematic of a base station for receiving video signals

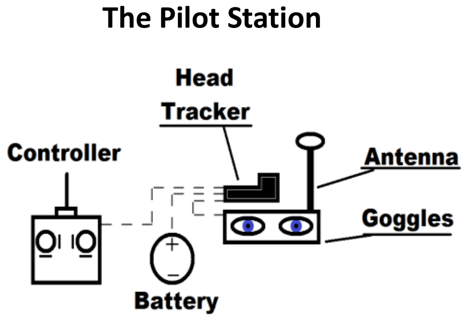


Figure 14: Subsystem schematic of the pilot station for controlling camera orientation and receiving video signals

The pilot station, shown in **Figure 14,** is used to receive video for first person view as well as control camera orientation through a variety of methods. The first method is to directly use the controller knobs, switches, or joysticks. The second method is to use the *M.I.G. Tracker V5 (Magnetic, Inertial, Gyro),* more simply called a "head-tracker." The head-tracker uses a combination of internal sensors to detect movement of the users head and transmits these movements to the controller. The controller then sends the signals

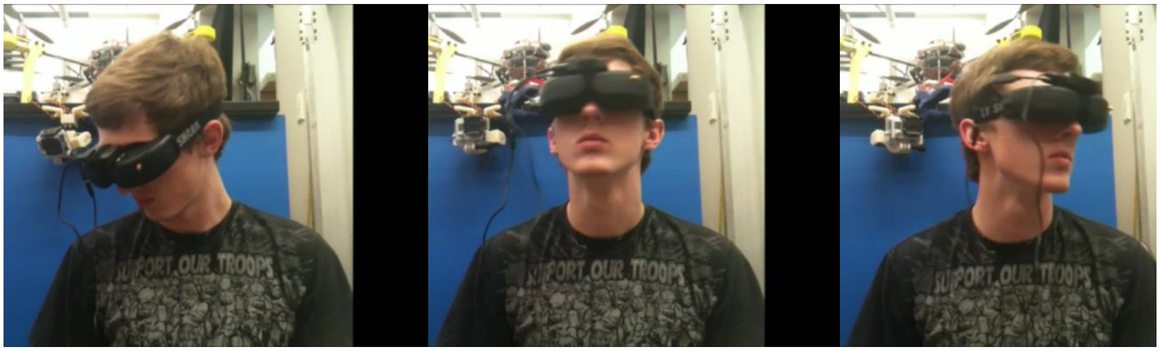


Figure 16: Demonstration of camera orientation control using a head tracker sensing user movement

received from the head-tracker to the on-board servo system. A demonstration of the head-tracking capabilities is shown in **Figure 15.**

A full system schematic is shown in **Figure 16.** Here one can see the video and control signals transmitted during operation.

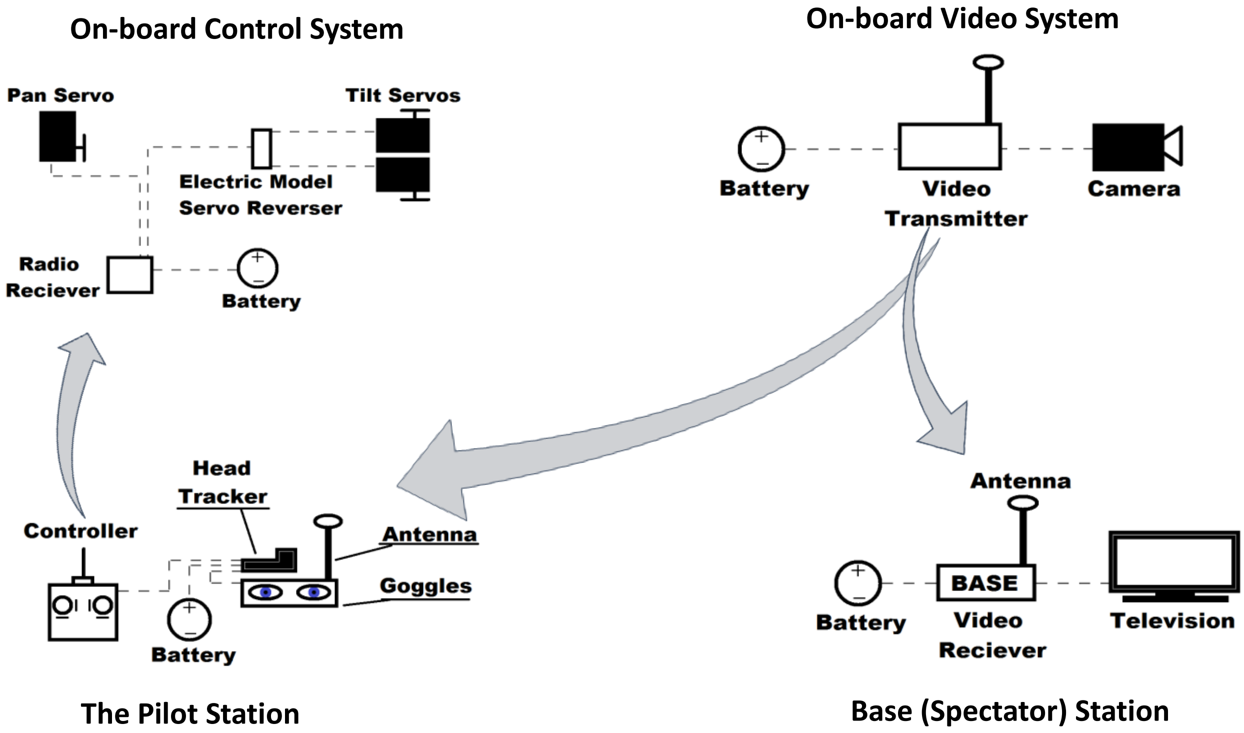


Figure 15: The full system schematics are shown above. The on-board vision system transmits live feed through radio frequencies to the pilot and spectator stations. The pilot system controls camera orientation through the head-tracker.

PHYSICAL DESIGN

The physical design was first dependent on components of the electronic system, attachment points, and size limitations imposed by our quadrotor. Secondary concerns arose by balancing the weight and strength, which led to a series of modifications to achieve.

[Identify the problem clearly]

A physical pan/tilt mount is needed to transmit servo rotation into motions to control the orientation of the camera.

[Determine criteria and constraints]

The maximum volume of the assembly must not exceed a six by six by six inch cube.

The weight of the assembly must not exceed two pounds.

The assembly must be able to support the weight of the camera and servos.

The assembly must not be prone to breaking during standard landing procedures.

The system shall have easily reproducible parts by members of WKU’s engineering department.

[Generate ideas to solve the problem]

The first assembly design, alpha, is shown in **Figure 17**. The alpha assembly resembles a large portion of camera mounts that were used for stabilization due to the location of the axis of rotation. While the goal of the project is to pan in the x-axis and tilt in the y-axis, the design was considered as it had the ability to keep the camera level with the ground.

[Select and construct a solution]

A beta assembly meeting our basic requirements was designed and built. The beta version changed the points of rotation and used a single servo for both directions of movement. The refinement allowed for pan/tilt motion of the camera, and reduced the distance to the camera from the center of rotation.

[Test and evaluate the solution]

Mathematically and experiementally, the servo had sufficient torque to raise the camera. However, a single servo was not powerful enough to maintain constant attitude, and only enough to temporarily lift the camera.

[Refine the design]

A third version, the gamma assembly, was virtually modeled. A second servo was placed concentrically, with

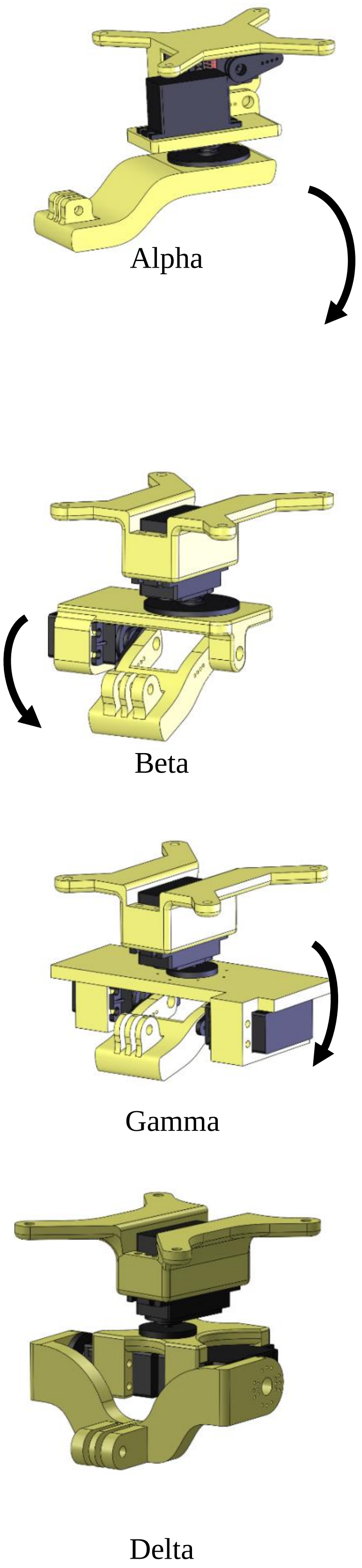


Figure 17: The design process can literally be seen as the pan/tilt assembly underwent four iterations from Alpha to Delta

respect to points of the servo horn rotation, with the first servo to control the camera tilt. The virtual model was an expansion of the beta version, and appeared to be functionally sufficient for our needs. Despite the existance of the solution, a few lessons were learned after the construction of the beta assembly. The servo wires were unforgiving when attempting to install the servo into the cut extruded through the walls used to house the tilt servo. The tilt-servo mount was bulky and took a larger volume than desired. The center of rotation for the pan servo was relocated to center the weight of the assembly. All of these issues were addressed during the redesign and the current design, the delta assembly, was developed.

[Test and evaluate the solution]

The gamma assembly was built and tested as an assembly, which is to say without installation on the quadrotor. There were minor concerns, such as the servo wires hanging freely and possibly catching on another component, and determining the appropriate length of wire was necessary for a full range of motion. However, these questions would be best addressed during installation. The new and current design was considered complete as it met aesthetic desires and functional needs.

The weight bearing components were manufactured from a Stratasys Dimension Elite, and the design took an “organic” appearance. Contours were commonly used to increase strength. These shapes are best seen in the delta assembly in **Figure 17**. 3D printers allow for such soft contours that traditional manufacturing methods could not create at a comparable cost. These contours eliminated the majority of stress concentrations caused by sharp corners and transitions between profile shapes.

The machining advantages were only part of the reason to manufacture the parts with a 3D printer. The density of the thermoplastic could be reduced to save on the weight budget of the assembly. The ability to reproduce replacement parts would be a simple process, well after the original designer had left the project.

With a nontraditional method of manufacturing parts, a few questions needed to be answered. First, there was the question of how the density of the plastic would affect the strength of each part. Parts could easily be overdesigned to create a good factor of safety, but the goal of the project was minimization and only information would permit a good design to be developed. Also, as there was a general need for the flight time given for every extra gram, payload testing was another offshoot of the project. Each of these sub-processes was performed to gain a better understanding of how to enhance the design and minimize undesirable effects.

PAYLOAD TESTING

One of the most common concerns with aerial vehicles is the relationship between payload and range (for our case, flight time). While vehicles using liquid fuels are better able to cope with an increased payload, platforms using batteries, such as our lab's quadrotor, are left with the question of what the proper weight is. Before determining what weight is ideal, there is need to know the relationship between payload and flight time.

To determine the relationship for our quadrotor, we first found the maximum payload capacity. This number was determined by adding mass in 0.4905 N (0.11 lb.)

increments, until the quadrotor was unable to rise continuously. The last measured weight was at 36.98 N (8.31 lbs.). From here, incremental decreases in weight were taken and flight times measured for each. Our flights were performed with the battery used for standard flights, a 3-Cell (3S) LiPo battery with the following specs:

- 5000mAh
- 11.1 V, 55.5 Wh
- 25C Continuous (125A) and 50C Burst (250A)

The testing results are plotted below in **Figure 18**, as expected an inverse relationship exists between the flight time and total system weight. What was not expected was the linear relationship between the two variables, which showed that no "sweet spot" exists regarding the weight of accessories. For this reason, the vision system weight needed to be minimized as best possible.

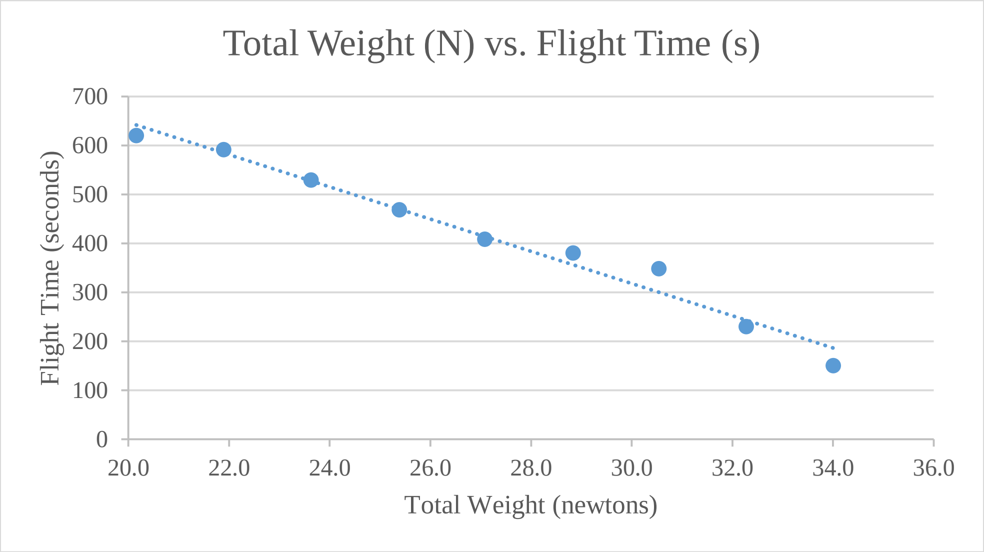


Figure 18: Results of WKU's quadrotor payload testing

MATERIAL TESTING

Background

A variety of material properties have been found for extrusion grade ABS plastic. However, given the range between the high and low values for the strength (~1700 psi to ~5100 psi) [9], our lab has performed tensile tests to determine the material properties of the thermoplastics used by our Stratasys Dimension Elite rapid prototyping machine. Furthermore, the materials research helps to define the differences that are created due to the orientation and density that the thermoplastic is extruded. Samples were created using standards as set forth by the ASTM document designated D638-03 for the creation of a Type I specimen. The total combination of desired orientation and density settings allow for six unique samples. Within our testing samples, the densities included solid, high density, and low density thermoplastic. Shown in **Figure 19,** two variations in orientation

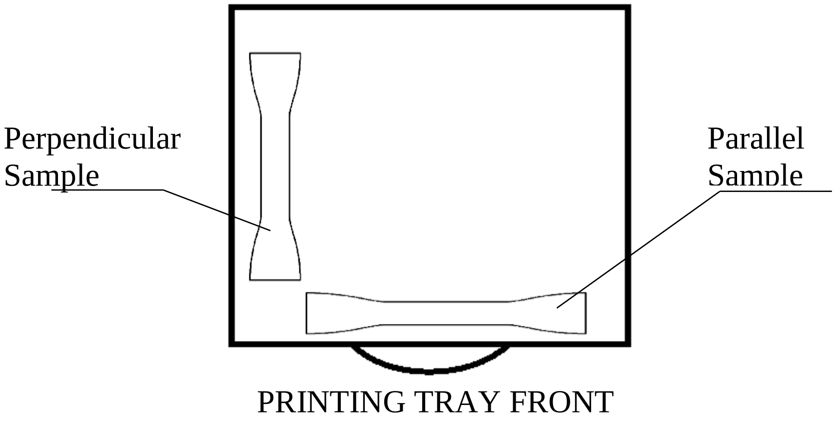


Figure 19: Two sample orientations, relative to printing tray, were used for our material properties testing. The first orientation was parallel to the front of the tray, on the x-axis. The second was perpendicular to the front of the tray, on the y-axis

were studied relative to the printing tray: parallel with the front of the tray (X-axis) and perpendicular to the front of the tray (Y-axis). By conducting tensile testing, the ultimate tensile strength was obtained for each type of specimens.

When printing parts, just as printing words on paper, the printer head follows a pattern. Where a paper printer is restricted to reciprocates along a linear path, a 3D printer has the ability to move in a variety of patterns. For our lab's printer, the printing "web" is created in a diamond pattern, hence the belief that strength differences may exist due to the printing orientation. Material – selection of 3D printing ABS plastic characteristics. An example of the web differences is shown in **Figure 20.**

Tensile Test Methodology

Measurements of height and width were recorded to determine the cross sectional area for each sample. The tensile testing machine digitally recorded the grip position and force applied in increments of 0.55 seconds. Stress was calculated by dividing the force over the specimen's cross-sectional area. The stress was then plotted against displacement to easily visualize the ultimate yield strengths.

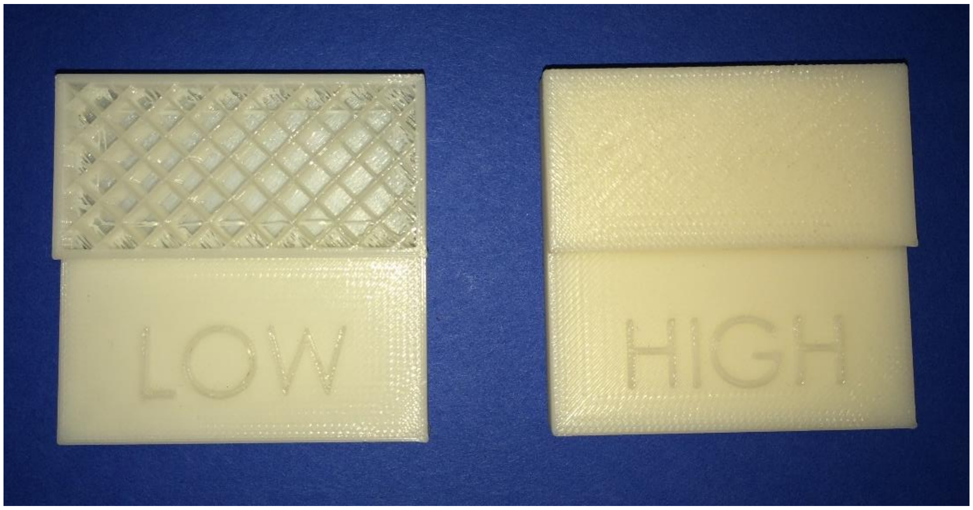


Figure 20: The printing "web" is a diamond pattern as shown above. The compactness of the diamond mesh varies between the selected material density. Low and high density webs are shown above.

During elongation of a sample, the molecular structure of the plastic transformed. The density of the plastic was low enough to notice the color change under normal lighting conditions. To improve understanding of the deformation of the specimens, high-speed video was captured of each test. Using a variety of high powered lamps, back-lighting was added to each sample. The transparency difference (seen by dark areas) indicate plastic deformation in the samples. As shown in **Figure 21**, the majority of cracks began and propagated along the darkest sections of the sample.

Material Testing Results and Conclusions

Analysis of the data showed clear differences in strength based on density. Plots of our data can be found in the Appendix on page 47. The simplified results follow in **Table 1**. Given the same density of material, it was found that there was no difference between the ultimate tensile strengths on a 95% confidence interval (using a student-T test) due to a 90 (ninety) degree offset in orientation.

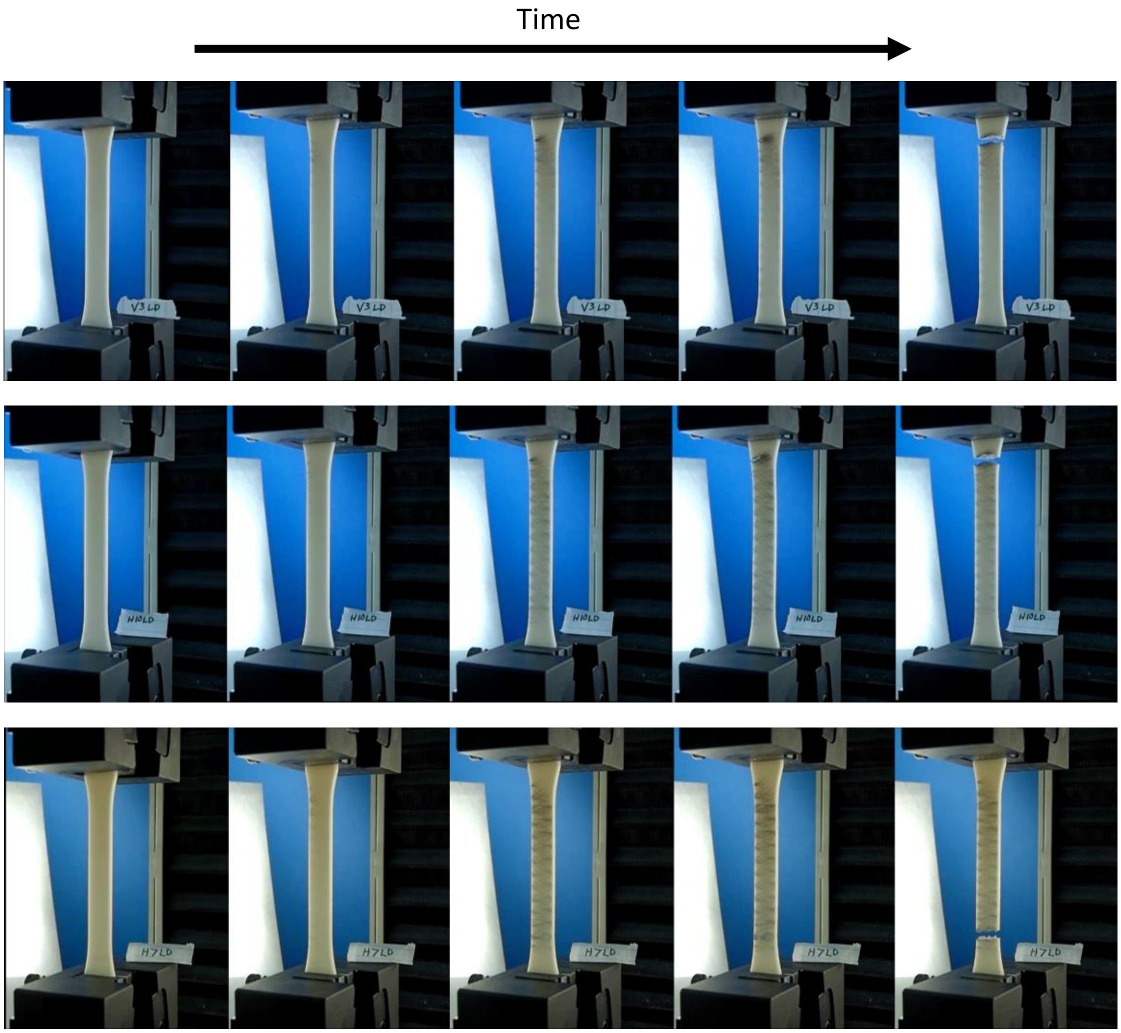
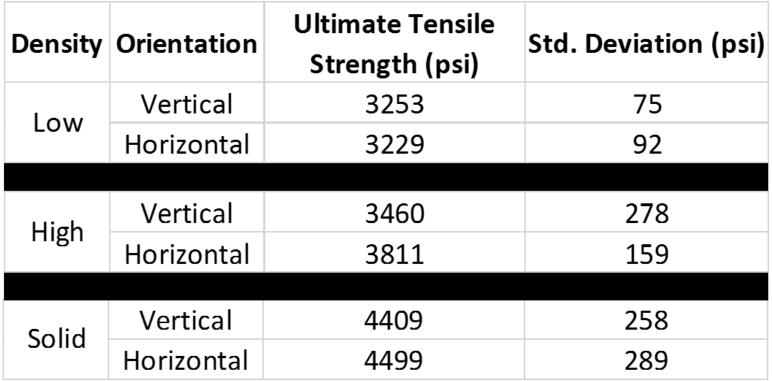


Figure 21: Three examples of tensile testing process are shown above. In each sample, the transparency differences due to deformation can be seen as dark sections of the samples

An exception exists for the high density samples. The deviations in the sample strengths may be present for a variety of reasons. These vary from how the sample was inserted in the testing apparatus, the surface finish, pre-stress, and temperature variations.

Table 1: Ultimate tensile strengths of Type I samples produced by WKU’s Stratasys Dimension Elite given variations in density and orientation



Density	Orientation	Ultimate Tensile Strength (psi)	Std. Deviation (psi)
Low	Vertical	3253	75
	Horizontal	3229	92
High	Vertical	3460	278
	Horizontal	3811	159
Solid	Vertical	4409	258
	Horizontal	4499	289

The critical factor that most likely affected the data was the lamps used to illuminate the samples when recording high-speed video. ABS plastic has a high thermal expansion rate and would thus be susceptible to material property changes due to heating.

Due to this observation, further testing is necessary to confirm our results. Environmental variables such as the temperature and heat flux on the samples will be tightly controlled during the following tests to ensure that repeatable and reliable data is produced.

In addition to supplementary tensile testing, more tests will be conducted on the orientation of the samples. As the printing mesh follows a checkered pattern tilted 45 degrees from the edge of the tray, we suspect that differences will exist for orientations differing by less than 90 degrees. After conducting in-plane orientation tests, our goals are to expand to testing samples printed orthogonal to the plane of the printing tray. Furthermore, flexure testing will also be conducted to provide values for the materials modulus of elasticity. By improving our understanding of the thermoplastic material properties, the design weight can further be minimized without the risk of creating a purely experimental design.

CHAPTER 5

RESULTS

EXPECTATIONS VS. REALITY AND SYSTEM IMPLEMENTATION

The initial project goals have successfully been surpassed, however further improvements are always possible. Currently, the system has a ninety-degree field of movement for both pan and tilt movements. The field of view (diagonally) of the camera varies from about seventy to one-hundred and fifty degrees. The variance is due to the ability to change the aspect ratio of the video with internal camera settings. The response time of the camera has not been quantified, but no noticeable latency has been seen between the transmitting and receiving components.

The camera is self-powered and does not reduce flight time directly. The servos controlling camera orientation as well as the video transmitter is powered through the battery used for flight. The servos consume 54.6 mW/hr (9.1mA @ 6.0V) and the transmitter consumes 600mW/hr. The summation of power consumption by the camera system is estimated as 760mW/hr. Our standard flight battery, with a 5000 mAh capacity, could power the camera system for just over six hours. The consumption rate of the camera is negligible compared to that estimated of the motors, which can from as little as 100,000 to just over 200,000 mW/hr.

The camera orientation is controlled through a head-tracker, which follows pan/tilt motions of the individual wearing the headset (shown below). The head-tracker addition allows a fully immersive experience for first-person piloting. The head-tracker has slight hysteresis and should be reset before each flight. If the accelerometer in the head-tracker fails or experiences significant drift during flight, the camera orientation can be manually operated through a remote control.

The size of the camera system is 4” by 5” by 5” and weighs 1.05 lbs. The assembly has been created to allow attachment to both the bottom and top of an

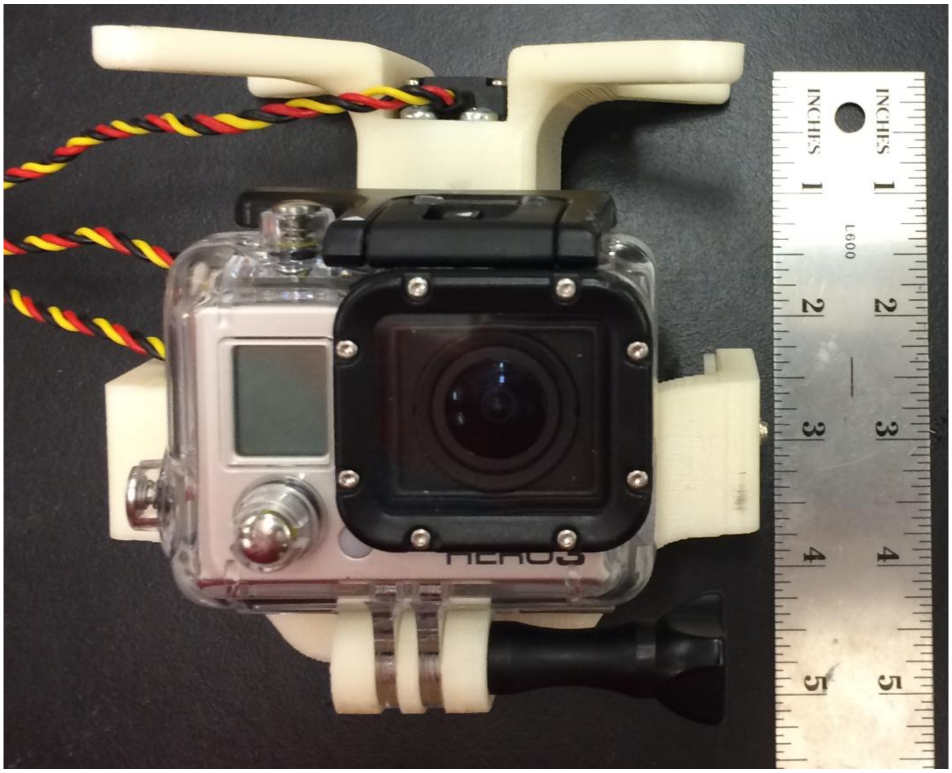


Figure 22: The camera mount is approximately 4" by 5" by 5" and weighs 1.05lbs.

Aeroquad™ plate. However, the center of mass will need to be altered before flights with a top-mounted camera will be safe and stable.

IMPLEMENTATION

FIRST PERSON VIEW

A first person view creates the illusion of being in the cockpit of a UAV during flight or the driver's seat of a ground vehicle. Hobbyists are more frequently using first person view in remote controlled (RC) aircraft to fly farther and higher than third person flight would allow. Advanced systems are capable of use without direct line of sight to the vehicle. While piloting experience and skills are the limiting factors of our lab's first person flights, long term goals include training pilots to fly first-person as they will be able to most efficiently collect the desired images.

TESTING FULLY INTEGRATED SYSTEM

We finished the design and installation of the camera system on the quadrotor. Our next step was to fly the quad and fully test the camera system. Our testing procedures would consist of short flights with the camera system to understand how changing the center of gravity would affect the maneuverability and agility of the device…

(SUDDEN CHANGE OF PLANS, GO TO THE NEXT PAGE)

RECONNAISSANCE OF THE CORVETTE MUSEUM SINKHOLE

A devastating event occurred at the National Corvette Museum on 12th February 2014. A sinkhole opened in the Skydome and consumed eight corvettes. Western Kentucky University's Engineering department was quick to respond sending Civil and Mechanical Engineers to help assist in the assessment of the damage. Subsequently, a unique opportunity arose for the four mechanical engineering students on the quadrotor team. Over the course of the day, our team used our quadrotor and the recently developed camera system to perform reconnaissance of the newly formed sinkhole.

A normal day of classes quickly escalated for the quad-team when a request to perform reconnaissance arrived. It would be the first time that the team had fully

Figure 23: What started as a normal day turned into a scramble to prepare the quadrotor for flight. From front to back, Darren Tinker, Will Johnson, and Zachary Lancaster all work to prepare for the day.

implemented the camera system during flight and well over two months since the craft had taken to the air. In fact, the quadrotor was not fully assembled at the time of the call. Tension was high as team members were pulled from class and the chaotic dash to scramble to the air began. While some members focused on reequipping the quadrotor with the appropriate accessories, others were performing system diagnostics to ensure the normal operating parameters were met. A go-bag was collected, full of video equipment, spare parts and a variety of tools. The team and their advisor loaded up and headed to the National Corvette Museum, each wondering what would be awaiting their arrival.

Stepping into the Skydome was overwhelming. The room was silent and the air was ripe with the odor of concrete dust, dirt, and hints of gasoline. A void stretched across the room, fifty feet in diameter and almost as deep. No words were worthy of speech.

Figure 24: The majority of the sinkhole at the National Corvette Museum is seen above in the image taken by WKU's quad-team

The team unpacked and prepped the quadrotor for a test flight. Once confidence was established on flight readiness, each member of the team knew his responsibility. Will Johnson was the designated pilot and would fly the device with the aid of our spotter, Zach Lancaster. Darren Tinker would operate the camera system and Jesse Reesor would monitor diagnostics and report the quadrotors telemetry status to ensure safe and steady operation.

The images captured by our quadrotor allowed the geologists and civil engineers to determine the structural integrity of the sinkhole. Without the capabilities of the quadrotor, an individual would have been required to rappel into the hole – putting human life at risk. Instead, the images collected by our device showed several key areas, not visible from the surface that allowed the experts to determine the sinkhole was stable and unlikely to expand further.

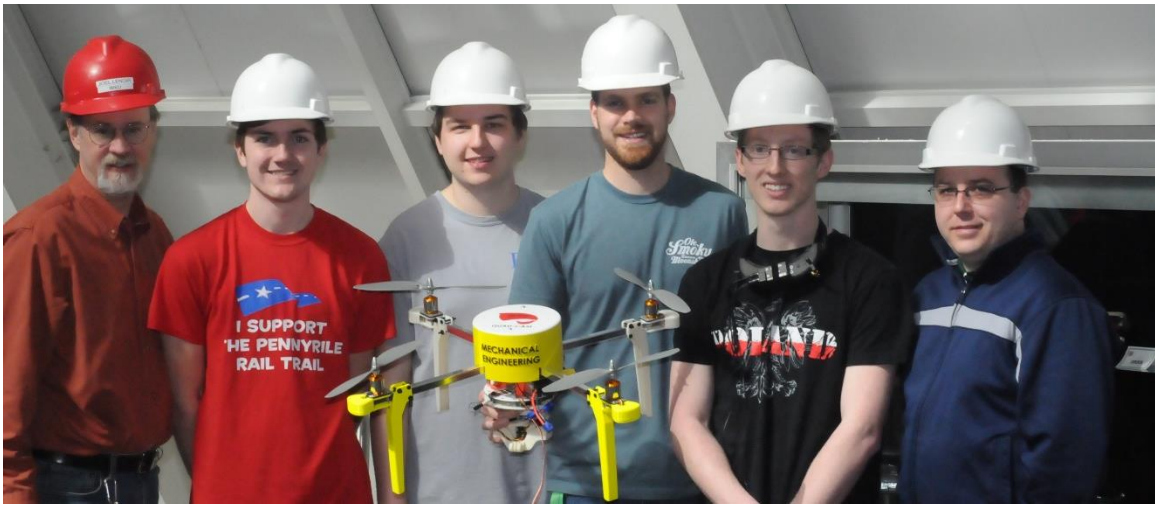


Figure 25: Our team received a once in a life time opportunity performing reconnaissance of the sinkhole.
From left to right: Joel Lenoir, Will Johnson, Zachary Lancaster, Jesse Reesor, Darren Tinker, and Troy Robertson

Figure 26: The one-millionth corvette shown the morning that the sinkhole opened

The experience at the Corvette Museum was one of a lifetime. Few students ever have such opportunity to incorporate their research projects with real world scenarios. **Figures 23 to 28** shown throughout this section were taken from the footage captured by our quadrotor. The course of events during that day show how a natural disaster can occur anywhere and how people will react as best possible to find a resolution. An important

Figure 27: A closer view of the corvettes on top of the rubble is shown above.

aspect revealed that day is how UAVs, which typically have a negative connotation, can be beneficial to society through reconnaissance as well as other means such as search and rescue.

Figure 28: The shadowed outline of the quadrotor is shown in the image captured above

CHAPTER 6

CONCLUSIONS

A SUMMARY OF LESSONS LEARNED

The design, installation, and implementation of a pan/tilt camera mount on our lab's quadrotor was completed successfully and is a foundation upon which other students can expand and improve. The increased and reinforced knowledge of additive manufacturing, mechatronic systems, design, and public relations are all valuable subjects that will prove worthwhile when pursuing future employment, projects, and research.

What had appeared to be a relatively simple task, grew into one much more complex and spawned miniature research projects that have gained momentum to become standalone projects for future students. The material testing, that originally was expected to be a simple process, entails significantly more work to understand the material properties of the thermoplastic. The project has opened the door for the university to perform interdisciplinary research, reconnaissance, and produce aerial imagery for the university. **Figure 29** is a visual summation of this paper given the frequency of words and is an example of how something that seems simple can cover much more.

Furthermore, the project opened the door to better understanding the design process and the reality of how it functions. It is depicted as a clean and organized process, but it can easily take a different and more chaotic form. The design process is helical and every subsequent step is dependent on the last. Just as in life, there are countless possibilities of where one can go, and the final destination is shaped by each step along the way.

Figure 29: The project encompassed a significant amount of research relative to what was expected during the project’s birth. *“The project appeared small, but was just faraway”*

CHAPTER 7

FUTURE APPLICATIONS

WHERE TO GO NEXT

The design process is continuous and ever expanding. While close to optimal, there are still improvements to be made. Passive video stabilization would improve the image quality recorded even when taking post-processing into account. As the quadrotor is becoming ever more reliable, a variety of mounts can be made to accommodate more cameras than the GoPro family. The video transmission and receiving antennas are subject to change as those purchased were the best commercially available. Given sufficient time and research, a custom transmitter and/or receiver design can be manufactured to offer a greater range of flight without interference or loss of signal.

The system may also be improved by varying the servos, camera, and physical mount itself. As mentioned in Chapter 6, the design process is dependent on each previous step. There are numerous solutions to creating a camera system. The farther back in the design process one desires to introduce change causes greater ripples and differences in the final product that is created.

Regarding applications of the system, first-person flight and reconnaissance were merely our team’s first step with the camera system and research with multi-rotors. Our goals are to expand uses of the current platform to photogrammetry, which is the ability to create models by stitching multiple photos together of an object, terrain, building, or any other physical object.

Furthermore, goals include expanding the camera mount onto other flight platforms. Our lab is currently designing an Octocopter to be used in a similar manner as our quadrotor. The aim of the new design is to carry a larger payload and have a longer flight time. The combination of these two qualities would allow for a higher quality camera to be adapted and subsequently higher quality images to be produced.

BIBLIOGRAPHY

[1] Aviastar, "All the Worlds Rotorcraft," Aviastar, 2006. [Online]. Available: http://www.aviastar.org/helicopters_eng/bothezat.php. [Accessed 8 April 2014].

[2] M. Cornblatt and D. Eli, "Game of Drones," 21 April 2014. [Online]. Available: http://www.gameofdrones.biz/.

[3] J. A. Matthews, "3D Printing breaks out of its mold," *Physics Today,* vol. 64, no. 10, pp. 25-28, 2011.

[4] N. Sabatini, "Unmanned Aircraft Operations in the National Airspace System," Washington, DC, 2007.

[5] Federal Aviation Administration, "Advisory Circular 91-57," Department of Transportation, Federal Aviation Administration, Washington, D.C., 1981.

[6] *Michael P. Huerta, Administrator, Federal Aviation Administration v. Raphael Pirker*, 2014.

[7] K. D. Atherton, Popular Science, 11 October 2013. [Online]. Available: http://www.popsci.com/article/technology/how-low-sky-and-more-questions-drone-

legal-case-might-resolve. [Accessed 8 April 2014].

[8] Fat Shark RC Vision Systems, 4 February 2014. [Online]. Available: http://www.fatshark.com/uploads/pdf/1745-1.pdf.

[9] M. K. J. M. P. B.M. Tymrak, "Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions," *Materials & Design*, vol. 58, pp. 242-246, 2014.

[11] M. Brain and W. Harris, "How Stuff Works," 2014. [Online]. Available: http://science.howstuffworks.com/transport/flight/modern/helicopter5.htm. [Accessed 18 April 2014].

[12] U.S. Centennial of Flight Commision, "Propellers and Rotors," American Aviation Historical Society, 2014. [Online]. Available: http://www.aahs-online.org/centennialofflight.net/essay/Theories_of_Flight/props/TH18.htm .

APPENDICES

Figures 30 through 32 represent the data collected during material testing of the thermoplastic used by our Stratasys Dimension Elite (3D Printer).

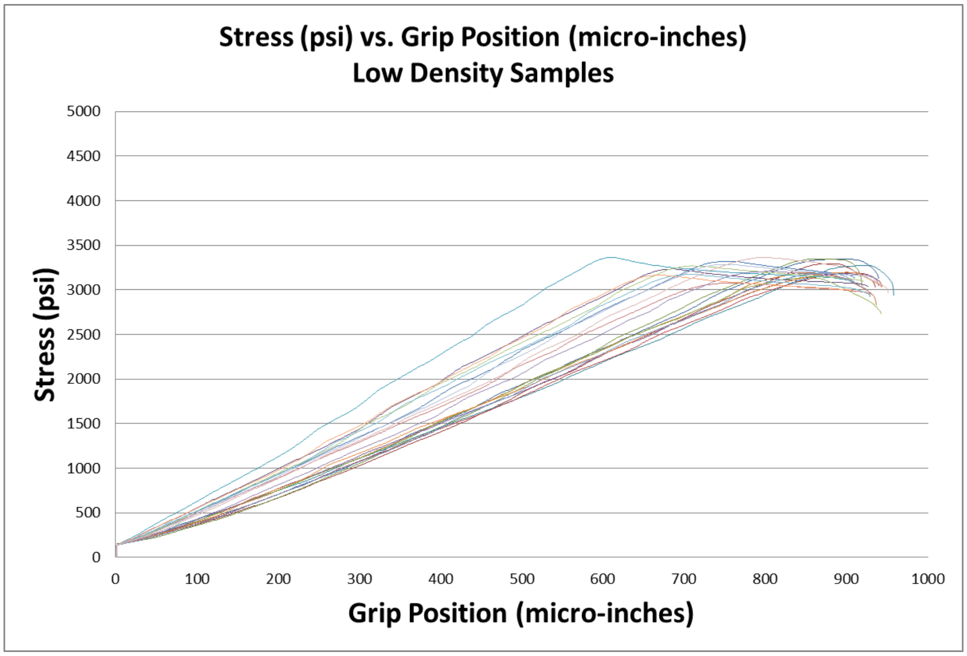


Figure 30: Low density tensile test sample data is shown above. The average ultimate tensile strength is approximately 3200 psi.

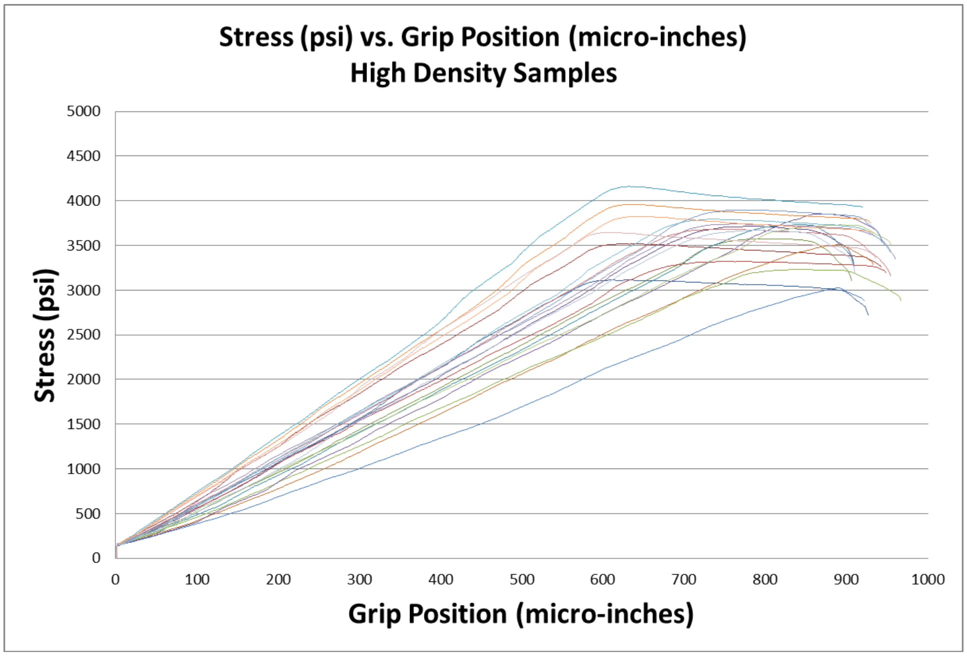


Figure 32: High density tensile test sample data is shown above. The average ultimate tensile strength is approximately 3600 psi.

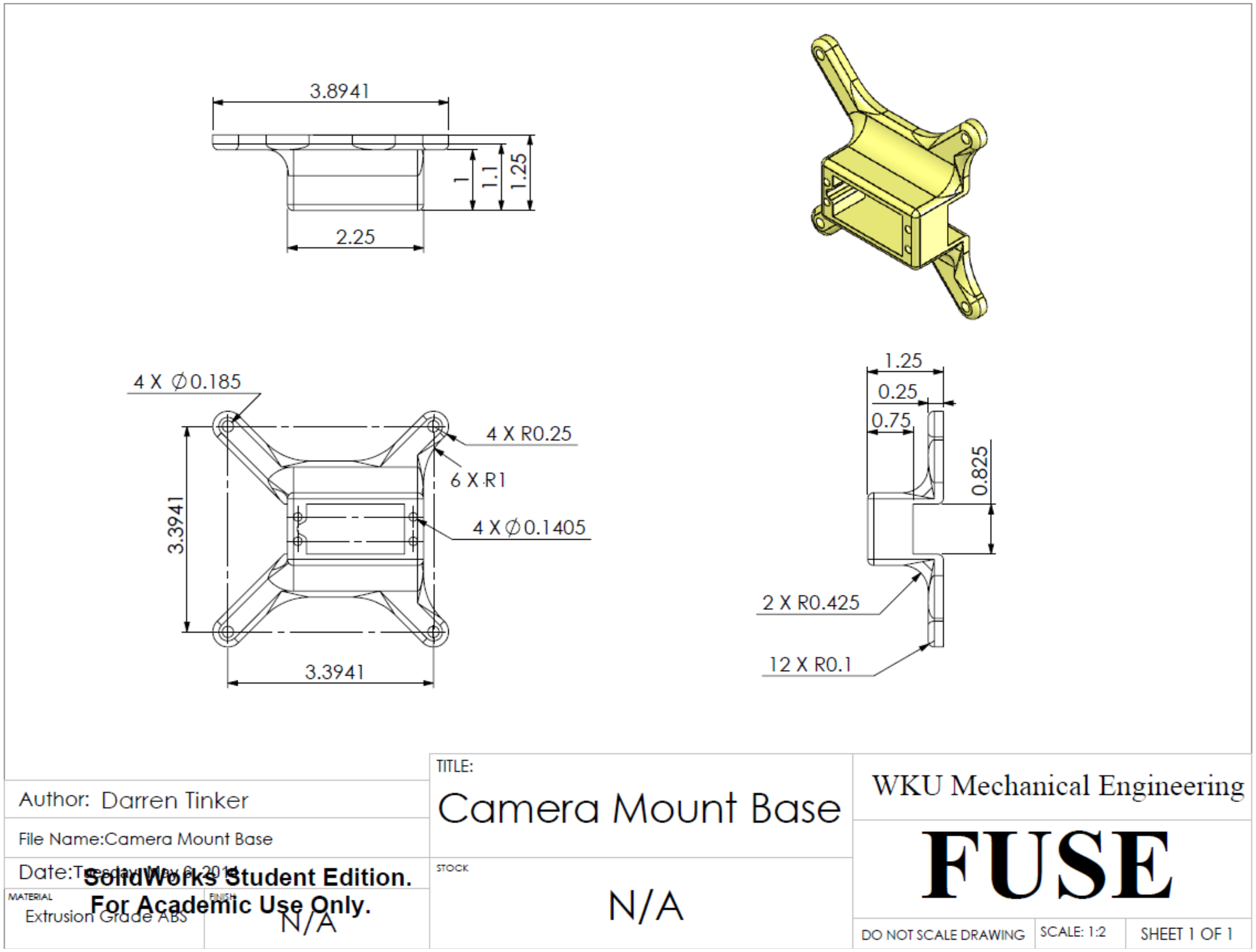
Figure 31: Solid density tensile test sample data is shown above. The average ultimate tensile strength is approximately 4400 psi.

Table 2: The bill of materials to purchase the camera system and other accessories for the project is shown above and continued on the next page

Component	Part Description	Supplier	Unit Price $	Qty.	Cost Sum	Group
M.I.G. Tracker V5 (Magnetic, Inertial, Gyro)	V5 Head Tracker	ReadyMadeRC	$ 67.99	1	$ 67.99	Accessories
FatShark 600TVL CMOS Pan/Tilt Cam	Coaxial Pan/Tilt Camera	ReadyMadeRC	$ 67.99	1	$ 67.99	Accessories
Go-Pro Hero 3 Black	Camera	Amazon	$ 399.99	1	$ 399.99	FPV Kit
Fat Shark Dominator Video Glasses	Headset	ReadyMadeRC	$ 299.99	1	$ 299.99	FPV Kit
Fat Shark Dominator 5.8GHz Receiver Module	5.8 Ghz Reciever	ReadyMadeRC	$ 33.99	1	$ 33.99	FPV Kit
ImmersionRC 600mW 5.8GHz transmitter	5.8 Ghz Transmitter	ReadyMadeRC	$ 69.99	1	$ 69.99	FPV Kit
5.8 GHz Circular Wireless Omni TX/RX Skew Planar Wheel Combo	Antenna Set	ReadyMadeRC	$ 80.98	1	$ 80.98	FPV Kit
Fat Shark Head Tracker to 3.5mm Data Cable (DX8, other)	Adapter for Head Tracker to Radio Note: Most JR/Spektrum radios do NOT have the correct trainer functions to work with a head tracker. So far, only the DX8 has been verified to work.	ReadyMadeRC	$ 9.99	1	$ 9.99	FPV Kit
32 GB Micro SD Card	SanDisk Ultra 32 GB MicroSDHC C10/UHS1 Memory Card with Adapter (SDSDQU-032G-AFFP-A)	Amazon	$ 27.79	1	$ 27.79	Other
Spare Go-Pro Batteries/Charger	Smatree Battery(1200mAh x 2 Packs) and Charger kits for GoPro HD HERO3, AHDBT-201, AHDBT-301	Amazon	$ 21.99	1	$ 21.99	Other
GoPro Replacement Housing for HERO3 Cameras	Skeleton Housing	Amazon	$ 28.49	1	$ 28.49	Other

Table 3: The continuation of bill of materials to purchase the camera system and other accessories for the project is shown below.

GoPro HERO3 Camera Cable (Audio and Video)	GoPro Cable	ReadyMadeRC	$ 8.99	1	$ 8.99	Other
EMS Servo Reverser JR/S/Z	Servo Reversing Y-Harnesss	Tower Hobbies	$ 19.69	1	$ 19.69	Other
Hitec HS-645MG High Torque 2BB Metal Gear Servo	High Torque Servos	Tower Hobbies	$ 31.99	3	$ 95.97	Other
Servo Extension Cord	Hobbico Pro HD Extension 24" Futaba J	Tower Hobbies	$ 6.99	2	$ 13.98	Other
Spektrum DX8	Transmitter	Horizon Hobby	$ 349.49	1	$ 349.49	Other
Total RFP Expenses					**Actual**	
					$ 1,951.61	



Author: Darren Tinker

File Name:Camera Mount Base

Date:Tuesday, May 6, 2014

MATERIAL
Extrusion Grade ABS

FINISH
N/A

TITLE:
Camera Mount Base

STOCK
N/A

WKU Mechanical Engineering

FUSE

DO NOT SCALE DRAWING

SCALE: 1:2

SHEET 1 OF 1

Figure 33: The camera mount base for attaching the system to an Aeroquad quadrotor

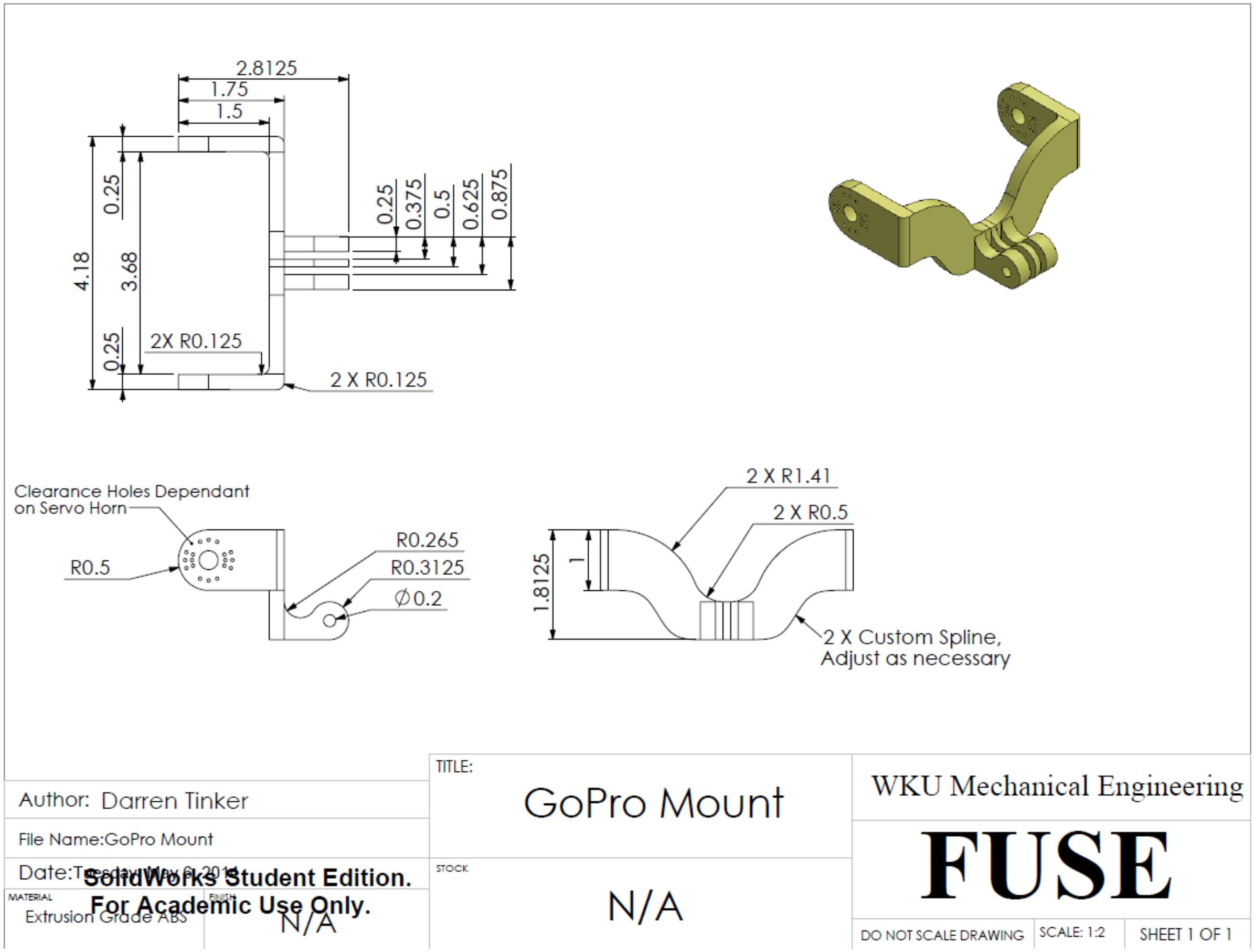


Figure 34: The GoPro mount for the camera system assembly

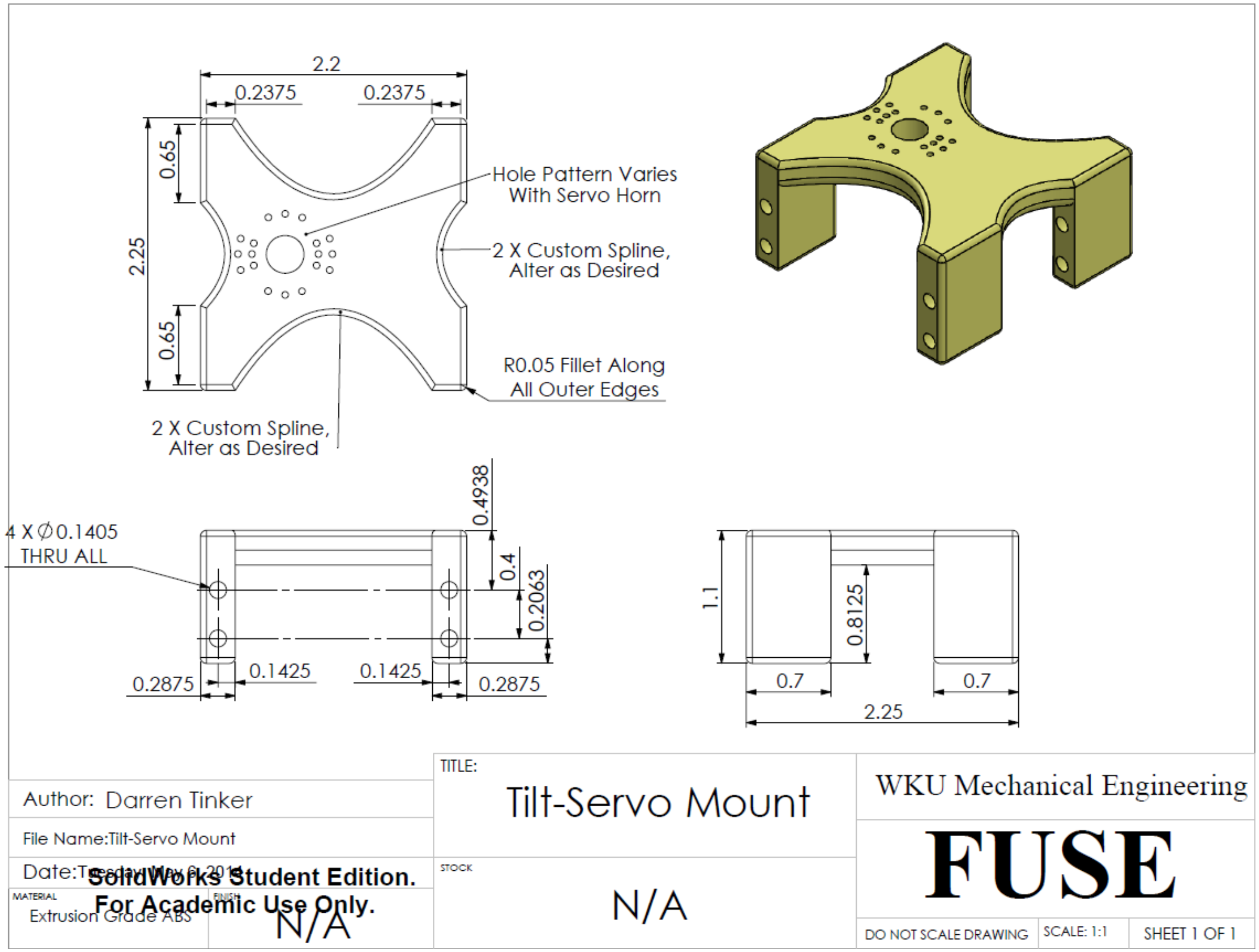


Figure 35: The tilt-servo mount for the camera system assembly