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Development of an Autonomous Blimp

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Abstract

The purpose of this project was to design and fabricate an autonomous dirigible-based platform that could be used to enable development of navigational controllers and provide multi-mission capability through modularity. The platform was designed to carry and interface with a variety of mission specific hardware through a standard interface. A customized hardware platform was designed including a propulsion system and integrated sensor suite. Multiple ground level tests were undertaken to determine sensor performance and the capabilities of the navigational programs.

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1. Introduction

1.1. Introduction

Compared to manned aircraft, unmanned aircraft have significantly better endurance and are more cost effective to operate for purposes other than the transportation of people. Manned aircraft require substantially larger volumes and lift capacity than an unmanned aircraft would need due to the requirement of comfortably fitting pilots. This extra payload requirement results in correspondingly larger fuel requirements for the operation of the aircraft. Not having the pilots onboard also means that the aircraft can stay in the air longer, as they have no need to account for the pilot getting tired, hungry, or distracted.

However, even unmanned aerial vehicles (UAVs) have their endurance limited by being required to constantly move at a minimum speed to maintain the necessary lift to remain aloft. A lighter- than-air (LTA) craft needs to only expend energy to move horizontally, all altitude adjustments can be made with only minimal energy expenditure. Rather than the energy required to generate lift, the main factors that determine energy expenditure are the size of the vehicle and the weather conditions it is operating in.

The ability to float in the air with minimal energy expenditure is important for vehicles that must remain in the air for long periods at a time or for companies that need to reduce the cost of flight. As energy costs rise, projects that require long term commitment of less energy efficient aircraft become increasingly expensive. Energy efficiency also directly effects the time an aircraft can remain in the air. This becomes important in cases such as search and rescue or surveillance missions. At natural disaster areas, search and rescue operations are greatly aided by an over-watch aircraft that can remain on station for long periods of time and be used to direct where efforts should be focused. For surveillance of important targets, the military either must ensure a new craft is on station before the previous one leaves for refueling or accept gaps in their observations. In both these cases, the greater fuel economy of an LTA aircraft would allow for fewer gaps in coverage due to refueling and fewer aircraft needed to maintain coverage for the same time period. Both of these situations require aircraft being in the air for long periods of time, bringing higher costs for fuel and other expendables. LTA craft can reduce these costs significantly, as the only expendables are helium leakage and electricity.

1.2. Project Statement

The purpose of this project was to design and fabricate an autonomous dirigible-based platform that could be used to enable development of navigational controllers and provide multi-mission capability through modularity. System design goals included a low cost and long endurance compared to a fixed or rotary wing UAV and accurate, autonomous navigation capability. Also, the platform was designed to carry and interface with a variety of mission specific hardware through a standard interface.

1.3. Summary

In Chapter 2, we present background research on blimp history and technology, past and current UAV technology, and previous attempts to develop an autonomous UAV. In Chapter 3, we elaborate on the goals and requirements of the system. Chapter 4 is composed of the system-level design methodology, highlighting the interactions between the various sub-systems. In Chapter 5, we describe the shell selection process including materials and aerodynamic characteristics. In Chapter 6, we describe the drive system design and revision process, including propeller and materials testing as well a trade study of several potential control schemes. In Chapter 7, we examine the power and control systems of the blimp. In Chapter 8, we discuss the gondola design process and an investigation of various materials for use in gondola construction. In Chapter 9, we describe the software architecture. In Chapter 10, we discuss mission modules. In Chapter 11, we summarize our deliverables for the project. In Chapter 12, we offer suggestions for future work. The report concludes with several appendixes detailing individual test results and specific procedures.

Chapter 2

2. Background

2.1.Introduction

The purpose of this section is to familiarize readers with historical and current blimp technology, UAV technology, the benefits of an autonomous blimp, and current efforts to develop autonomous blimps. We first address the history of Lighter-Than-Air (LTA) aircraft, highlighting their applications and the science behind them. We then review previous and existing UAV technology and describe the role that it fulfills. Next, we consider the benefits to creating an automated blimp, especially relative to fixed wing aircraft and UAVs in similar roles. Finally, we examine other efforts to create an autonomous LTA vehicle including their methods and their degrees of success.

2.2.Blimp History

LTA craft have existed since the late 1700's when the first hot-air balloon was constructed and flown by Joseph-Michel and Jacques-Etienne Montgolfier. [1] Initially, LTA vehicles were used primarily for entertainment and reconnaissance for the military. Until the early 1900's, hot-air balloons were unable to travel horizontally unless propelled by the wind. The only control the pilots had was to increase the temperature of the balloon to fly higher, or to let it cool to fly lower. Today the largest uses of hot-air balloons are recreation, tourist sightseeing, and racing.

The first well known example of a powered LTA craft was produced in 1900 by Ferdinand von Zeppelin. This craft, shown in Figure 1 utilized breakthroughs in lightweight gasoline engines and aluminum frames. [2] This craft was the first LTA craft that was able to move independent of the prevailing winds. [3]

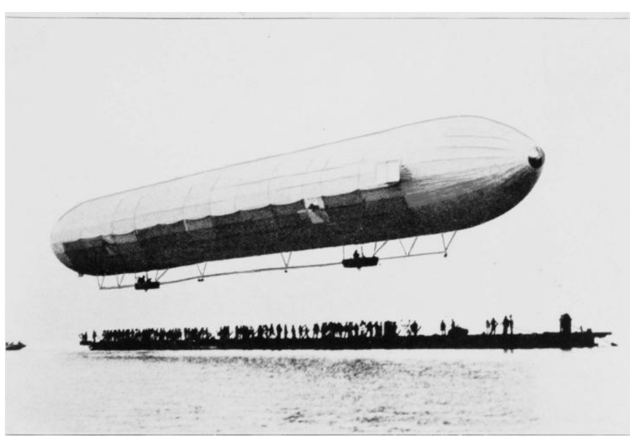

Figure 1: The First Zeppelin
(http://inventors.about.com/od/xzstartinventors/ss/Zeppelin_2.htm)

The World War 2 era saw both the rise and fall of the airship as a vehicle. Germany was the source of a great many of the world's passenger zeppelins, but due to increased tensions with the United States, their offers to purchase helium were refused. As a result, the airships used hydrogen, a dangerous substitute for helium. Due to the high cost of helium, other countries attempted to use hydrogen as well. [4]

The practice of filling airships with flammable hydrogen led to several major accidents which reduced the popularity of LTA craft. The R-101 was a British airship that suffered a failure which resulted in the airship crashing. While the impact was rather gentle (very few injuries resulted), it set off the hydrogen which brought about the deaths of most of the passengers and crew. Another major accident was the Hindenburg incident, shown in Figure 2, in which a large passenger zeppelin caught fire on landing, killing 35 of the 97 people onboard. [5] This significantly reduced the public's confidence in passenger blimps, resulting in a marked decrease in use.

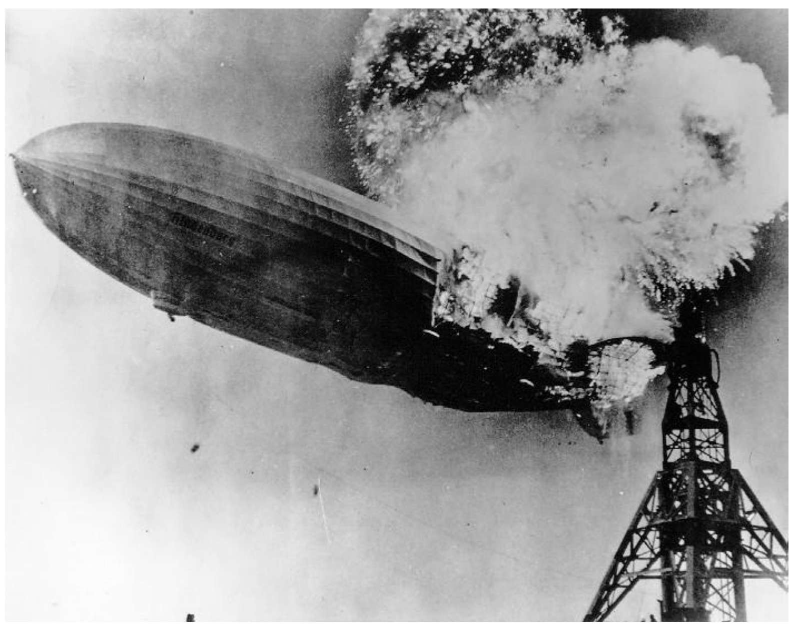

Figure 2: The Hindenburg Explosion
http://en.wikipedia.org/wiki/File:Hindenburg_burning.jpg

During the war, most of the research for aircraft was focused on jet engines as they were much more useful as an offensive weapons platform than blimps. When World War 2 ended, most aviation production and research continued to be focused towards jets, while development of airship technology declined.

The initial modern military application of LTA technology was the usage of aerostats, medium-altitude tethered balloons, as sensor platforms. [6] Aerostats, in concert with launching towers around military bases, were able to provide their operating bases with round the clock bird'seye views without the cost of a detailed drone or aircraft and the runways fixed-wing aircraft would require. Aerostats, such as the one shown in Figure 3 have also been utilized by the United States Border Patrol to aid in spotting illegal immigrants and smugglers. In addition, foreign countries such as Israel and Mexico have used aerostats for military surveillance and boarder security. [6]

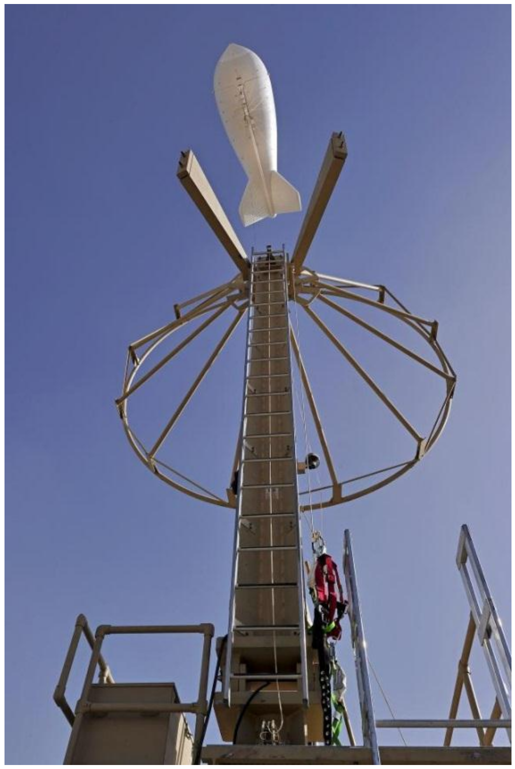

Figure 3: Military Aerostat Providing Aerial Surveillance (http://usarmy.vo.llnwd.net/e2/-images/2010/12/10/94252/)

Mobile LTA vehicles have also been created to act as surveillance platforms. An example of mobile LTA craft can be seen in DARPA's ISIS project, a next generation aerial early warning system based off of Airborne Warning and Control Systems (AWACS) technology. When the ISIS system was combined with Lockheed's High Altitude Airship (HAA), shown in Figure 4, a sensor platform was created that can fly at over 65,000 feet for over thirty days. [7] These systems hold great potential in the surveillance world as their ratio of operating cost to flight time is a great improvement over current fixed-wing AWACS aircraft.

Figure 4: Lockheed's High Altitude Airship
(http://www.ohio.com/community/airship26cut-1.226739?ot=akron.PhotoGalleryLayout.ot&s=1.226722&pt=1)

There are three classifications of LTA craft, shown in Figure 5. The non-rigid craft are airships that have no solid structure around their gas bag. Hot air balloons and blimps fall under this category. [8] Semi-rigid aircraft are wrapped in an incomplete frame to reduce the stresses on the gas bag. [8] Rigid aircraft are the craft that are thought of when talking about a Zeppelin. The gas bags in rigid airships are encased inside a structure. Rigid airships are able to withstand the most stress as a result of the structure preventing damage to the gas bags. This allows them to maintain their aerodynamic shape at higher speeds.

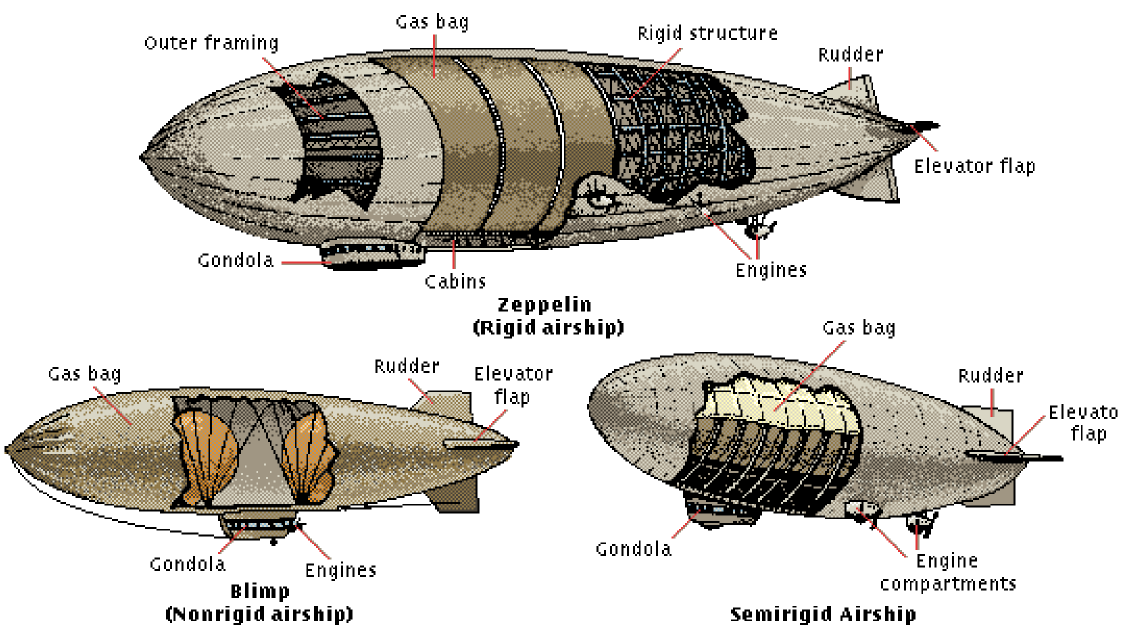

Figure 5: Different Types of Airships
http://library.thinkquest.org/18033/media/airship.gif

LTA craft fly using the principle of buoyancy. The airship's gas bags are filled with a gas with a density lower than that of air (hydrogen, helium, etc.). The lower density makes the craft lighter than the air it displaces, leading to a buoyant force. This force can be represented as coming from the center of buoyancy of the shell, as seen in Figure 6, and is derived using the formulas shown below.

$$Theoretical\ Maximum\ Bouyant\ Force = \ Density\ of\ Air * Volume\ of\ Shell$$

$$Actual\ Lift = Theoretical\ Bouyant\ Force - Weight\ of\ Gas\ in\ shell - Weight\ of\ Shell$$

$$\sum F_{Lift} = \rho_{Air} V_{Shell} - \rho_{Gas} V_{Shell} - \ m_{shell} g$$

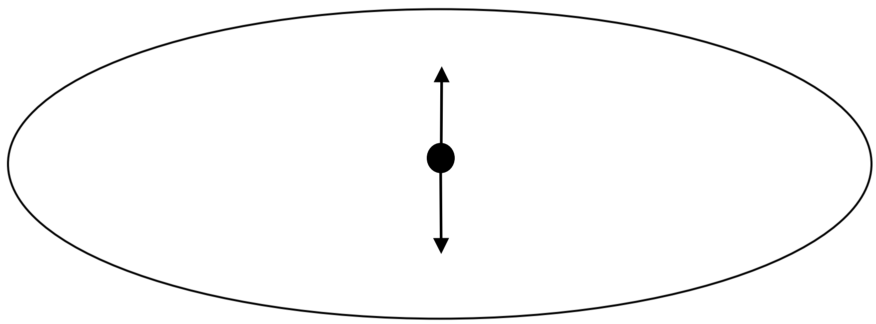

Figure 6: Location of Buoyant Force in a Blimp

An LTA vehicle by itself has no motive power and would just float like a balloon. While this is acceptable for some uses, to control its horizontal movement a blimp needs a method to generate horizontal thrust. This is generally achieved through the use of two or more motors. Creating a difference between the outputs of the two motors leads a turning moment about the center of mass, enabling steering, which can also be accomplished using vertical control surfaces on the tail or use of a directed thrust system. Vertical movement can be controlled using changes in buoyancy, changes in pitch, or direct vertical thrust. [9][10] Direct vertical thrust can be generated by altering the angle of the motors to tilt them up or down.

2.3. Unmanned Aerial Vehicle History and Technologies

The first generation of unmanned aircraft was developed during World War 1 in the form of aerial torpedoes, devices created to destroy enemy airships and stationary targets. These weapons are the ancestors of modern day cruise missiles. The earliest aerial torpedoes were created through the simple expedient of taking a full sized manned heavier than air aircraft and retrofitting it with a system that could control the craft via radio. [11] These were later replaced by purpose built weapons such as the Kettering Bug shown in Figure 7.


KETTERING BUG AT USAF MUSEUM (GVG / PD)

Figure 7: WW1 era Flying Torpedo
(http://www.vectorsite.net/twcruz_1.html)

In World War 2, the use of unmanned craft began to expand into different roles, with unmanned aircraft serving as sensor platforms as well as target practice drones [11]. One such application was as a training tool for American antiaircraft gunners. The Culver PQ-14, shown in Figure 8, was a radio controlled full sized aircraft, the controllers would fly it from the ground simulating attack patterns, as antiaircraft gunners attempted to shoot it down. The drone, being a full sized aircraft, allowed American antiaircraft gunners to gain valuable practical experience shooting down an aircraft without risking a pilot. [11]

Figure 8: WW2 era unmanned training target (http://www.vectorsite.net/twuav_01.html)

The United States saw success in creating unmanned aircraft loaded with explosives that would collide with enemy ships and ground targets. The US modified a bomber with remote controls and filled the aircraft with explosives. The modified bomber had to be piloted into the air and the crew would then bail out after arming the explosives. Another aircraft, following the now unmanned airplane, with the pilot remotely controlling the drone, would guide the craft into its target. After an accident that killed the modified aircraft's crew before they ejected, the project was canceled. [11]

Also during World War 2, the Germans began to develop guided bombs. The Germans created the V2 rockets, shown in Figure 9, which were bombs with rocket motors and rudimentary guidance systems. These rockets used gyroscopes for lateral stabilization and an accelerometer for speed control. The rockets were aligned to the target azimuth and stayed on course using an onboard analog computer. Later versions utilized radio "guide beams" from the ground for more precise navigation. [12]

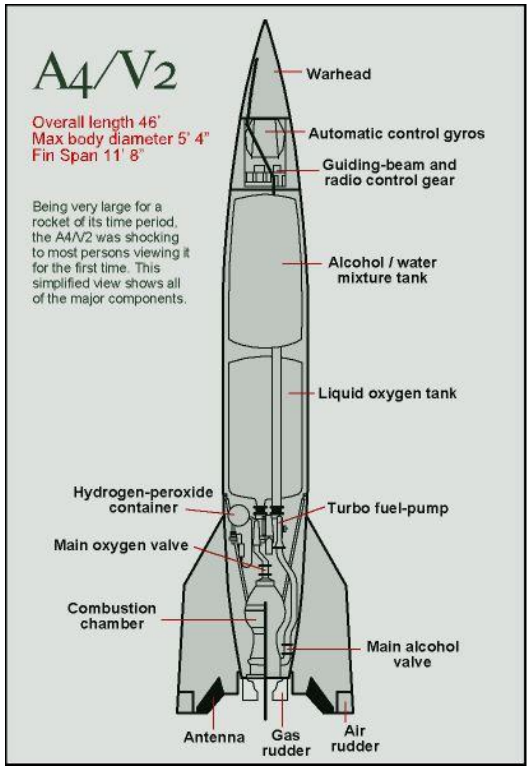

Figure 9: Diagram of the V2 rocket
(http://www.v2rocket.com/start/makeup/design.html)

Germany also created a bomb called the Fritz X with fins that were controlled by a bombardier on the mother ship that dropped the weapon. [11] The Fritz had a bright glowing flare on the tail that would allow the bombardier to know where the weapon was as he guided its descent towards the target. During the war, one of these bombs was able to successfully sink the defecting Italian battleship *Roma*. [11]

In the years after World War 2, unmanned aircraft continued to be used by the military, but mostly in the role of a sensor platform. During tests of nuclear weapons, the military would convert several B-17 bombers into drones, full of sensor equipment, and fly them over, or even through nuclear blasts to collect data without having to sacrifice pilots. [13] Data collected from these experiments included how aircraft were affected by the shockwaves from nuclear weapons at varying altitudes and distances and radiation measurements. [13]

Unmanned aircraft began seeing use again during the Vietnam War. The AQM-34, Figure 10, was deployed and operated from DC-130 aircraft and were entirely remotely controlled. [14] During the war these drones saw use as reconnaissance and ground support vehicles, utilizing AGM-65 Maverick air-to-surface missiles and other smart bombs. [14] They were even used to drop propaganda leaflets onto enemy populations. [14]

Figure 10: AQM -34
(http://usafhpa.org/350thSRS/350sea.html)

2.4. UAV Control

There are currently two widely used methods for controlling unmanned aircraft. The first method is to use remote control. In this method, a human pilot controls the aircraft remotely via a wireless link. The pilot is not actually in the aircraft; however, he has complete control of the vehicle. The Predator drone (as shown in Figure 11) utilizes the system described above, but has the capability to use the next described system. [15]

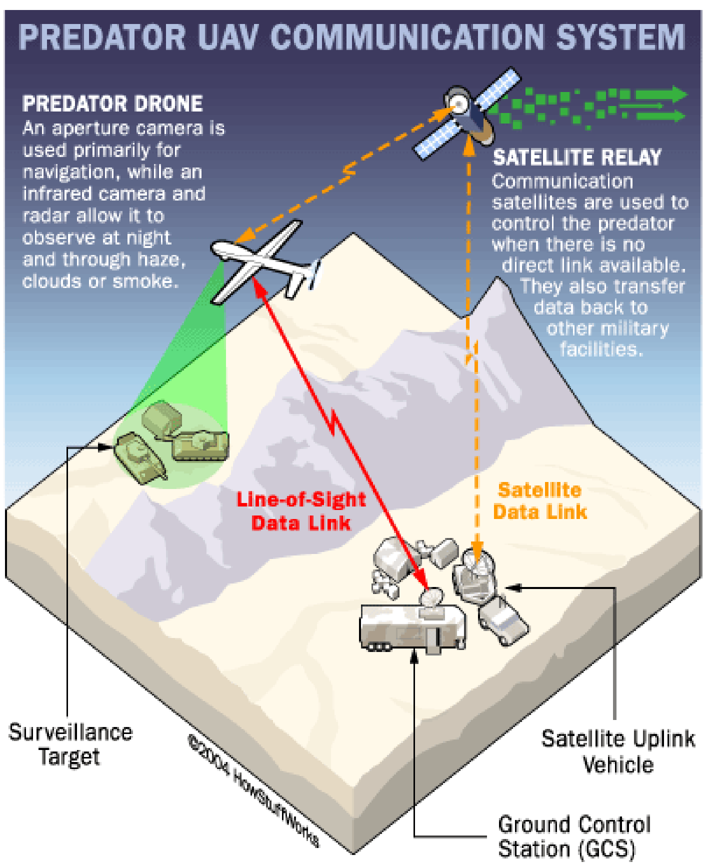

Figure 11: Predator UAV Communication System
http://science.howstuffworks.com/predator6.htm

The second method of controlling a UAV is autonomous control, where the aircraft is flown by an onboard computer. [15] Basic control and navigation of the aircraft is performed by the computer. High level decisions, such as destination selection and weapons deployment, are made by an observing controller who is in communication with the UAV.

The technology that had been created to build guided, unmanned aircraft was applied to individual munitions as well. Smart missiles and bombs, also known as precision-guided munitions (PGMs), are munitions intended to precisely hit a specific target. [16] Smart missiles and bombs, such as the one shown in Figure 12, are able to change their course in flight to home in on their target. This can be achieved using a variety of technologies. The first such technology to be used was radio control in which a pilot remotely steered the missile to its target. Later, infrared and lasers were used to illuminate or “paint” a target which the missile could then home in on. [16] Finally, satellites were used to guide missiles to their targets using GPS.

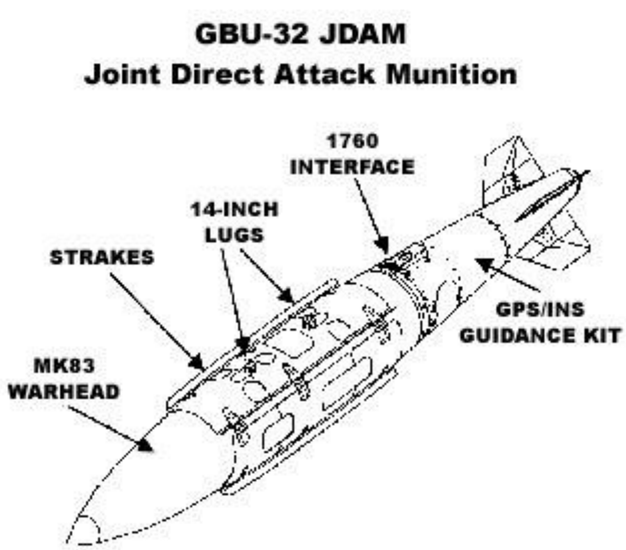

Figure 12: Example diagram of a PGM.
http://science.howstuffworks.com/smart-bomb2.htm

It has not been until the last fifteen years that UAVs could really be considered truly autonomous. The military’s goal with the reconnaissance UAVs has been to advance drone technology such that a single controller can handle multiple drones at the same time. [11] This requires sophisticated Artificial Intelligence (AI) to both control the aircraft and analyze the data gathered by its sensors. This would enable the aircraft to function with minimal controller attention and monitoring until user input is required, at which point the UAV would alert its controller. [11] Currently this goal has not been met; however, UAV systems are nearing this point.

Currently, most UAVs are used by the military for surveillance and air support. For example, the MQ-1B Predator System used by the United States Air Force is a medium-altitude, long-endurance UAV used for close air support, air interdiction, intelligence gathering, surveillance, and reconnaissance. [17] The Predator, shown in Figure 13, was originally designed in 1996 for reconnaissance only, but was changed to a multi-role aircraft in 2002 with the addition of AGM-114 Hellfire missiles. [17] Other UAVs in use by the US military include the MQ-9 Reaper, the RQ-11B Raven, the RQ-170 Sentinel, the RQ-4 Global Hawk, the Scan Eagle, and the Wasp III. These UAVs provide intelligence, surveillance, and reconnaissance as well as real-time direct situational awareness and target information. Another UAV used by the US air force is the QF-4 Drone, a full-scale, reusable drone used as a target for weapons system evaluation.

Figure 13: Armed Predator Drone
(http://www.sanfranciscosentinel.com/?p=121232)

2.5. Benefits of a UAV Blimp

The combination of capabilities present in an LTA vehicle provides benefits not typically available to an aerial platform. According to a paper on using autonomous platforms for rescue surveillance systems by a team at Kobe University in Japan, “Unmanned aerial vehicles (UAVs) are better options to perform [rescue surveillance] precisely, safely, and quickly. Especially an autonomous blimp is the best option. It is a kind of lighter than air (LTA) vehicles [sic] and it has some advantages beyond the other UAVs like helicopters or planes with regard to safety for victims, easy use to fly [sic], high mileage, and lower-sky availability" [18]. Phrased another way by the same team in a systems and controls paper presented at an IEEE conference, "A blimp can fly at low altitude with low noise, safety and long flight availability [sic], and it has higher energy efficiency than the other aircraft" [18]. These attributes make blimps an excellent platform to be modified into UAVs.

A blimp's endurance makes it very well suited for use as a UAV. As UAVs don't require pilots, the only thing constraining the time a blimp can spend in the air is its ability to generate propulsion and lift. Because the blimp does not need to expend energy generating lift, it can expend all of its energy on propulsion, making the same amount of energy last longer. This capability gives blimps a distinct advantage in terms of staying in the air longer for the same amount of energy compared to heavier-than-air platforms. Additionally, as it does not require constant propulsion, a blimp can shut down its propulsion systems and drift, only activating periodically to maintain position thereby conserving energy.

Currently, fixed-wing UAVs have endurances measured in hours, whereas LTA UAVs are predicted to have endurances of several weeks [18]. A recent statement from Northrop Grumman announced a new, 250 foot long autonomous hybrid blimp/ lifting body design capable of maintaining flight for upwards of three weeks. This is a significant improvement over the endurance of the current leader in UAV technology, Northrop Grumman's Global Hawk, which can only remain in the air for 35 hours [19]. Additionally, because of lower required power expenditure, low power yielding solar cells or other power generation methods can be used to further increase flight time on larger blimps. This longer time-over-target capability allows for fewer gaps in coverage and less time and fuel spent returning to base rather than performing its mission.

Another benefit of the blimp platform is its maneuverability. A blimp can pivot in place, ascend and descend much like a helicopter in a straight, vertical line, and hold position without circling. These characteristics make blimps able to access areas that their fixed wing counterparts cannot. It also means that, unlike most fixed wing aircraft, blimps can take off and land vertically. Blimps do not need to maintain speed to maintain lift, so they can loiter and make slower passes where a fixed wing aircraft cannot. Because a blimp has a single, unchanging source of vertical thrust, unlike the uneven thrust provided by a helicopter, it has better stability than most platforms in low wind conditions. This stability is very important when it comes to missions like surveillance, item delivery, or acting as a beacon.

Blimps have several features that make them substantially safer to automate than fixed or rotary wing aircraft. For one, a blimp does not immediately lose altitude if it loses control or power temporarily. As the blimp does not need constant control input to maintain lift, a loss of control or a slight error would not instantaneously cause a loss of altitude. Instead the blimp will either drift or drive in the incorrect direction. As the blimp would not be moving especially rapidly, there would likely be time for human intervention to prevent a crash. In the event this time was not available, the low speed of the blimp would likely result in a gentle impact. Similarly, power failure would result in a drifting balloon. Unlike an aircraft that loses power and crashes, a drifting balloon and its payload are more likely to be recoverable.

The blimp platform also handles payloads differently than other aircraft. Traditional aircraft trade payload for range and endurance, as it takes substantially more energy to lift a larger payload. For a blimp, no additional energy is expended maintaining altitude once the payload has been lifted. For a fixed wing aircraft, maximum payload is determined by the lift generating capacity of the wings and the maximum thrust that can be generated by that aircraft's engines. For the blimp, payload is determined by the volume of the shell. The thrust it can produce only effects the speeds the craft can operate at and the acceleration that can be achieved under specific operating conditions. This means that blimps can have higher payload limits on a larger scale than fixed wing aircraft. It has even been theorized that blimps could be designed to lift as much as 1000 tons, considerably more than even the heaviest lift aircraft. [20] This is also a significant improvement over previous generations of airships. For example, the Hindenburg, the largest airship ever built, could only lift 160 tons. [21] As an additional benefit and unlike a regular aircraft, the lift generating force for the blimp comes from helium, which can be reused for multiple payloads. This is a distinct advantage over the fuel used in a fixed wing aircraft, which needs to be replaced after every trip.

Finally, blimps have a lower operating cost than other platforms. Because a blimp can take off and land vertically, it only requires a refueling point and an area large enough to take on its cargo. This represents a substantial cost savings in facilities to service a blimp drone when compared to a traditional drone, which requires a runway. [22] Additionally, the low fuel consumption of a blimp produces significant cost savings. For example, Northrop Grumman has released figures on the new LTA reconnaissance platform they are developing, the long-endurance multi-intelligence vehicle (LEMV). According to their press release, "[The LEMV] can stay aloft for weeks on around 18,000 pounds [8,000kg] of fuel. [It will cost] about $20,000 to keep the vehicle in the air for three weeks. It's vastly cheaper to operate than many conventional aircraft today" [23]. Blimps can also handle similarly scaled payloads more cheaply than fixed wing aircraft. Unlike fixed wing aircraft that have to expend more fuel to lift more cargo, the fuel requirements of blimps vary only in that a slight increase in fuel usage is required to accelerate a heavy payload to the same speed as a light payload. The relative costs per pound of a variety of transportation methods are shown in Table 1.

Table 1: Cost of Various Shipping Methods

Platform Type (MT=Tonne)	Cost Per Tonne-Kilometer ($)	Average Speed (MPH)	Average Capacity (Tonnes)	Operating Restrictions	Source
Airship (20 MT Capacity)	1.50	80	20	Cannot operate in severe weather	[24]
Airship (200 MT Capacity)	0.20	80	200	Cannot operate in severe weather	[24]
Airship (1000 MT Capacity)	0.06	80	1,000	Cannot operate in severe weather	[24]
Truck (USA, Rural)	0.30	31	6.574	Must use existing roads	[25]
Truck (USA, Established Routes)	0.06	65	23.6	Must use existing roads	[25]
Train	0.03	19	9,072 (100 cars)	Must use rails	[26]
Ship	0.007	17	215,200	Requires water and port	[26]
Air Freight	0.37	560 (747-400)	112.5 (747-400)	Requires Large Airport	[26], [27]
Helicopter	13.98	149.6 (Huey II)	4.5	Limited range	[22], [28]

2.6. Current Autonomous Blimp Technology

In an effort to take advantage of the benefits described above, several attempts have already been made towards the development of an autonomous LTA platform by a variety of commercial enterprises, a team working at Kobe university in Japan, and a team at the United States Coast Guard Academy.

Many projects have been conducted on a small scale to prove the autonomous blimp concept and there are several commercially available products that can be modified to create an autonomous platform. The most common of these is the BlimpDuino platform by DIY drones. It consists of a Mylar balloon, two motors, a servo, and a circuit board with integrated accelerometers and gyros. [10] This platform has been used for previous projects at WPI and was considered as a platform for a FIRST robotics competition based around the creation of an autonomous blimp. [29] It is a very small platform suited only for indoor use with no additional payload and has limited applications outside of recreation. There have been several projects undertaken to give these craft the ability to navigate autonomously using infrared (IR) range sensors [10] and ultrasonic sensors [30] to detect altitude and obstructions, with varying degrees of success. The blimp's small size, low speed, and limited operating area allow for very simple maneuvering and navigation systems. [10]

Figure 14: A BlimpDuino Platform [10]

A team at Kobe University in Hyogo, Japan, has been working on several indoor and outdoor blimps, on both larger and smaller scales than the one that this project is concerned with. These platforms have been used indoors and outdoors to test various control methods. These include optically based navigation systems and GPS based controls. In order to develop reliable path planning and angular control, the team tried various methods of dynamic control, including inverse optimal tracking and dynamic control segmented into angle control, lateral and yaw motion, and pitch control. Unfortunately, once the blimp was deployed outside, they were unable to maintain a straight heading or a desired angle due to wind conditions and interference between multiple control surfaces. They were however able to maintain a programmed track to within 10m longitudinal displacement and 5m lateral displacement using the inverse optimal control method. [18][31][32][33][34]

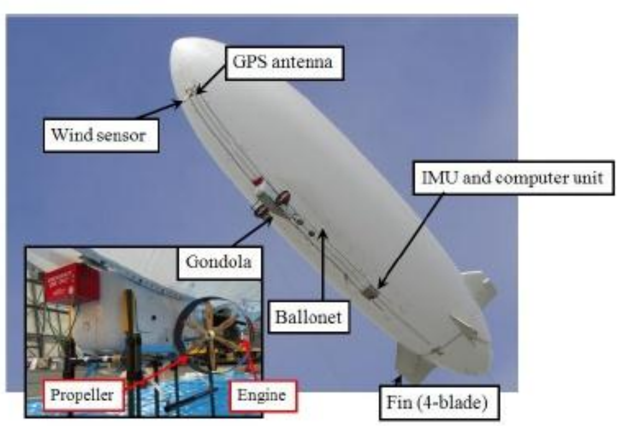

Figure 15: A Kobe University Outdoor Blimp

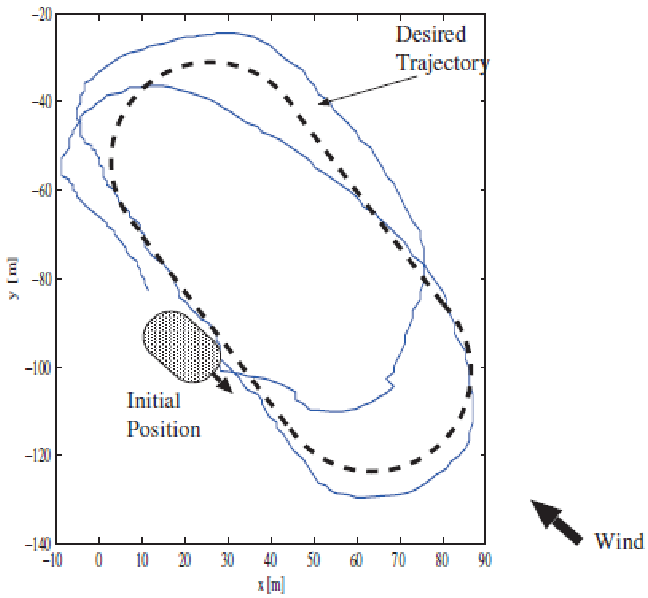

Figure 16: Track of Kobe University Outdoor Platform [31]

Students at the United States Coast Guard Academy have attempted a project similar in scale to this MQP. They endeavored to design an indoor blimp which would use ultrasonic ranging to determine its position. The data from the ultrasonic sensors would then be transmitted to a base station, where the readings were fed into a dynamic model of the blimp in MATLAB. This model, combined with desired course and speed inputs from the user, was utilized to generate motor output commands, which were then transmitted back to the blimp for execution. The gondola was created from a kit and a utilized a commercially available sensor and communications suite. The project ran for a period of one year. While the group did not complete their project, they did successfully develop a model of their blimp's propulsion system, utilized a proportional-derivative controller to determine their motor control signals, and achieved communication between their blimp and the ground station [35].

Figure 17: Coast Guard Project Blimp [35]

2.7. Summary

This chapter presented a history of blimps and familiarized readers with relevant terminology. It then discussed the history of autonomous aerial vehicles and the variety of methods that can be used to control them. Finally, it explored the advantages to using a blimp over a fixed or rotary winged aircraft and examined current efforts to create an autonomous vehicle to take advantage of the blimp platform's unique characteristics.

Chapter 3

3. Goals and Requirements

3.1. Introduction

In this chapter, we describe the initial design goals of the blimp and the requirements that were developed to meet them. These requirements then drove the design of the blimp systems described in later chapters.

3.2. System Goals

The purpose of this project was to design and fabricate an autonomous dirigible-based platform that could be used to enable development of navigational controllers and provide multi-mission capability through modularity. To accomplish this, our goal was to design a blimp and payload system capable of the following:

A. outdoor operation
B. autonomous navigation
C. performing multiple roles
D. endurance flights
E. two-way communication with a base station

Each of these capabilities will be explained in more detail below.

3.2.1. Outdoor Operation

As a blimp incapable of navigating outside of a perfectly calm room would be of limited utility; outdoor operation is a primary design consideration. To that end, we have defined a set of conditions under which a model of the size we are using should be able to operate. These conditions, hereafter referred to as the Standard Operating Conditions (S.O.C.), are as follows:

A. Wind Conditions: ≤5 knots
B. Temperature: 15°F to 110°F
C. Precipitation Levels: clear to mist/light rain
D. Altitude: 10-100 ft.

These requirements are more restrictive than calm flight indoors and the ability to operate under them will require appropriate mechanical design, sensor selection, and drift compensation, all of which will be scalable to larger platforms and more severe conditions.

3.2.2. Autonomous Operation

Autonomous operation as it applies to this project is defined as following a path of waypoints, including maintaining position at a waypoint, with minimal deviation from that path. In this case, we have defined reaching a way point as coming within 15 ft. horizontally and 6 ft.

vertically outside the resolution of the onboard Global Positioning System (GPS). The GPS, as well as an Inertial Measurement Unit (IMU) and a barometric altimeter, will serve as the primary navigational equipment for the blimp. Obstacle avoidance, while desirable and a benefit to navigation, has been judged to be unfeasible for the exploratory nature and short time period of this project. As a result, the safety in any path will be introduced through careful route planning and the ability of the blimp to adhere to that path, hence the tighter tolerances on acceptable maneuvering limits.

3.2.3. Performing Multiple Roles

In order to create a platform with greater utility, the blimp will be capable of multiple roles. This will be done by incorporating interchangeable "mission modules" into the gondola design. Mission module hardware will vary depending on which task the blimp is to perform. Provisions will be made for each module to have two-way communications with the main controller, the ability to share power with the main blimp systems, and issue steering commands to the blimp as necessary. All of these interactions will take place over a standardized interface. Some examples of possible packages and missions include: search and rescue, range extension, delivery, fire spotting, advertising, communications relay, and swarm control.

3.2.4. Endurance Flights

Another appeal of the blimp platform is its endurance. On the small scale that we are operating, we will endeavor to reach 90 minutes flight time using only the onboard battery. For comparison, similarly powered fixed wing aircraft have endurances of 20-30 minutes. The amount of batteries, and thus the endurance of the blimp, can be increased significantly as the scale of the blimp and its weight limit increases.

3.2.5. Two-Way Communication with a Base Station

Finally, the blimp will be capable of two-way communications with its base station. The reasoning for this is two-fold. The first reason was a mandate by the FAA that all autonomous aircraft have a two way link to ground control that overrides automatic controls for safety reasons. Our backup controls will also increase safety during landing procedures and allow for aborted missions. Secondly, a data link would allow for updates to mission plans based on changing conditions, the return of position and status information, and the communication of mission specific data.

3.3. System Requirements

In order to fulfill the goals listed above, the system must meet several requirements. System goals satisfied by requirement indicated in square brackets. Distances are from a point in the center of the gondola.

1. Can navigate to designated GPS coordinate to within 15 ft. horizontal, 6 ft. vertical displacement, outside the resolution of the onboard GPS, from the destination coordinate within Standard Operating Conditions (S.O.C.) using only the onboard GPS system, an inertial measurement unit, and a barometric altimeter [A, B]
2. Can maintain position at designated GPS coordinate to within 15 ft. horizontal, 6 ft. vertical displacement, outside the resolution of the onboard GPS, using only the onboard GPS system, an inertial measurement unit, and a barometric altimeter, within S.O.C. for a period of no less than 1 hour. It is allowable for the vehicle to drift from the designated area by no more than 30 ft. laterally and 15 ft. vertically, for no more than 5 minutes of the above hour, consecutively or non-consecutively.[A, B]
3. Interchangeable mission specific hardware up to 3 pounds capable of two-way communication with the main controller using serial communications and is capable of power sharing with the main batteries [C]
4. Can stay aloft with 6 knot airspeed for a minimum of 90 minutes using only onboard battery and solar power under S.O.C. [D]
5. Can utilize two-way communication with the GCS sufficient to communicate telemetry and instructions(see subsystem) at a range of at least 200m [E]

3.4. Summary

In this chapter, the goals and requirements of the project were introduced and discussed. The five main goals of the project include outdoor operation, autonomous operation, multiple role capability, flight endurance up 90 minutes, and two-way wireless communication with a base station. Based on these goals, system requirements were created.

Chapter 4

4. System Design

4.1. Introduction

The purpose of this chapter is to describe the higher level design of the blimp's architecture, including the division of subsystems and environment in which each system operates. The specifics of the design of each system and their interactions will be addressed in later chapters. This section is intended primarily to give readers a context for the more system-specific chapters to follow.

4.2. Sub-system Divisions

The system was divided into three nominally independent sections: the drive system, sensors, and control system. Each system was modular and could be replaced with an alternative or larger system without damaging the overall functionality of the platform, furthering the ability of the blimp to change in scale or form factor. Additionally, the system utilized a prebuilt shell and a custom fabricated gondola to house the electronics and drive system, but they were not active in the dynamic structure and were not considered part of the system for control purposes.

The total system was divided up into sub-systems based on both the similarity of function of each component in the sub-system and the ability of a set of components to be modularly replaced without affecting the other subsystems. In other words, components that performed a similar function were grouped together and components that were interdependent were grouped together.

4.3. Sub-system Responsibilities

Each sub-system was created to address a specific area of responsibility.

The drive system is responsible for propulsion, directional control, and override capability. It accomplishes this by selecting between signals from the RC override controller and from the Robovero and passing those signals to the motor controllers and servo for implementation. This system has its own separate power system to ensure that control is maintained even if power is lost to the controller and sensors.

The sensor system is responsible for determining current location and orientation. The blimp's latitude and longitude is determined via GPS and its altitude is determined by the barometric altimeter. This system uses the Robovero's built in IMU to determine its orientation.

The control system is responsible for parsing sensor input, control signals, and task lists to provide input to the drive system. All processing tasks can be handled by either the onboard Gumstix® Overo® processing board during normal use or by a laptop during testing. All of the signals into and out of the processor are routed through a Robovero® expansion board to the other two subsystems, the communication board, and the mission modules.

4.4. Sub-system Design

The final design of the system is shown in Figure 18 below. Divisions between sub-systems are indicated by dotted lines.

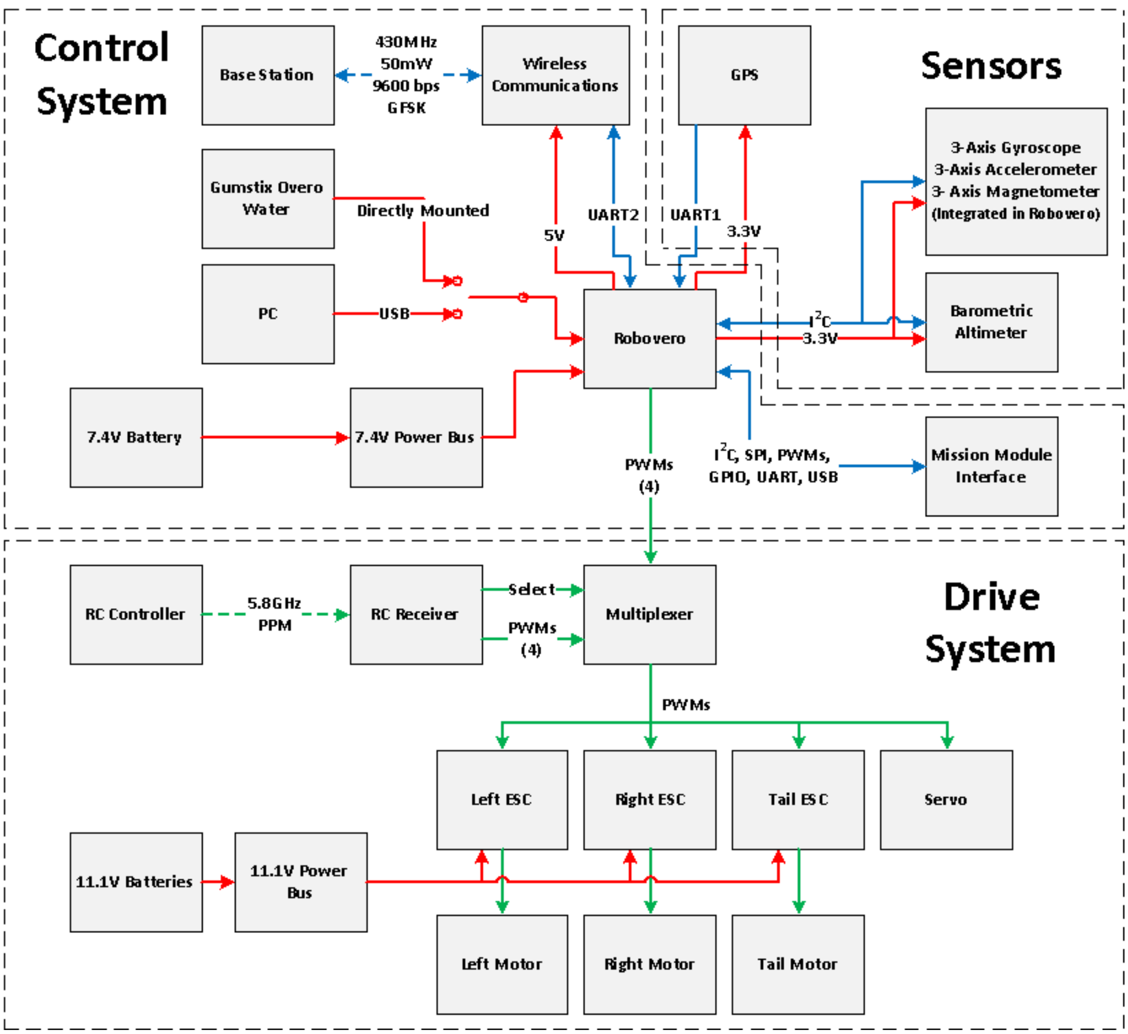

Figure 18: Overall System Design Diagram

Each subsystem was designed independently, with the only point of commonality being the interface at the Robovero®, which ties all of the systems together. Each system's component level design was driven heavily by its function and hardware configuration. Each system will be described in more detail in its dedicated section.

4.4.1. Drive System

The design of the drive system was directly driven by the design of the hardware, which is further discussed in section 6. The drive system needed to be controllable from both the processor and an RC receiver in order to ensure that the operator can take manual control if required. As a result, the control input from the Robovero® is routed into a multiplexer, which selects between automatic control and control from a hobby aircraft RC receiver and passes the selected set of control signals to the rest of the drive system. Each motor required by the drive system design must be driven by an electronic speed controller (ESC), which uses PWM signals from the multiplexer and provides power to the motors according to that input. These PWMs operate at 50Hz with a duty cycle range of 5% to 10%. The servo was controlled directly by a PWM signal from the multiplexer. In order to ensure that the operator can maintain control of the blimp at all times, the drive system, including the RC override, is powered independently from the rest of the system. This ensures that, in the event of power failure in the control or sensor system, the drive system still functions and the blimp can be landed under remote control. Conversely, this also ensures that, in the event of power failure in the drive system, the electronics remain functional to broadcast the blimp's location for retrieval.

4.4.2. Sensor System

Sensor selection was driven directly by the system goals, specifically section 3.2.2. As each sensor was specifically selected to interface with the Robovero®, no interfacing components were necessary. The sensor system was grouped together out of similarity of function, rather than interdependence and each sensor can be switched out without affecting the others. Each sensor was powered by either the 5 V or 3.3 V rail of the Robovero®. This system was not required to be powered independently from the processor, as its only purpose was to provide input to the control system. If the control system loses power, there would be no point to having the sensors still be powered.

4.4.3. Control System

The selection of the processing segment of the control system, the Overo® and Robovero®, was driven by the predefined structure of that system. The two components were designed to work together in a specific way, with the Overo® mounted directly to the Robovero®. Additionally, the ability to use a laptop to directly control the Robovero® was designed into the system. Because the Robovero® can only accept input from one processor at a time, the laptop and the Overo® cannot control the system simultaneously. The control system is powered separately from the drive system, for the reasons described in section 4.4.1.

Also under the control system is the communications system. This was grouped in to this segment due to its similarity of function, even though it could be switched out without affecting other sections of the processing system. It was grouped in this section due to its role in the system's command and control structure, passing the commands from the base station to the processor and telemetry generated by the processor back to the base station. It interfaces with the Robovero®, which in turn passes the data transferred over the link to the Overo®.

Finally, the mission module interface is listed under the control system. This system was included because it has the potential to exert control over the navigation functions controlled by the processor, the mission modules to send data for analysis to the processor, and for the processor to control the mission modules. The decision to allow the mission module to deliver control signals and data to the blimp was the result of analyzing the tradeoffs between an isolated mission module and one more integrated into the processing structure of the main blimp. By requiring that mission modules do all of their processing onboard and only pass control instructions to the gondola, the processing requirements for the main controller and connection requirements would be vastly simplified. On the other hand, requiring the mission modules to do their own processing with limited connection to the main blimp would deny the modules access to the blimp's sensors and communications system, as well as driving up the cost of the module by requiring each module to have its own processor.

Conversely, if the processing for the mission modules is handled by the main processor, the mission modules are dramatically cheaper, have access to the full processing power of the blimp, and can utilize the native hardware of the blimp platform. It would, however, mean that the communications lines between the mission module and the main controller become far more complex. It was decided that this was a worthwhile trade in exchange for driving down the cost of a mission module.

4.5. Summary

In this chapter, the high-level system design of the blimp was discussed. The system is divided into three sub-systems: the drive system, the sensor system, and the control system, each with its own areas of responsibility.

Chapter 5

5. Shell selection

5.1.Introduction

This chapter describes the selection of the helium containing shell used to lift our blimp. It begins by evaluating the decision to purchase a shell rather than manufacturing one ourselves. It then goes through the process of selecting a prebuilt shell; include material and supplier selection, as well as an aerodynamics evaluation of each shell.

5.2. Shell Purchasing Rational

The design of the blimp was focused on being as cost effective and simple as possible. This focus allowed a minimization of assembly and materials costs, as well as decreasing the time requirements of construction. This reduction was a necessity with our limited time and manpower. In order to further this goal, it was initially decided that any design we considered would need to utilize a prebuilt shell. This was because the design and construction of a shell would be a major undertaking that would severely reduce the time available for the construction of the rest of the system and was outside of the scope of the project. Additionally, due to our lack of experience in shell construction, it was decided that any product made by the team would be of significantly inferior quality to a commercial product and would likely consume sufficient resources and time to make the remainder of the project unfeasible. The shell determines the abilities of the rest of the system. It drives thrust requirements, lifting capacity, and helium requirements. Because we already decided to use a prebuilt shell, the design process for the shell consisted of selecting a material, manufacturer, and shell shape.

5.3. Material and Manufacturer Selection

Most commercially available advertising blimps are made from polyvinyl chloride, polyurethane, or Mylar. Mylar was rejected almost immediately due to durability concerns, availability, and poor helium retention. Mylar is extremely brittle, with very low resistance to puncturing. It was not available cheaply with a lifting capacity sufficient to our needs and, while making a Mylar balloon is possible, it was already decided that making our own balloon was not feasible. Finally, testing on a small scale revealed that Mylar has significant helium retention problems. Experimentation on a Mylar Blimpduino shell showed a loss of roughly 1/8th of the volume of the shell within approximately 12 hours of filling.

Polyvinyl chloride (PVC) is a more common material which is available from many companies. However, it is thicker and heavier than polyurethane with inferior helium retention and longevity. PVC also suffers yellowing and degradation when exposed to UV radiation. This is a significant problem in a blimp that will be spending large amounts of time outdoors. The expense of the material is variable as well, but in general, higher quality PVC shells are more expensive than their polyurethane counterparts. As a result of all of these factors, we elected to use a polyurethane blimp shell. Southern Balloon Works, a company that deals primarily in manufacturing advertising balloons, was selected for their solid reputation and large selection of affordable polyurethane shells. They additionally posted test data showing that their shells could be significantly overinflated before rupturing. [36] This was a significance concern, as the blimp will be fully inflated at cold temperature and then stored inside, resulting in expansion as the helium warms to room temperature.

5.4. Shell Shape Selection

The next decision was the selection of a shell shape and size. Southern Balloon works offers two shell configurations, advertising and camera blimps. The advertising blimp is a “typical” blimp configuration, Figure 19, while the camera configuration, Figure 20, has a wider front and fits a larger amount of helium in the same length, resulting in more lift.

Figure 19: Advertising Blimp (http://www.southernballoonworks.com/blimps/advertising-blimps-indoor-outdoor.html)

Figure 20: Camera Style Blimp
(http://www.southernballoonworks.com/images/blimps/payload/16UP.jpg)

This camera profile, while it does result in more lift, also results in substantially more drag. We decided that, for expense reasons, the blimp must be fillable with less than one 300 ft^3 tank of helium. This narrowed our options down to either a 15ft camera blimp or a 16ft advertising blimp. Our operating conditions call for 1 knot maneuverability in a 5 knot head wind, which is a 6 knot total airspeed.

$$F_{Drag} = \frac{1}{2}\rho v^2 DA$$

Where:

$$\rho = air\ density = 1.204\ kg/m^2$$
$$v = air\ velocity\ relative\ to\ blimp = 6\ knots = 3.09\ m/s$$
$$D = drag\ coefficient = .25 = .025\ with\ a\ 10x\ safety\ factor\ [44]$$
$$A = surface\ area\ exposed\ to\ wind$$
$$A_A = front\ profile\ of\ advertising\ blimp = 8.55\ m^2$$
$$A_C = front\ profile\ of camera\ blimp = 11.70\ m^2$$

Using the above formula for drag, it was determined that the camera blimp form factor experienced 16.81 N (3.78 lbs) of drag force at 6 knots and the advertising blimp experienced 12.29 N (2.76 lbs) of drag force at 6 knots. As each of these shells has approximately the same lift capacity, we elected to use the advertising blimp shell, with its lower drag.

5.5.Summary

In this chapter, the blimp shell selection process was discussed. A 16 foot, polyurethane advertising blimp from Southern Balloon Works was selected.

Chapter 6

6. Drive System Design and Construction

6.1.Introduction

In this chapter, the design and construction of the drive system is discussed. Several possible control schemes are considered and the drive system selection parameters are outlined. This chapter then describes the testing of axle materials and propellers for use in the drive system. Finally, this chapter outlines the testing of the drive system and the changes that resulted from that testing.

6.2.Drive System Requirements

The design of the propulsion system was driven by the system requirements. The system requirement driving each propulsion subsystem requirement is included in parenthesis.

1. In order to maintain the 6 knot airspeed required by (4), system needed to generate at least 3 lbs of thrust. This was derived from the drag equations shown in the shell selection section.
2. The drive system must be able to control altitude, yaw, and airspeed to meet (1) and (2). This requires the blimp to be able to pivot and change altitude without leaving the area specified in requirement (2) for holding position. It must also be able to vary its airspeed to compensate for wind and desired velocity.
3. The drive system must accept control from the processing subsystem to meet (1) and (2).

We initially considered three designs for our propulsion system, based off the “standard” designs for small-scale and large scale blimps, as well as a tail rotor driven version of the large scale design.

6.3. Tilt-able Motor Design

The first design was based on a standard configuration for small scale blimp propulsion that is seen on several of the previous autonomous projects, such as the Blimpduino and several designs from the Kobe University blimp project, as well as most commercially available hobby RC platforms. This design consisted of two large ducted fans or propellers (the main thrusters) mounted equidistant from the centerline of the blimp on a rotating axle. An example of a blimp using this configuration is shown in Figure 21.The two main thrusters provide both altitude and yaw control. Altitude control is provided by pitching the thrusters up or down. Because the blimp is neutrally buoyant, the only force resisting the upwards or downwards thrust generated by the thrusters is the drag of the blimp shell. Once this drag is overcome, the directed thrust will pull the airship upwards or downwards depending on fan orientation. Yaw control is achieved though differential thrust. A difference in thrust between the motors creates a turning moment about the central vertical axis of the shell, leading to rotation about this axis (yaw).

Figure 21: Commercially Available Advertising Blimp
http://advertising-balloons.com/advertising_balloons.htm

The greatest benefit of this design was its simplicity. The main thruster assembly consisted of three motors, one gear set, and a single axle. This created significantly fewer potential failure points than a vectored thrust or ballasting system. The simplicity of this system type also lead to reduced costs due to the lack of complex components and the low quantity of components required. The yaw created by this system is decoupled from its forward speed, leading to more predictable control methods. Also, the system can be fully implemented without any modifications to the shell, saving significant time and effort. Finally, the system has relatively simple dynamics calculations due to the induced forces being located at equal spacing symmetrical to the center of mass of the blimp.

The system has two primary drawbacks: a weak turning moment and the inability to simultaneously climb and turn without inducing a roll. While the differential thrust from the motors can produce a turning moment, they are not located very far apart relative to the length of the shell. This means the moments induced by drag on the nose and tail while turning require greater input on the part of the motors to compensate than if the turning force was generated at the nose or tail (see Figure 22). This is a reason that most airships using this design are on a smaller scale and lack vertical stabilizers which impart an additional drag force during turning. Maneuvering in wind also produces resistance to turning, which is why most blimps of this design are used primarily indoors.

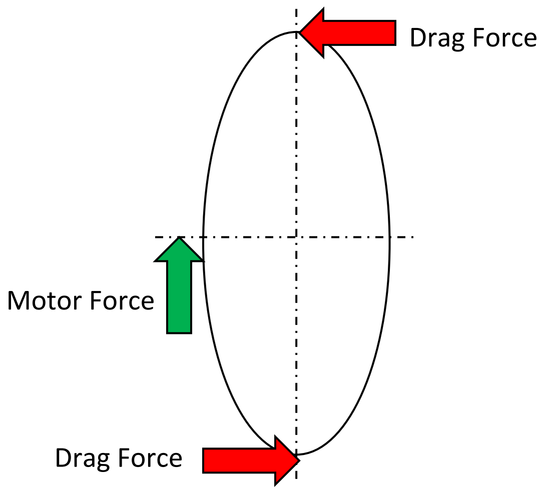

Figure 22: Free Body Diagram of Blimp in Right Turn (Top)

The inability to simultaneously climb and turn without inducing a roll is another disadvantage of this system. It creates instability during maneuvers where it is important for the blimp to be able to determine its orientation on a plane relative to the ground, which requires sensor compensation for rolls. It also removes some of the dynamic predictability that made this design attractive. Because of the blimp's tendency to roll with this drive system, the angle of the propellers will need to be restricted based on the speed of the blimp to limit roll.

6.4. Ballast and Control Surface System

The second system that was considered was the standard system on larger blimps. The drive system used on larger, manned airships consists of three parts: main drive motors, ballonets, and control surfaces, shown in Figure 23. The main drive motors are two or more motors fixed on the side of the gondola which provide forward thrust. Ballonets are smaller gas bags inside the main shell with a valve to the outside. The ballonets provide altitude and pitch control. This is done by pumping air into and out of the ballonets, making the blimp heavier or lighter respectively to control altitude, in a manner similar to water being pumped into and out of ballast tanks on a submarine. Pitch control is achieved by controlling the relative volumes of the fore and aft ballonets. Finally, rudders and elevators on the tails give yaw and additional pitch control [9]. Due to our decision not to modify the shell, the ballonets were unfeasible, but the combination of fixed motors and control surfaces are a viable combination.

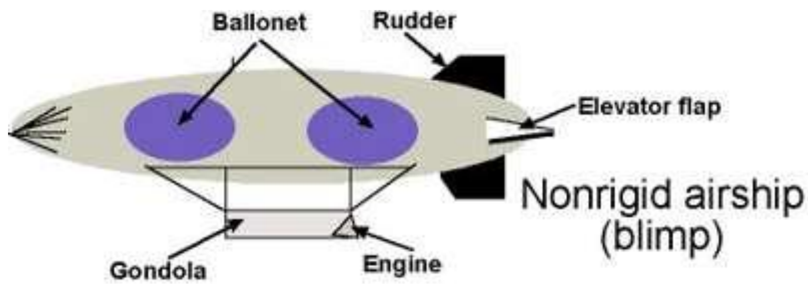

Figure 23: Large Airship Drive System Components
(http://2.bp.blogspot.com/_b08RWB-bfFM/Sx0To0XK2GI/AAAAAAAABOs/IYctk9WRTuM/s400/airship_types1.jpg)

This configuration has the advantage of having the turning force located at the tail, leading to a greater turning moment. This means it can turn more powerfully, a necessity in strong winds. The downside to using this method to control yaw, however, is that the generated turning moment is dependent on the amount of air hitting the control surfaces, and thus the airspeed of the blimp. This means that the system will not be able to turn in place and will turn more slowly at low speeds. Similarly, it will not be able to ascend and descend without forward motion. Both turning and changing altitude will have a considerably larger turning radius than the aforementioned system.

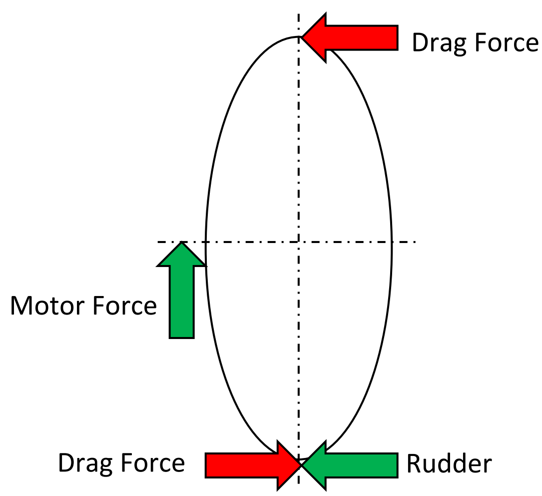

Figure 24: Location of Force Vectors in control surface system

This configuration has both advantages and disadvantages in terms of stability and predictability. Unlike the previous system, the pitch and yaw are decoupled, so it can climb and turn simultaneously without the force of the motors inducing a roll. This allows it to remain more level and reduces required corrections and uncertainty in the autonomous piloting algorithms. It does, however, increase complications in the algorithm because the system requires that the blimp have forward airspeed to turn. This means that the system needs to take the required forward motion into account if trying to maintain heading in place or maintain altitude, making place holding significantly more difficult. It is also less easy to predict the turning moment that will be created because the speed of the blimp and the wind speed will significantly affect the turning radius.

This choice of configuration has a final disadvantage in that it requires additional servos to actuate the control surfaces, as opposed to the tilt-able motor design. This would cause an increase in weight and power requirements for the drive system, as well as requiring an increased number of outputs from the controller.

6.5. Tail Rotor Drive System

The tail rotor version is similar in principle to the ballast and control surfaces system, with the turning force being generated at the tail. In this case, the elevators and rudders are replaced by fans. These fans would be bi-directional and located in each of the fins, equidistant from the center. This is to prevent unbalanced forces about the centerline of the shell from inducing a roll. The fans in the upright fins would act as a rudder and the fans in the horizontal fins would act as an elevator. The locations of induced forces are shown in Figure 25.

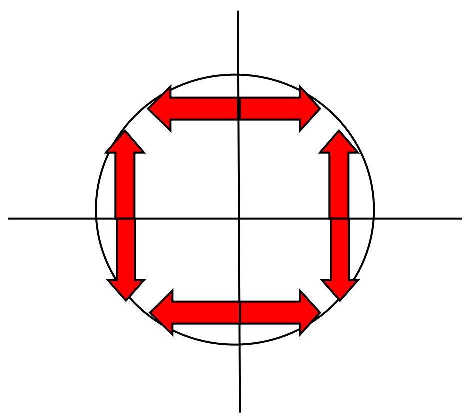

Figure 25: Location of Forces from Tail Rotor System (View from Rear of Blimp)

This system has the advantage that, as it does not require airflow over the fins to turn, it can turn in place. However, it still cannot ascend and descend in a vertical line, only change pitch. Additionally, this design would have significantly larger weight and power requirements than either of the other systems.

6.6. System Selection

The selection of the drive system was based off of several characteristics: stability, simplicity, power requirements, maneuverability, weight, and handling. Stability refers to the tendency to roll or make unintended motions while executing turns or altitude changes. Simplicity refers to the number of required control outputs, the amount of required hardware, and the ease of installation. A simpler system will have fewer moving parts, thus fewer failure points, and require fewer computations by the processor to execute turns or changes in altitude. Power requirements were estimated from the number of elements drawing power and the amount of power that they will require. The more power a drive system requires, the more batteries will be needed for the blimp to maintain maneuvering power for the 90 minutes we have specified. As batteries are one of the heaviest components on the blimp, this is a significant concern. Maneuverability is determined by the space required to execute turns and changes in altitude. Finally, handling refers to the responsiveness of the system and its ability to turn and change altitude when wind is present.

Each system was given a ranking in each category. These are displayed in Table 2.

Table 2: Drive System Types Comparison

System	Stability	Simplicity	Power	Maneuverability	Weight	Handling	Score	Total Rank
Tilt-able motor	3	1	1	1	1	3	10	1
Control Surfaces	1	3	2	3	2	2	13	2
Tail Rotor	2	2	3	2	3	1	13	2

As the highest ranking system overall was the tilt-able motor design, that was the system we initially chose to utilize. Our initial version was constructed as seen in Figure 26.

Figure 26: Initial Drive System Design

6.7. Axle Material Selection

The two primary concerns when selecting a material for the axle were the weight of the material and the amount it deflected when loaded with two pounds of weight, the maximum force that could be output by one of the motors. Five materials were tested to determine their suitability for use as an axle.

Each material was tested to determine how much it deflected at a full load. The materials were clamped to a bench with 18 inches of material protruding over the edge. A board parallel to the test piece was installed in the clamp to serve as a reference for measurements. The unloaded setup is shown in Figure 27.

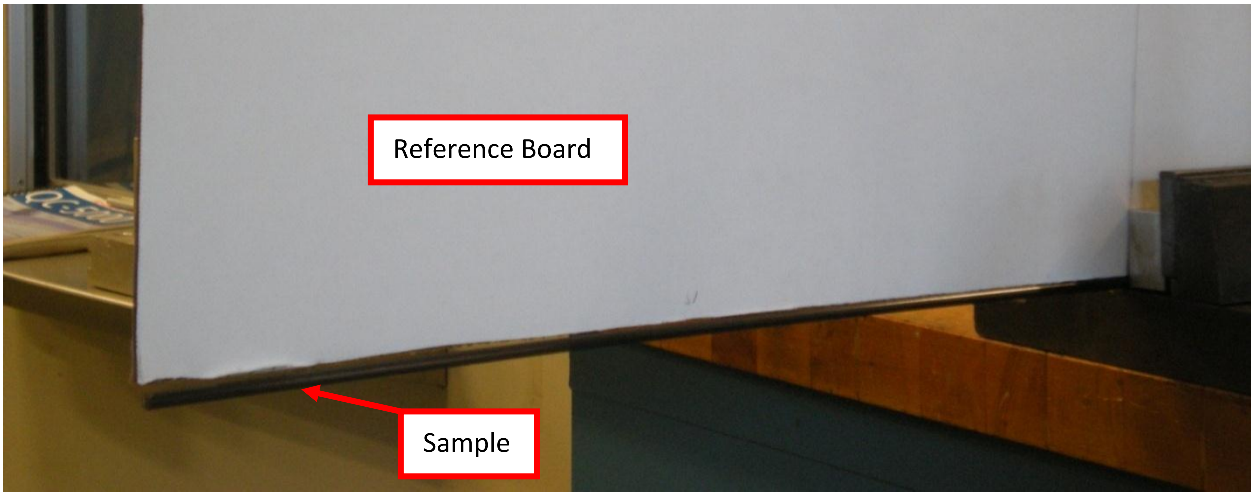

Figure 27: Unloaded Deflection Set-up

A scale and weights were hung 0.5 inches from the end of the beam. The beam was then loaded incrementally up to the two pounds specified above. The loaded setup is shown in Figure 28.

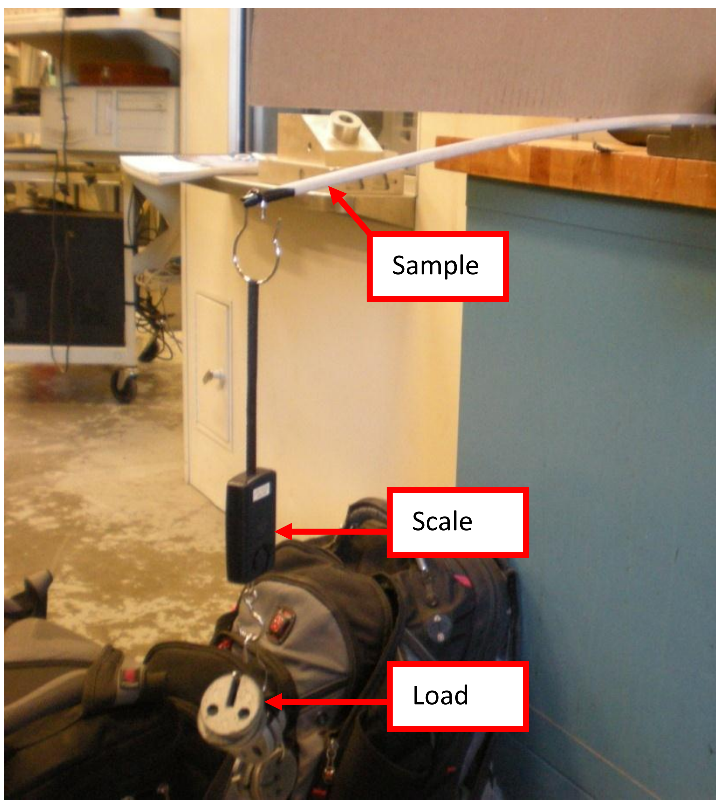

Figure 28: Loaded Deflection Test Set-up

The performance of each material is shown in Figure 29. Due to its rapid failure, the ¼ in. dia. wooden dowel has been excluded.

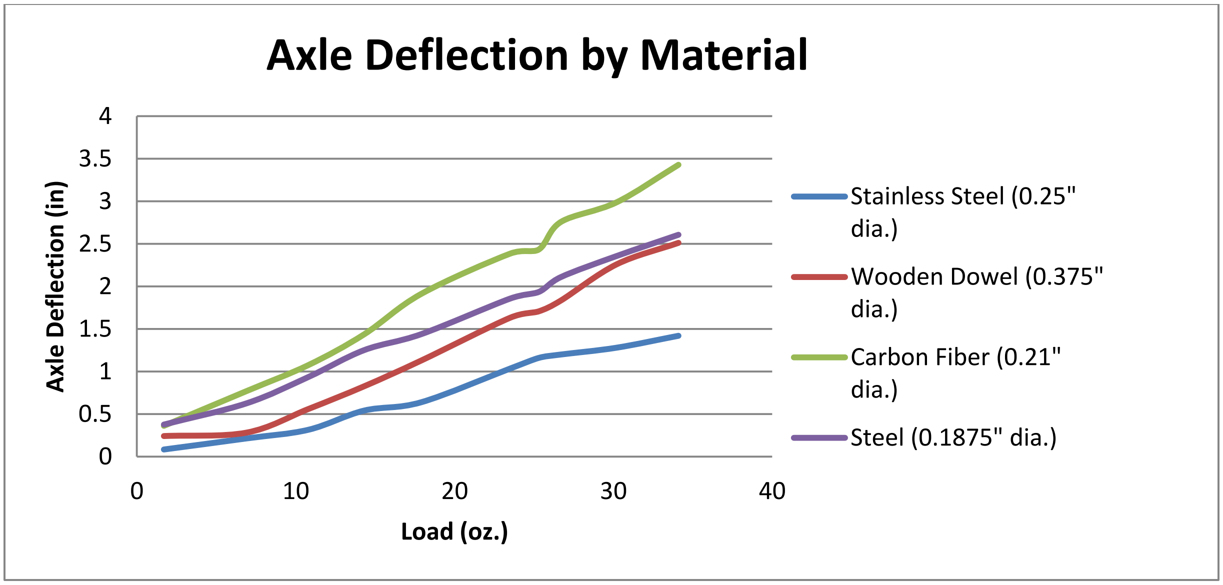

Figure 29: Axle Deflection Under a Point Load

The results of the tests and weight properties of each material are shown in Table 3. Deflection and weight were weighted equally and both were optimized when at the smallest value possible. Therefore, when plotted on a scatter plot, as shown in Figure 30, the material closest to the origin is the optimal material.

Table 3: Experimental Summary Table

Material	Diameter	Weight Per 18in of material (g)	Maximum Deflection (in)
Wooden Dowel	0.3750	22.50	2.512
Wooden Dowel	0.2500	14.49	N/A
Steel Rod	0.1875	67.50	2.607
Carbon Fiber Rod	0.2100	18.00	3.429
Stainless Steel Rod	0.2500	113.04	1.420

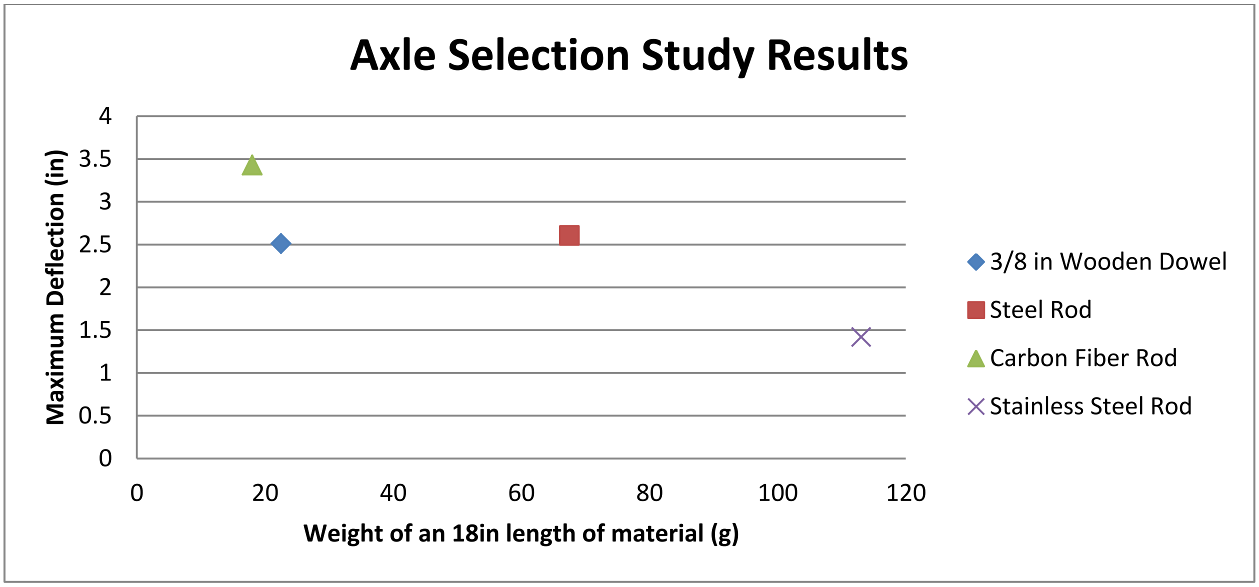

Figure 30: Axle Selection Study Results

By this evaluation, the optimal material for our purposes is the 3/8 inch diameter wooden dowel.

6.8. Motor and Propeller Selection

As the blimp was unlikely to reach similar speeds to a fixed wing RC aircraft, we selected motors with a higher power output, but low Kv (rpm/volt). After considering many motors, we found one that gave a thrust rating for its use with a specified propeller profile. As this kind of information was not generally provided, this documentation made the motor a very attractive choice. This motor was able to achieve the desired thrust of 1.38 lbs. at well below its full power, giving it a significant reserve of available thrust for turning and maneuvering. The motor's low power requirements, which reduced battery requirements, and reasonable price led to our decision to use the Turnigy Brushless Outrunner 2830 800kv motor in our design.

The servo model was selected because we had them on hand and their power ratings were sufficient to counteract the gyroscopic effect of the blades, which was the primary force resisting rotation of the axle.

Similarly, we looked at propellers that function best at low speeds. These "slowflyer" props are generally of a low pitch and high diameter and created more thrust at lower speeds. The possible propellers were evaluated based on their performance at a variety of wind speeds. The motors were tested in order to determine whether or not the purchased motors met their posted specifications (Table 4) and were sufficient to drive the blimp and which is the optimal propeller to use to maximize thrust. The propellers were tested using a custom designed test stand diagrammed in Figure 32 and shown in Figure 33. The system consisted of two arms placed at right angles to each other with a pivot at the corner. The motor was fitted in the upright arm with six inches of clearance from the base to allow for an eleven inch propeller to spin without impacting the base. Another rest was placed on the bottom arm at a distance equal to the height of the center of the motor above the point where the pivot contacts the ground. This created two arms of equal length, meaning that any force exerted horizontally at the motor mounting point was represented as a downward force at the rest on the lower arm. If this rest is placed on a scale which is zeroed with the motor turned off, any thrust generated by the motor will be visible directly as a weight on the scale. The test stand was verified using a load cell to generate force in place of the propeller. This test stand was then placed in front of a fan to simulate a head wind.

Table 4: Turnigy 2830 800kv Brushless Motor Specifications

Recommended Prop	8x4~10x4.7
Thrust (g)	540~800
Kv (rpm/v)	800
Weight (g)	54
Max Current (A)	14
Max Voltage (V)	11
Power (W)	160
Length B (mm)	32
Diameter C (mm)	28
Can Length D (mm)	15
Total Length E (mm)	48

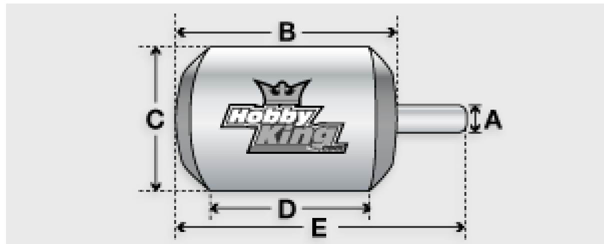

Figure 31: Reference Dimensions for Motor Specifications Table

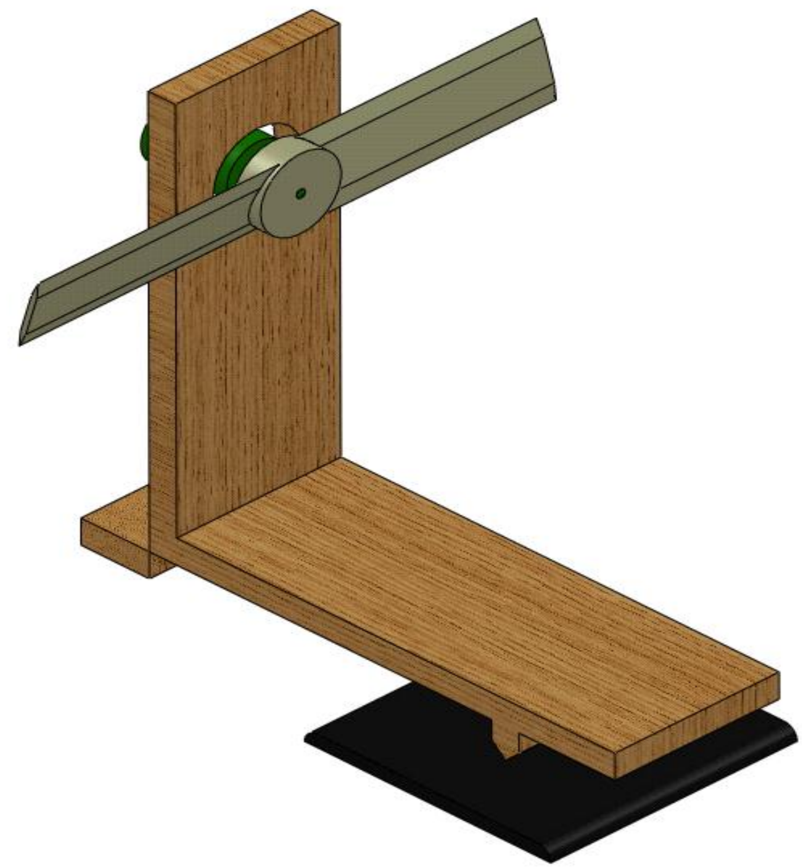

Figure 32: Diagram of Motor and Propeller Test Stand

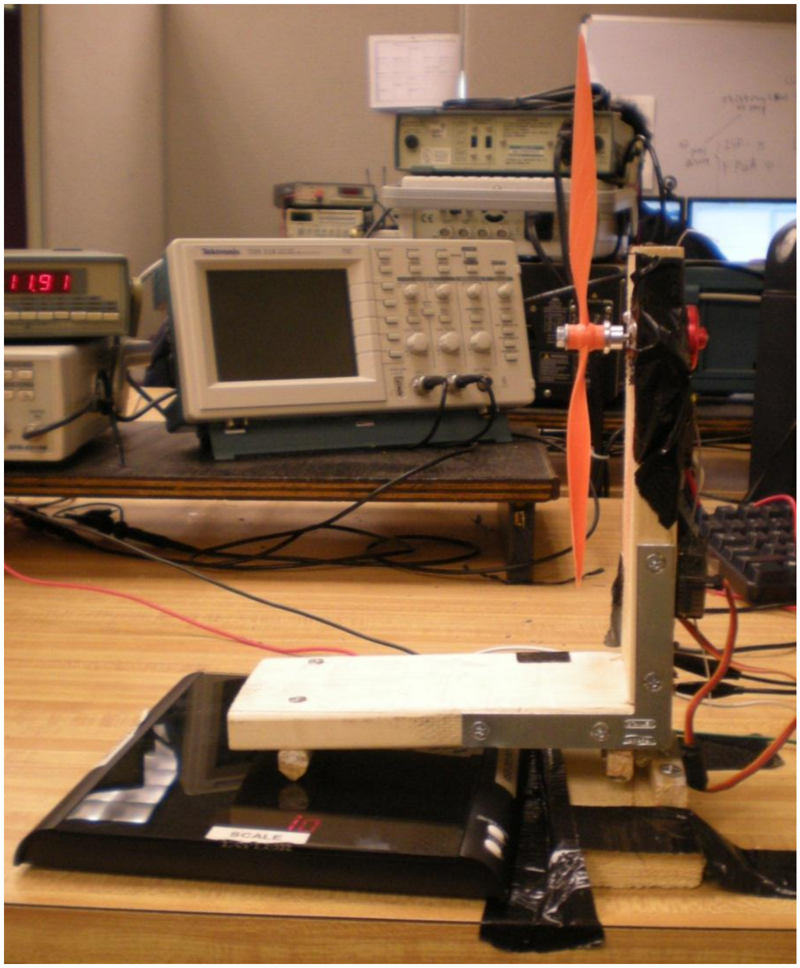

Figure 33: Photo of Propeller and Motor Test Stand

The resulting thrust from an equivalent amount of power for each propeller at zero, five, and seven knot wind speed are shown in Figure 34 through Figure 36. Each propeller is labeled by its dimensions, where the first number is the diameter of the propeller and the second is the pitch the distance which the propeller will move though a solid substance per rotation. For example, a 9x3.8 propeller has a diameter of 9 inches and a pitch of 3.8 inches. The third data point for the 11x3.8 propeller was corrupted, so the remaining data points were extrapolated. We tested two different styles of 10x4.7 propellers, labeled B and O, for black and orange, for the colors that each style came in. Each curve ends at the power drawn when the esc is sent its maximum PWM signal from the receiver. As most of the propellers of the same diameter draw approximately the same maximum power, the approximation for the 11x3.8 propeller ends at approximately the same location as the curve for 11x4.7 propeller.

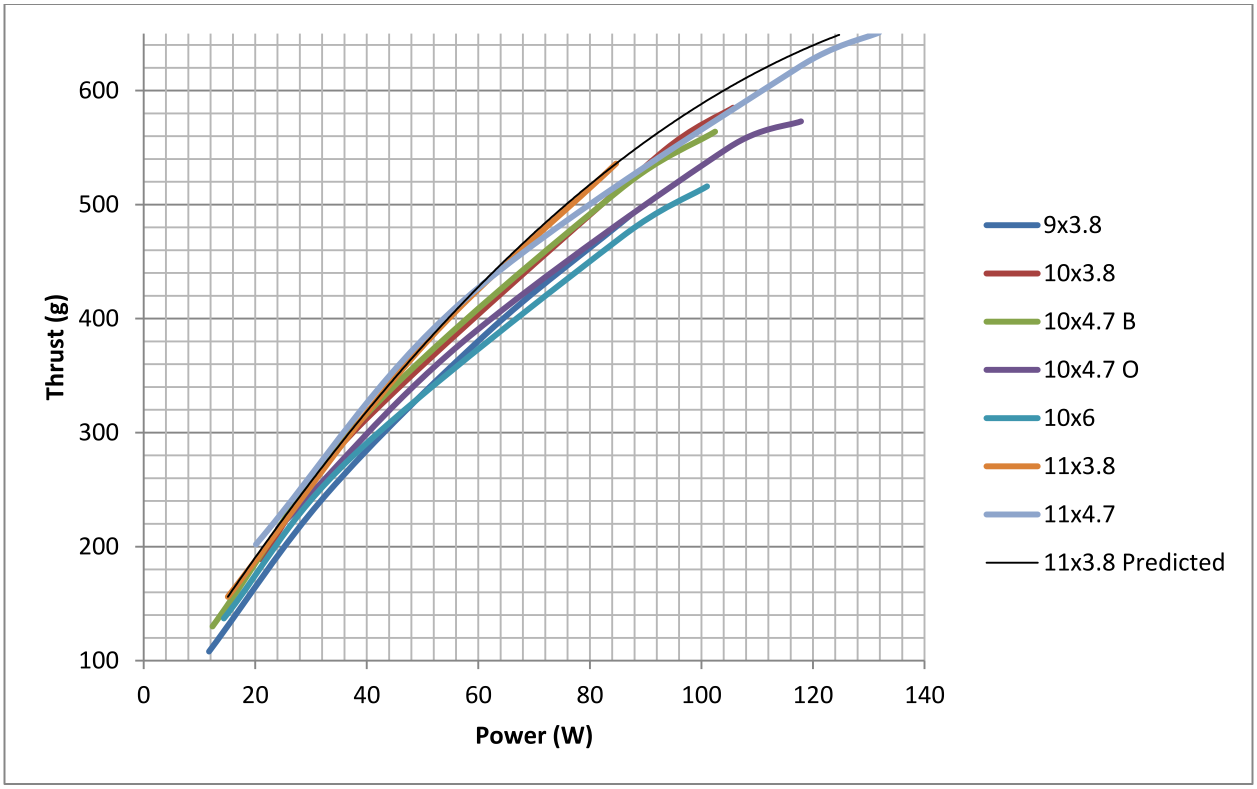

Figure 34: Thrust for Given Power at Zero knots Wind Speed

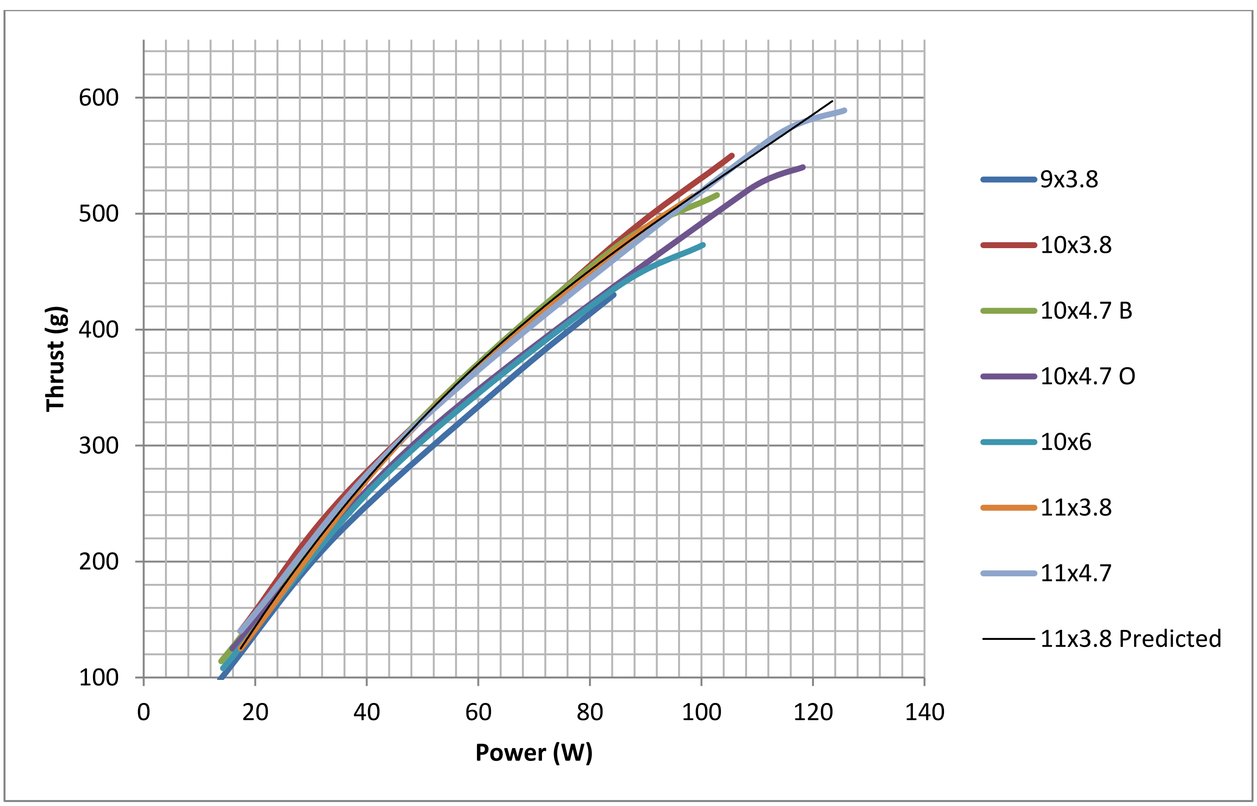

Figure 35: Thrust for Given Power at Five knots Wind Speed

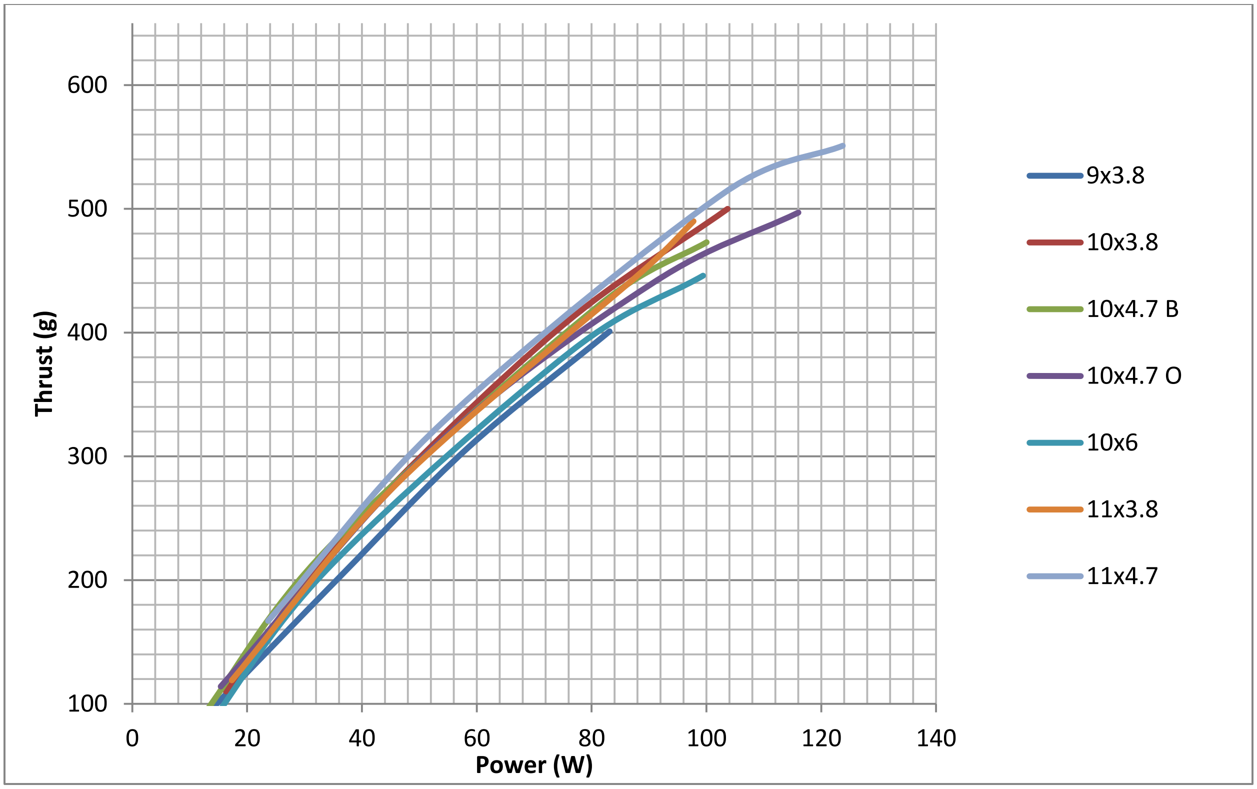

Figure 36: Thrust for Given Power at Seven knots Wind Speed

At a zero knot wind speed, the motors performed as stated in their specifications, though towards the lower end of that range. The propellers to be used were selected based on their efficiency. This was determined by how much thrust they generated relative to the power they were provided. Both of the 11 inch diameter propellers consistently generated the most thrust of a given amount of power regardless of the wind speed. Their relative efficiencies are compared in Figure 37.

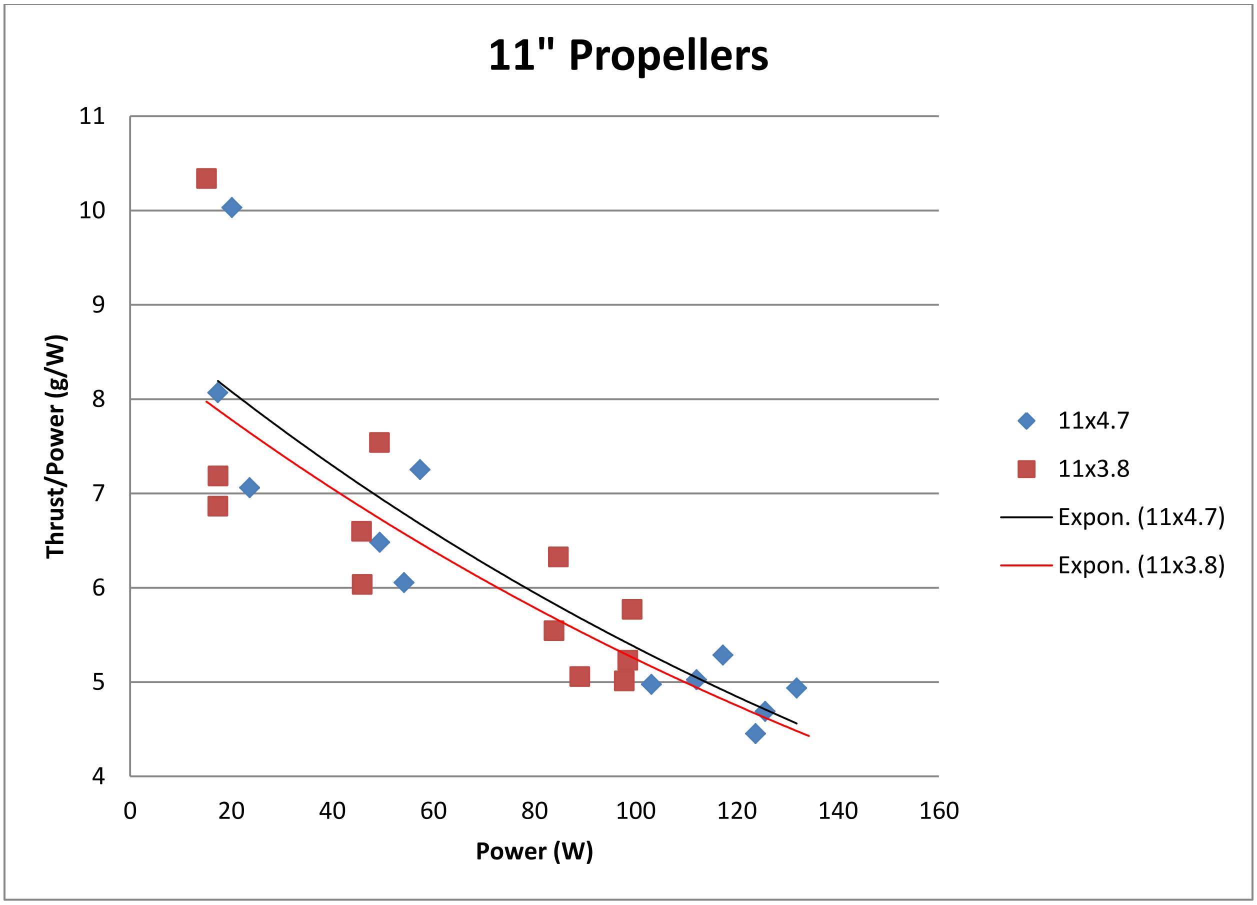

Figure 37: 11" Propeller Comparison

Between the two 11 inch propellers, the lower pitched 11x3.8 propeller was more efficient at speeds under 5 knots. At speeds greater than this, the 11x4.7 propeller had a higher efficiency. Overall, the 4.7 pitch prop had a better efficiency with the analysis weighted towards higher speeds. As the blimp has been designed to maintain a 1 knot forward velocity in 5 knot wind speeds, it will likely be operating towards the higher end of our tested range. In this case, the conditions favorable to the 11x4.7 propeller will be in effect the majority of the time. This leads to the selection of the 11x4.7 propeller the primary propeller, with the option to switch to the 11x3.8 if operating speeds are more often less than 6 knots.

6.9. RC Override

The drive system must also be controllable from the ground and that control must override any signals from the processor. This is not a functional requirement, but a legal one. The FAA requires that all autonomous aerial vehicles have the ability to be controlled by a pilot and to have the pilot's instructions override those of the autopilot in order to ensure that the aircraft can avoid collisions (per FAA 14 CFR part 91.113, Right-of-Way Rules). In order to ensure that the override works regardless of the functionality of any other system, this requirement was handled strictly within the drive system. In other words, as long as the drive system has power, we will be able to remotely control the blimp. In order to implement this, the control inputs to the speed controllers for the motors pass through a two input switch. This switch can select between accepting inputs from the processor and an RC receiver powered by the main power to the drive system. The switch is controlled by a digital channel from the RC receiver. The details of the design and construction of the RC override will be discussed in Section 7.7: RC Override Technical Overview.

6.10. Phase One Testing and Resulting Modifications

Our first tests of the drive system were conducted indoors, where wind would not be a factor. This first round of testing was specifically designed to test the maneuverability of the system and our ability to control it using the RC override system controls. The specific tests are detailed in Appendix H: First Flight Test and Results. The first finding of this testing was that the motors began to oscillate in plane with the propellers. This prompted both the re-balancing of the propellers to reduce the instability causing the oscillations and the construction of braces to restrict the movement of the axle and engines relative to the gondola. The braces, shown in Figure 38, were designed as a simple truss structure, intended to minimize the added weight from the braces. Each is composed of a single acrylic connector on the axle, three attachment points on the gondola, and three carbon fiber tubes between them. The attachment points were composed of hot glue in the prototype version and replaced with acrylic brackets and steel screws on the final gondola. They are arranged with one tube anchored to either side of the axle and a third below it. Each member is alternately in tension or compression depending on the orientation of the propellers.

Figure 38: Prototype Axle Bracing System

The ground testing showed that the system generated fairly powerful turning moments about its centerline. However, once we attached the gondola to the blimp, the tail fins and air resistance of the shell were sufficient to almost negate the moment generated through differential thrust. To generate a larger turning moment, we incorporated elements of the tail rotor drive system into the design. The tail rotor system was the only one that could still turn in place, but generated its turning moment from the tail. The initial design was created with only a single tail rotor, to limit added weight and power requirements. It was decided that another would be added only if testing determined that a single tail rotor was insufficient. The tail rotor was placed in the lower fin, to reduce the required length of wire and to remove potential balance issues. This appears to be the standard form factor for blimps with only a single tail rotor, as seen in Figure 39.

Figure 39: Small-Scale Blimp with Tail Rotor
http://www.p-wholesale.com/upimg/13/553a2/rc-blimp-258.jpg

After the modifications, the blimp, still with the prototype gondola, appeared as shown in Figure 40.

Figure 40: Blimp after Phase 1 Testing and Modification

6.11. Phase Two Testing and Resulting Modifications

The second phase of drive system testing consisted of both indoor and outdoor tests. The specifics tests conducted are listed in Appendix I: Second Flight Test and Results and Appendix J: Third Flight Test and Results. These tests determined effects of high wind conditions on the blimp and the need for another modification to the gondola to prevent the drive system from impacting the shell. High winds both overpowered the turning system and caused significant drift. The blimp was forcibly turned into the wind and the main motors were able to drive it forward and to control altitude, but the drive system was not able to change heading. This indicated the potential to land in winds higher than our specified operating conditions, but not to navigate.

The accident, described in detail in Appendix J: Third Flight Test and Results, where the propeller impacted the shell indicated the need for another modification. While the braces prevented the axles from moving relative to the gondola, there was nothing preventing the gondola moving relative to the shell. This allowed the right hand propeller to power upwards into the shell during testing, shearing the shaft of the motor and risking a rupture of the shell. To prevent any further chance of this, a set of braces was installed to prevent movement of the gondola relative to the shell. These consisted of an upright member with an acrylic cap from the axle braces and a set of flexible panels attached to the top of the gondola. These braces are designed to function under compression when the propellers are pointed upwards and prevent the joining piece of the axle brace from moving closer to the shell. This system was tested statically with manual force at the motor attachment point and successfully ensured that the motor maintained a consistent distance from the shell. The final gondola, with bracing, is shown in Figure 41.

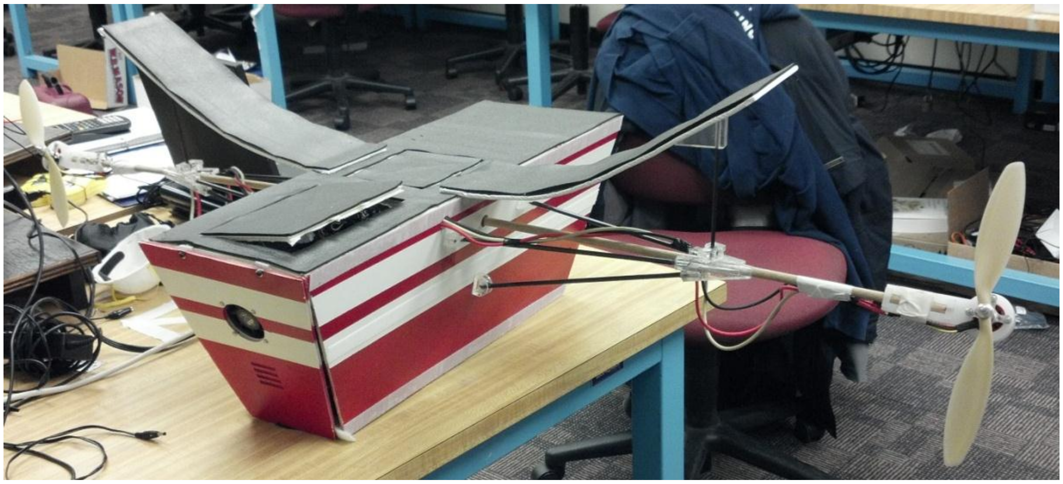

Figure 41: Final Gondola, with Anti-Roll Bracing

6.12. Summary

In this chapter, the design and construction of the drive system was discussed. Several possible control schemes were discussed and a tilt-able motor design was selected. Several possible axle materials were tested and a 0.375 inch wooden dowel was chosen. Turnigy Brushless Outrunner 2830 800kv motors were selected for the main drive motors. Testing of propellers of various lengths and pitches led to the selection of 11x4.7 propellers. In order to comply with FAA Right-of-Way rules, an RC override was designed and constructed. Drive system testing led to the addition of a tail rotor for turning and additional bracing of the axle.

Chapter 7

7. Electronics Design

7.1.Introduction

In this chapter, we discuss the design of the electronics for the blimp. This includes the requirements for and selection of the processor, the sensor selection processor, the requirements and design of the power system, and the development of the RC override controller.

7.2. Processor Requirements

The selection of the processor was driven by the system requirements. The system requirement driving each processor requirement is included in parenthesis.

1. Processor must have capability to handle the calculations necessary to calculate telemetry and drive commands necessary to fulfill requirements (1) and (2).
2. Processor must be able to interface with subsystems
3. Processor must have input from the radio control system
4. Processor must not exceed the size and weight limitations of the blimp

In order to meet the system requirements, the processor must operate above a minimum speed, below a maximum power usage, and must fit within size and weight constraints. The required speed of the processor is determined by the software tasks that it must perform. These tasks include: reading sensors, analyzing sensor data, performing navigation and task planning, controlling servos and motors, responding to commands from the base station, and providing telemetry to the base station. These tasks can be split into two categories: computationally simple tasks that must be performed frequently and computationally complex tasks.

The computationally simple tasks include reading sensors and controlling motors and servos. In order for the system to effectively operate in real-time, these tasks must be performed frequently. The frequency of these tasks must be sufficient for the system to meet System Requirements 1 and 2 which outline the navigational tolerances. Transmitting telemetry is also a relatively simple task; however, it must be performed at a rate of 2Hz.

The computationally complex tasks include analyzing sensor data, performing navigation and task planning, and responding to commands from the base station. Analysis of sensor data must be performed as quickly as sensor readings are being collected. Analysis must be complete before the next reading takes place. Navigation and task planning calculations must be performed quickly enough to satisfy System Requirements 1 and 2. The system must also be able to respond to input from the base station with no noticeable delay to the operator.

Power usage should be minimized in order to meet part 4 of the System Requirements. Weight should be minimized in order to provide enough additional lift to meet part 3 of the System Requirements. The processor must also fit within the space allotted in the gondola.

7.3. Processor Selection

Several different processors were considered for control of the blimp platform. These options can be seen below in Table 5. They were compared based on processing speed, available I/O, cost, power requirements, physical size/ weight, and memory.

Table 5: Processor Comparison Table

Supplier	Product	Cost	Notes
Neuron Robotics	DYIO	$149.00	Lots of I/O, needs Gumstix to control it
Gumstix	Gumstix Overo Water	$169.00	720MHz, 512MB ram, 512MB flash, needs expansion board
Gumstix	RoboVero (expansion board)	$99.00	Integrated IMU, SPI, I^2C, CAN, UART, GPIO, USB
Gumstix	Pinto TH (expansion board)	$27.50	USB, GPIO
Technologic	TS7400	$99.00	200MHz Arm9, 32MB RAM, 32MB flash, USB, Ethernet, DIO
Glomation	GESBC-3130	$45.00	180MHz, 32MB RAM, 128MB flash, SPI, I^2C, DIO
Beagle Board	BeagleBoard-xm	$149.00	1GHz Arm, 800MHz DSP, 512MB RAM, SPI, I^2C, USB, Ethernet
Panda Board	Panda Board	$174.00	Dual core 1GHz, 1GB DDR2 RAM, USB, I^2C
Leopard Board	Leopard 368	$149.00	400MHz, designed for video processing
Ardupilot	Mega	$199.00	Designed to be an autopilot
Texas Instruments	MSP 430	$1.00-$20.00	Inexpensive microcontrollers, very low power
Atmel	AVR	$1.00-$15.00	Inexpensive microcontrollers

The Gumstix Overo Water COM was chosen to be the main processor for the blimp due to meeting the requirements of processing power and minimized energy usage as well as having a lightweight and compact design. The 512 MB of onboard NAND flash is capable of storing all of the code necessary for this project. The processor's speed ensures that processing and calculations will be done in near real time as was specified in the requirements.

Specifically, the Overo Water was chosen over the other Overo models for several reasons. The main differences between the Overo models are:

- onboard NAND (flash memory),
- a DSP (Digital Signal Processor), and
- WIFI/ Bluetooth.

The Overo Water has onboard NAND and a DSP but it does not have WIFI or Bluetooth. The onboard NAND is non-volatile memory used to store the kernel and software. This is useful because it eliminates the need for a bootable microSD card to run the module. The microSD card is then free to be used for additional data storage or not at all. The DSP can be used for image processing and would therefore be useful to several potential blimp modules including surveillance, search, obstacle avoidance, and many other possible modules. The WIFI and Bluetooth capabilities were deemed unnecessary for two reasons. First, the limited range of those wireless protocols would limit the allowable distance between the blimp and the ground control station. Second, WIFI and Bluetooth have relatively high power requirements compared to simpler wireless protocols such as the wireless RS232 modules chosen for telemetry streaming.

7.4. Sensor Requirements and Selection

In order for the autopilot to function, the blimp must be able to determine its own position and altitude. This means that it must be able to determine its X, Y, and Z coordinates (latitude, longitude, altitude) as well as its orientation (pitch, roll, and yaw). The accuracy requirements are driven by our maneuvering requirements and the specific sensors used are described in section 3.1.2.

As described in section 3.1.2, a GPS will be used to determine the latitude and longitude of the blimp. We searched commercially available hobby GPS receivers for one with the minimum available error in our price range. A comparison of several GPS receivers can be found below in Table 6. The 50 channel D2523T Helical GPS Receiver was chosen because it had the best accuracy for the lowest cost. Its antenna is omnidirectional, which allows the blimp to ignore the orientation of the module in relation to the sky. Data is output in standard NMEA strings over a TTL/UART connection, which allows for easy integration to the Gumstix system. The selectable 1-4 Hz update rate allows the blimp to provide updated location data at the required 2Hz. The component's stated accuracy is < 2.5 meters, which even assuming an error of 200% means that the blimp would still be within 5 meters of the desired location. The module has a cold start of 29 seconds assuming open sky, which means that the module will acquire a GPS position fix before any preflight checks are completed. The maximum velocity and acceleration that the GPS can handle, 1000 knots and 4G respectively, are well within the expected flight characteristics of the blimp.

Table 6: GPS Receiver Comparison Table

Model	Protocol	Channels	Accuracy & Rate	Cost
D2523T	NMEA or UBX binary	80	<2.5 m at 4 Hz	$79.95
Lassen IQ	TSIP, TAIP, NMEA, RTCM SC-104	12	5.0 - 8.0 m at 1 Hz	$49.95
FV-M8	NMEA	32	2.6 - 3.3 m at 5 Hz	$99.95
LS20031	NMEA	66	3 m at 5 Hz	$59.95

As GPS based altitude detection is known to be less accurate than GPS based horizontal positioning, it was decided to use an alternate method for altitude detection. To be beneficial, the barometric altimeter requires accuracy greater than the greatest possible accuracy of the GPS, which in this case was 2.5 meters. Similarly to searching for the GPS, we searched for a commercially available barometric pressure sensor with the sensitivity we wanted that was within our price range. We selected the BMP085 barometric altimeter. It has a theoretical accuracy of ±2.5 ft, which is a significantly greater accuracy that that of the GPS. It communicates through an I^2C interface, meaning it can interface with the Robovero directly. Additionally, it is temperature compensated and equations were provided for all conversions. These are both significant advantages over most other commercially available barometric pressure sensors.

Finally, the orientation of the blimp will be detectable by the IMU built into the Robovero. This contains a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer.

7.5. Power Systems Requirements

1. The batteries must be able to provide power to the motors and electronics for a minimum of 90 minutes.
2. The batteries must fit within the weight requirements of the system.
3. The electronics and motors must exist on separate power systems.
4. The power systems must include a safety mechanism to prevent cross charging batteries.

7.6. Power Systems Implementation

The batteries were selected based primarily on two criteria: weight and energy capacity. Based on the motor and propeller tests in Section 6.6, the motors we had selected draw 60 W per motor when operating at 0.828 lbs of thrust per motor. This thrust value is the calculated value to overcome drag at 6 knots with a safety factor of three. As the nominal voltage of the batteries is 11.1V, this leads to a current draw of 5.41A. Therefore, a minimum battery capacity of 8.1 Ahr will be required to operate the blimp for 90 minutes as specified in our requirements. In order to maximize the blimp's possible payload capacity, the weight of the batteries was minimized. To this end, lithium polymer batteries were selected for their very high energy density. As the project also had budget limitations, cost was another significant factor we sought to optimize. The trade studies for the two separate power systems are shown in Table 7 and Table 8.

Table 7: Battery Selection for the Motor Power System

Name	Type	Cost	Voltage	mAhrs	Weight	mAhr/lbs	$/mAhr
Tenergy Li-Ion 18650	Li-Ion	$99.98	11.1 V	7800	0.9375	8320	$0.0128179487
Tenergy Li-Ion 18650	Li-Ion	$26.99	11.1 V	2200	0.33125	6641.51	$0.0122681818
NiMh 12V	NiMh	$87.99	12 V	10000	3.35	2985.07	$0.0087990000
ZIPPY Flightmax 4400mAh 4S1P 15C	LiPoly	$28.48	11.1 V	4400	0.927	4746.49	$0.0064727273
Rhino 4900mAh 3S1P 11.1v 20C	LiPoly	$39.95	11.1 V	4900	0.776	6314.43	$0.0081530612
ZIPPY Flightmax 5000mAh 3S1P 20C	LiPoly	$31.72	11.1 V	5000	0.8642	5785.7	$0.0063440000
Turnigy nano-tech 1800mah 3S 20~40C Lipo AIRSOFT Pack	LiPoly	$11.77	11.1 V	1800	0.3307	5443	$0.0065388889

Table 8: Battery Selection chart for the Electronics Power System

Name	Type	Cost	Voltage	mAhrs	Weight	mAhr/lbs	$/mAhr
#THP12502SP45	Lipo	$32.99	7.4	1250	0.167	7485.03	$0.0263920000
#EFLB12502S	Lipo	$16.99	7.4	1250	0.194	6443.3	$0.0135920000
Venom 2S	Lipo	$16.99	7.4	1320	0.163	8098.16	$0.0128712121
Losi	Lipo	$49.99	7.4	2000	0.1896	10548.5	$0.0249950000
Turnigy nano-tech 2000mah 2S 15~25C	Lipo	$9.26	7.4	2000	0.2337	8557.98	$0.0046300000

In order to extend the runtime of the blimp, multiple lithium polymer batteries will be connected in parallel. This adds together the energy capacity of the batteries; however, it could potentially cause damage to the batteries. If the batteries are at different charge levels, the battery with a lower charge will draw power from the battery with higher charge until they reach equilibrium. This could result in dangerously high current between the batteries while this cross-charging is taking place.

Based on results found on numerous RC hobby forums, many people have had success connecting lithium polymer batteries in parallel without protection circuits. Generally, people who had success on the forums seemed to follow the rule of thumb that both batteries should be fully charged to within 0.1V of each other before connecting them in parallel to avoid dangerous cross-charging currents. A member on one of these forums posted the following guidelines [37]:

> *"Some general rules for series and parallel battery pack connections.*
> *1) Parallel connections increase current and capacity without changing the voltage. Serial connections change the voltage and typically keep the current and capacity the same.*
> *2) Always make sure that all parallel connected battery packs are the same voltage before connecting them so they do not draw much current when they equalize themselves.*
> *3) Try to use batteries with similar current and capacity rating when you make a battery system. In parallel systems it is obvious why the battery packs used should have the same voltage. Current and capacity may not be as critical for a parallel pack but could cause the system to go out of balance when a lower capacity pack drops voltage before the higher capacity pack."*

For the highest level of safety, protection circuitry can be added to prevent cross-charging. Several options exist for such circuitry:

1. Diodes
2. Ideal Diode Controllers
3. Microcontroller with ADCs and switches on each battery
4. Fuses

1. The simplest method of battery protection would be to put a diode in series with each battery to prevent cross-charging. However, diodes have a forward voltage drop which will decrease the voltage available to the motors thereby decreasing the maximum motor power. Diodes with the lowest possible voltage drop should be chosen. Unfortunately, it is difficult to find diodes with both low forward voltage and with a high enough current rating (maximum 14A per battery). Schottky rectifiers are the best diodes for this application. They have forward voltage drops between 0.3V and 0.5V and forward currents between 15A and 25A. Schottky rectifiers are also the cheapest option costing approximately $3.00 per diode. [38]

2. An ideal diode controller is an integrated circuit that monitors battery voltage and controls two external pFETs for over-voltage and reverse-current protection. This option is more efficient than diodes because the reverse-battery pFET behaves as an ideal diode thereby minimizing the forward voltage drop. Under reverse-bias conditions, this pFET turns off thereby preventing the battery from cross-charging. This solution requires one ideal diode controller, two pFETs, and various resistors and capacitors for each battery. Of the three solutions, this one requires the most components and is the most expensive (approximately $50.00).

3. A custom ideal diode controller could be constructed using a microcontroller with an ADC and pFETs or solid state relays on each battery. The microcontroller would monitor the voltage of each battery. Only the battery with the highest voltage would be switched on at a time. This would discharge all of the batteries evenly and since only one battery is providing power at any given time, there will be no cross-charging. This would be the most complicated option to construct as it would require many components and some minor embedded programming.

4. Like diodes, fuses are a simple, single-component solution to the problem. Fuses would be selected to prevent dangerous cross-charging currents. Unfortunately, in this situation, the maximum supply current required by the system is 14A whereas the maximum safe charge current is only 4A. This makes it impossible to use fuses to limit cross-charging as any fuses that could prevent dangerous cross-charging would also fail during normal operation.

Due to cost and time limitations, it was decided to implement the solution utilizing diodes. In order to prevent cross-charging, a diode was placed in series with each battery, as shown in Figure 42.

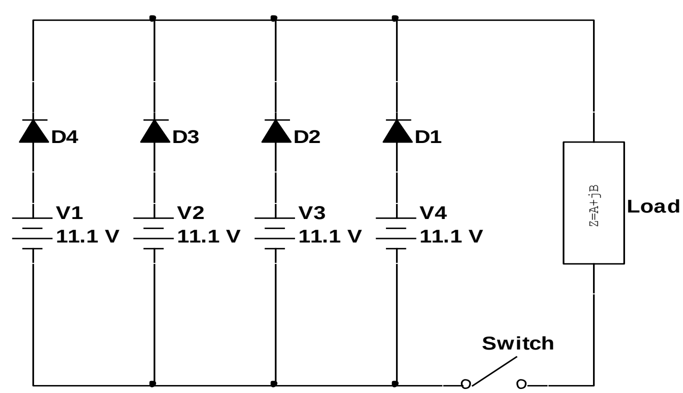

Figure 42: Battery Protection Circuit Schematic

7.7. RC Override Technical Overview

As discussed in section 6.9, a remote manual override of the drive system was a legal requirement. This involves overriding the four PWM signals used to control the two drive motors, the pitch servo, and the tail rotor. To accomplish this, a circuit was designed to utilize one of the additional PWM channels of the RC receiver to be used as a select signal for a multiplexor which selected which control signals (those from the processor or those from the

RC receiver) would be passed to the drive system. The PWM signal to be used as the select signal is a 50Hz PWM with a maximum duty cycle of 10% and a minimum duty cycle of 5%. The goal was for this PWM signal to be converted to a logic 1 (5V) at 10% duty cycle and a logic 0 (0V) at 5% duty cycle so that it could be used as the select signal for the multiplexor.

This circuit was divided into four stages:

1. Second-order filter
2. Amplifier
3. Comparator
4. Multiplexer

The second-order filter is used to convert the PWM signal from the RC receiver into an analog signal. The filter was designed to have a natural frequency of approximately 50Hz in order to achieve the best conversion from PWM to analog. At high duty cycle (10%) the output of the filter is approximately 0.4 V and at low duty cycle (5%) the output of the filter is approximately 0.25 V. This signal is then amplified by a non-inverting operational amplifier with a gain of 10. The output of the amplifier stage is therefore approximately 4 V at high duty cycle and 2.5 V at low duty cycle. The output of the amplifier stage is connected to the non-inverting input of a comparator. The inverting input of the comparator is connected to a potentiometer which provides an adjustable reference voltage. This reference voltage is tuned such that the output of the comparator is logic high (5V) when the signal from the amplifier is corresponds to the high duty cycle PWM and the output of the comparator is logic low (0V) when the signal from the amplifier is corresponds to the low duty cycle PWM. 1/30 feedback is provided to the non-inverting input of the comparator to provide hysteresis to prevent chatter. The now logic level signal from the comparator is then used as the select signal for a quad 2-to-1 CMOS multiplexor. The inputs to the multiplexor are the control signals from both the processor and the RC receiver. The outputs from the multiplexor are connected to the motor controllers and servo. The circuit schematic is shown in Figure 43 and the simulated performance of the system is shown in Figure 44 and Figure 45.

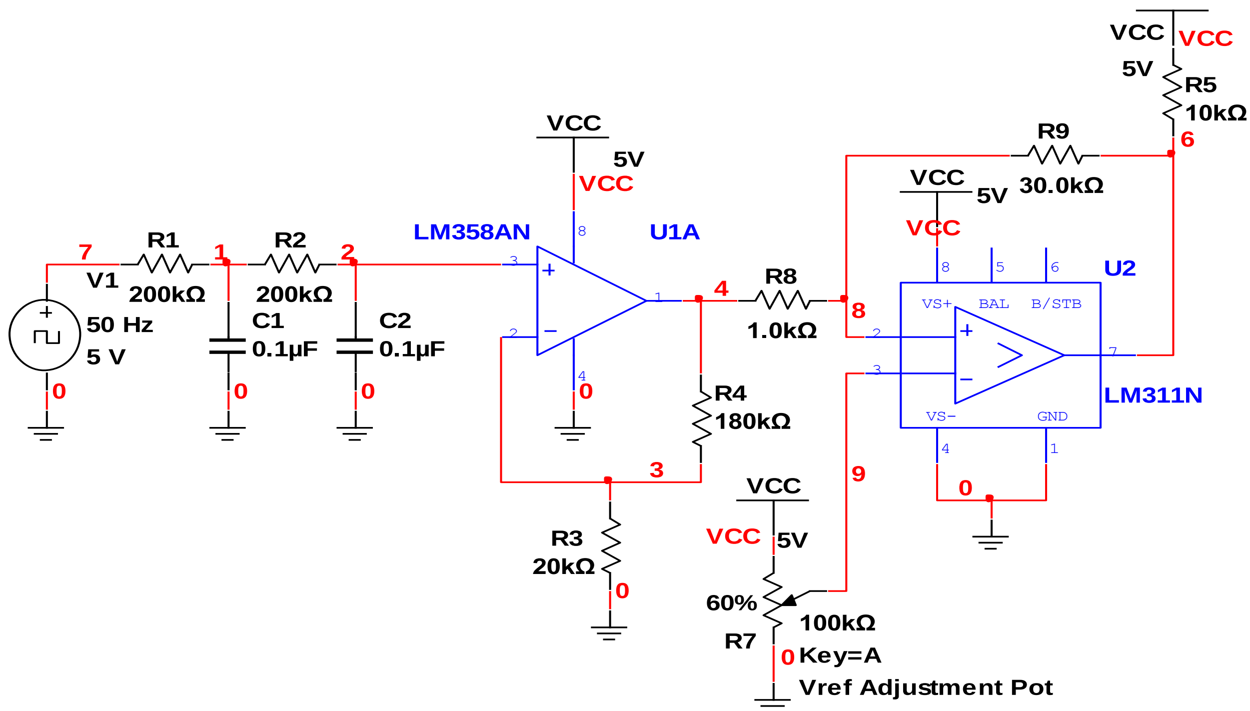

Figure 43: Circuit Schematic for RC Override

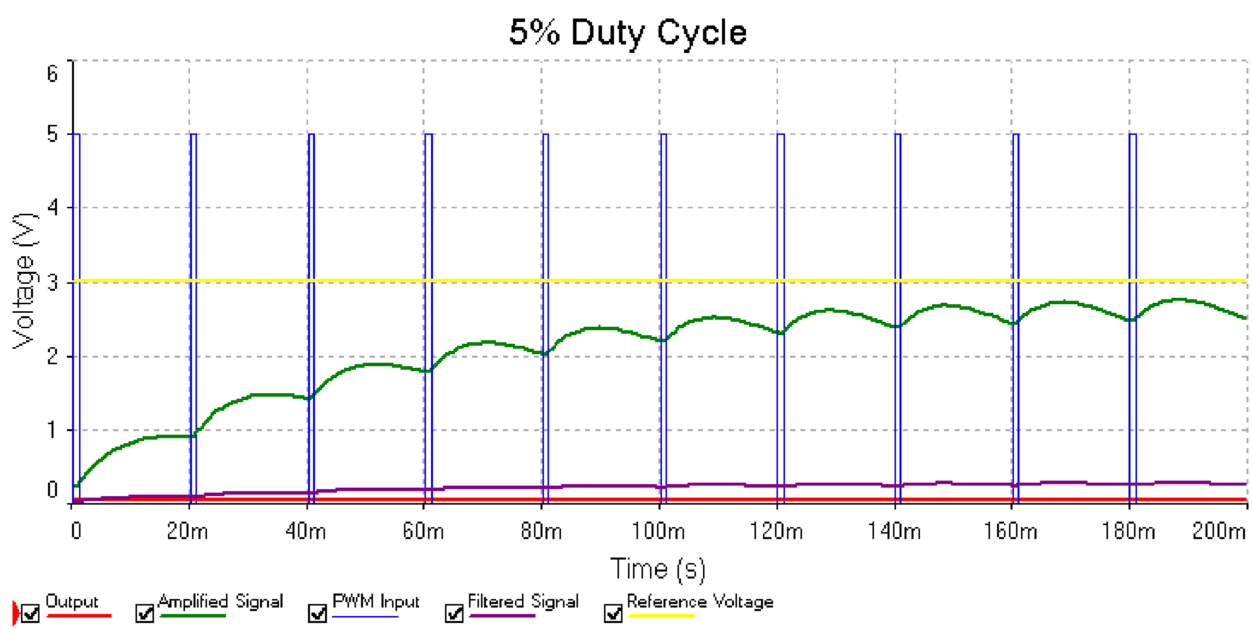

Figure 44: Simulated Output of Override at a 5% Duty Cycle

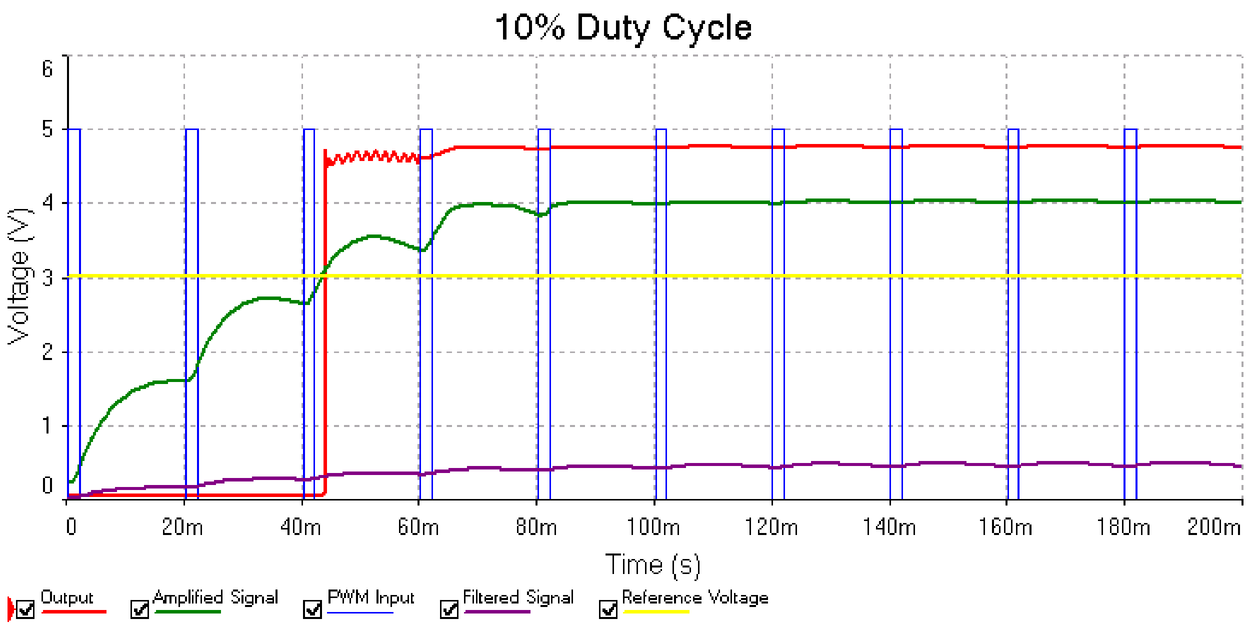

Figure 45: Simulated Output of Override at a 10% Duty Cycle

7.8. Summary

In this chapter the design of the electronics systems of the blimp was discussed. These systems included the processor, the sensors, the power systems, and the RC override. The Gumstix Overo Water COM and Robovero expansion board were chosen for the processor system. A D2523T Helical GPS Receiver, BMP085 barometric altimeter, and the Robovero's integrated IMU were selected for the sensor system. The RC override circuit was designed to utilize a PWM channel from the RC receiver to be used as the select signal for a multiplexer on the control lines for the drive system.

Chapter 8

8. Gondola Design and construction

8.1.Introduction

In this chapter, we present the design process for the gondola, which is the container for the electronics and drive system. This chapter lays out the goals, initial design, and redesign of the gondola. It also details the program of materials testing undertaken to determine the optimal gondola material.

8.2. Gondola Design Goals

The gondola for the blimp was designed primarily to be a container for the other systems. It was designed in two iterations, named the Mark 1 (Mk. 1) and Mark 2 (Mk. 2) gondolas. The initial design goals for the Mk. 1 gondola design were as follows:

1. The gondola needed to have mounting points for the components of the drive, sensing, and processing systems.
2. The gondola needed to keep its contents protected from the outside environment under S.O.C.
3. The gondola needed to be able to withstand the forces of the motors as well as forces on the tether point.
4. The mission module section needed to be able to accommodate numerous different configurations of equipment and secure that equipment within the gondola.
5. Paths were required for cable connections between all of the compartments.
6. The gondola needed to be as light as possible while accomplishing all of these goals.

8.3. Design of Mk. 1 Gondola

The Mk. 1 was designed based on these design goals. The intent was to create a gondola that was usable, but was intended to be replaced with an improved version based off of our experience working with the prototype. In order to provide mounting points for each component, the decision was made to compartmentalize the inside of the gondola, as shown in Figure 46. The compartments were separated by subsystem. This led to the creation of the electronics, battery, drive system, and mission module compartments. The electronics and batteries occupied the forward section of the gondola. The drive system section was located in the center of the gondola to allow the motor shaft to be closer to the center of gravity of the blimp. The mission module section would be in the rear and would have no floor to allow for different configurations of the mission modules. The servo assembly for pitch control, located in the drive system section, used a rail system to allow it to be raised or lowered in order to experiment with different vertical positions of the motor axle. The gondola's final exterior shape was that of an inverted pyramidal trapezoid. This design included sloped sides to give the hull a more aerodynamic shape. It was decided that the battery compartment would occupy the bottom of the two forward locations in order to keep the largest weight source lower for additional stability. The internal compartments were divided by walls with gaps that were intended to be used for cable management, allowing cables to be routed through the various compartments. The Mk. 1 was designed in Solidworks, a 3D CAD program that allowed for designing individual components as well as assembling them within software to verify correct fitting. The design for the gondola allowed for every surface to be laser cut from foamcore board before being fitted together and secured with epoxy. After the epoxy solidified, fiberglass was wrapped around the central section to add structural rigidity as well as to create a surface on which to secure the tether's attachment point.

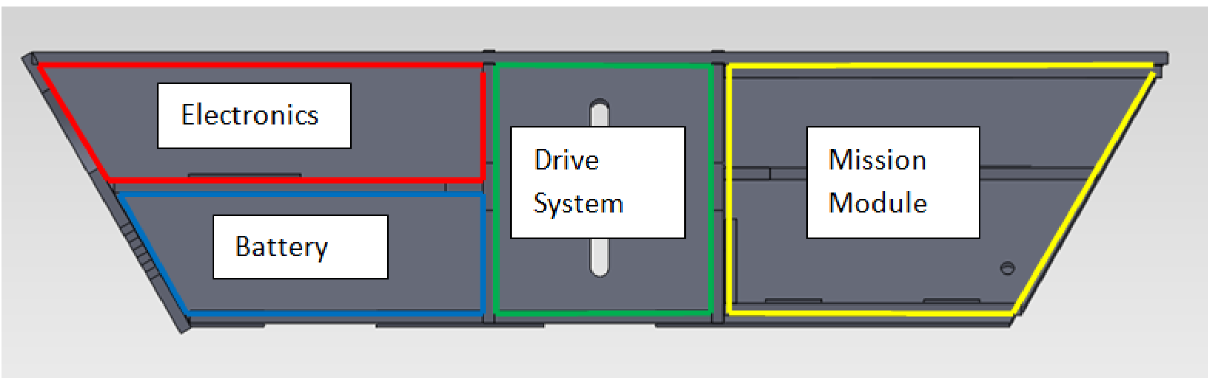

Figure 46: Internal Divisions of Mk. 1 Gondola

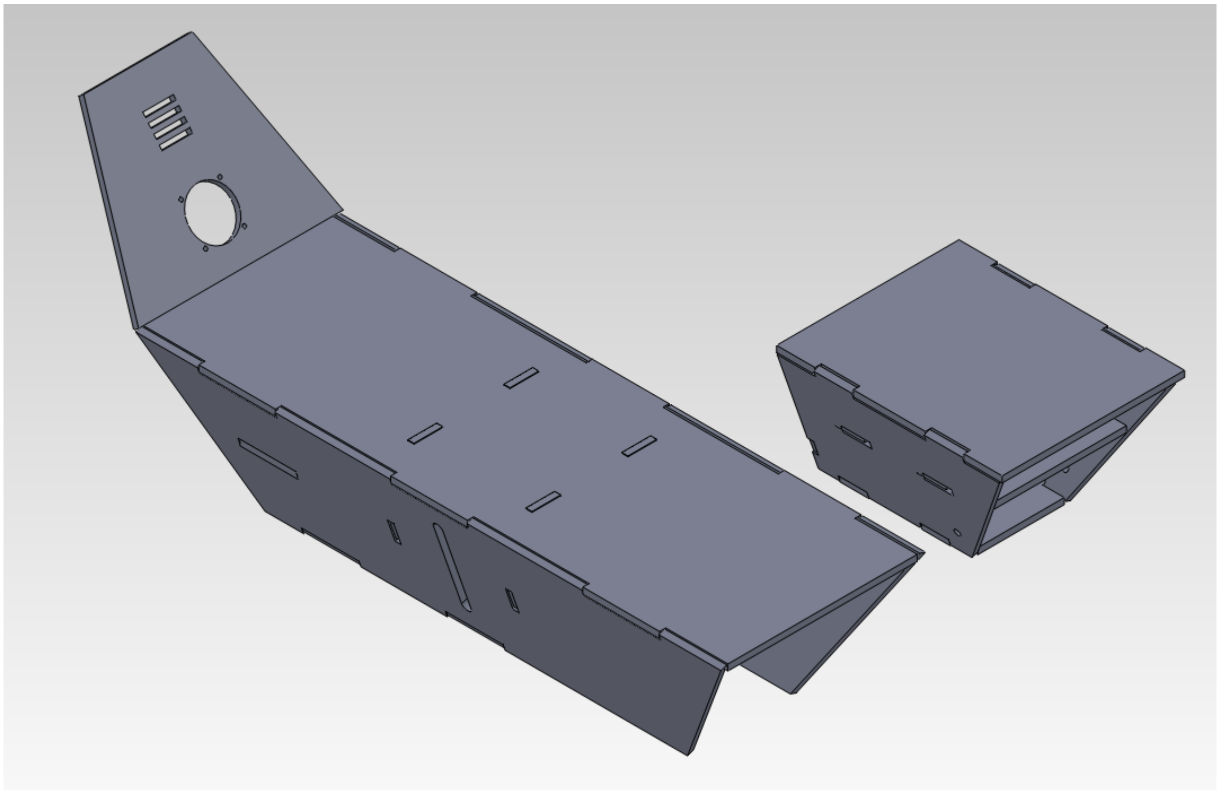

Figure 47: CAD model of the Mk. 1 Gondola

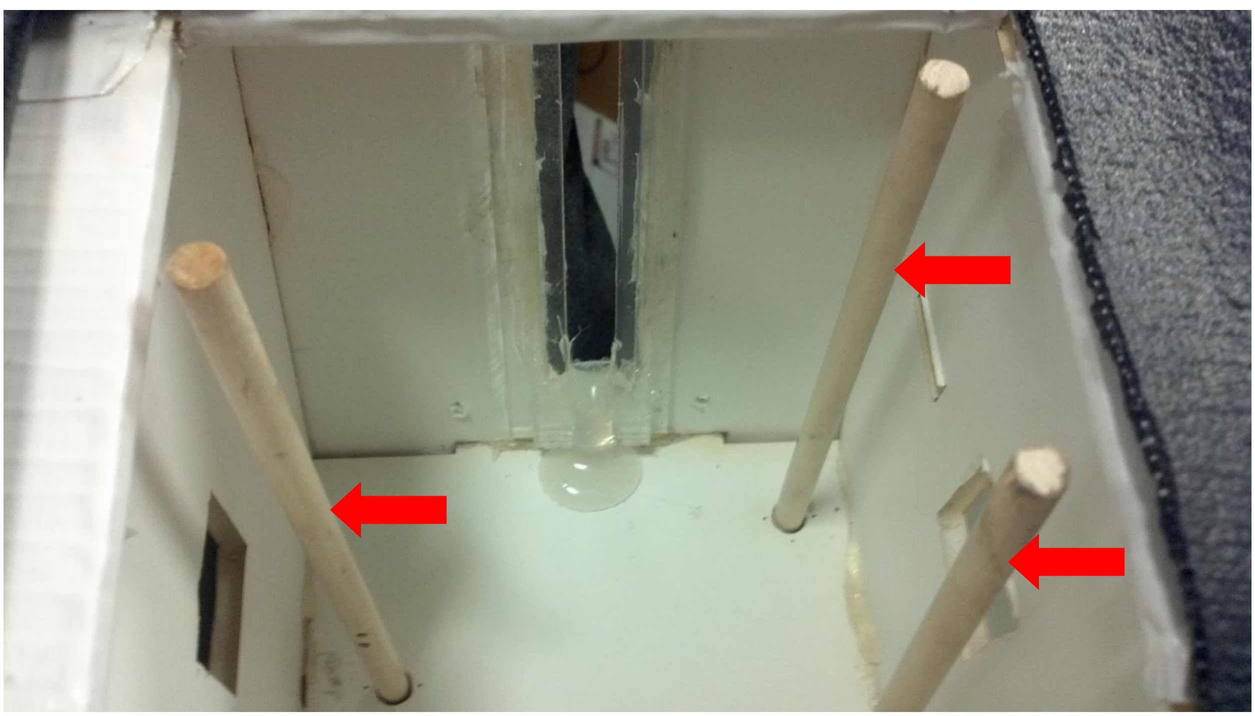

Figure 48: Mk.1 Servo Bay with Mounting Rails.

8.4. Problems with the Mk. 1 Gondola

During the process of adding the internal components to the Mk. 1 gondola, it became apparent that a redesign would need to occur for greater ease of access to the gondola's internal areas. The drive system compartment access hatch, despite being sufficient for the addition and removal of the servo assembly was not spacious enough to easily accommodate the tools needed to secure the assembly into place. The electronics compartment had been correctly sized to accommodate all purchased components with additional space for minor cable management; however the enclosed space was very difficult to work in. Other problems with the original gondola design became apparent during testing. During RC testing, it became apparent that there was sufficient play in the axle rotation gear system to allow the gearing to skip, creating an offset that the eventual controlling computer would be unaware of. In the Mk. 1, a tether post that would extend down from the gondola had been considered and then discarded in favor of a loop mounted to lower surface of the gondola for the tether to attach to. During testing, it was determined that the loop allowed the safety tether to drift into the propellers. It was also an insufficient point for the ground crew to grab onto as the vehicle attempted a landing. The original Mk. 1 design included holes in the internal structure to allow for cable routing, but these turned out to be difficult to work with and insufficient for the amount of cables that needed to pass through them. In constructing the Mk. 1, only part of the outer hull was coated in fiberglass and was overly coated in fiberglass resin, resulting in excessive weight, sharp edges that required sanding, and a very unattractive patchy appearance.

Figure 49: Mk.1 Gondola Exterior View

8.5. Modifications to the Mk. 2 Gondola

The Mk. 2 design addresses each of these problems to ensure that the final product is much easier to modify, repair, and use. The servo compartment had a larger access hatch that allows for tools to more easily reach the necessary points on the servo assembly. The difficulties with reaching the electronics were solved with the addition of a top hatch that allows for the manipulation of components and wires from above. The Mk. 2 was wider and taller, allowing for greater volume in the electronics and battery bays for cable management. The Mk. 2 includes the original tether post concept, which runs through a fiberglass reinforced section of the gondola bottom to prevent the post from being ripped out if exposed to severe forces. The post keeps the tether safely out of the way of the propellers except in conditions of extreme rolling and allows for easier ground handling during landing and unpowered movement. To correct the issues with internal wiring, the internal structure includes wide channels dedicated to cable management that do not require great accuracy to thread cables through and allows for the passage of a greater number of cables. The Mk. 2 construction had no fiberglass on the outer hull, resulting in a much smoother appearance as well as an even strength gradient across the hull.

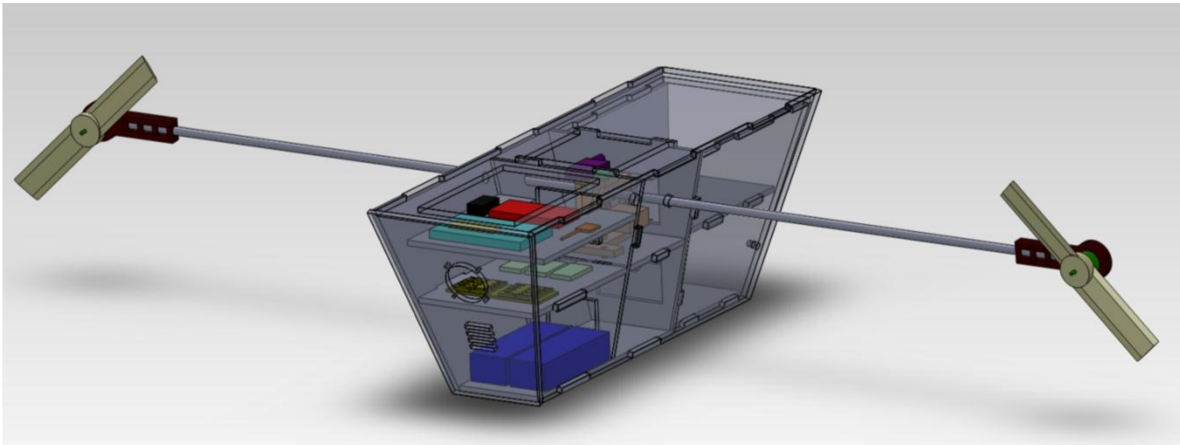

Figure 50: CAD model of the Mk. 2 Gondola

8.6. Materials Testing and Selection

In addition to these solutions, a program of testing was undertaken to determine the optimal material for gondola construction. The possible materials for the gondola were evaluated based on several characteristics and weighted by the importance of that characteristic to the function of the gondola. The materials and their scores, converted to a unitless scale, in each category are summarized in the table below. How each category was evaluated and why it was assigned a particular weight is explained below the table.

Table 9: Numerical Approximation of Material Attributes

Material	Tensile Strength (0-5)	Deflection Strength (0-5)x2	Weight (0-5)x3	Appearance (0-5)x1	Total
Acrylic	2	1	0	5	8
Cardboard	.3	0	15	2	17.3
Cardboard with Fiberglass	1	10	4.3	2	17.3
Foam Core	.3	1.2	15	4	20.5
Foam Core With Fiberglass	1.3	7	3.42	2	16.6
Corrugated plastic	0	0	13.62	3	16.62
Fiberglass	5	--	7.92	2	9.9

Tensile Strength:

The tensile strength of each material determines how it handles longitudinal forces, forces being applied in tension. Testing to determine the tensile strength of the materials was conducted using an Instron stress testing machine, a load cell capable of tracking both applied force and position. The samples tested were identical in size and shape, each with a profile within the tolerances specified in ASTM D638-10 (Standard Test Method for Tensile Properties of Plastics) for Type I (less than .28 in) materials. The dimensions of the test samples are shown in Figure 51. Each sample was cut from its parent material using a laser cutter, with the exception of the fiberglass which was cut using a band saw.

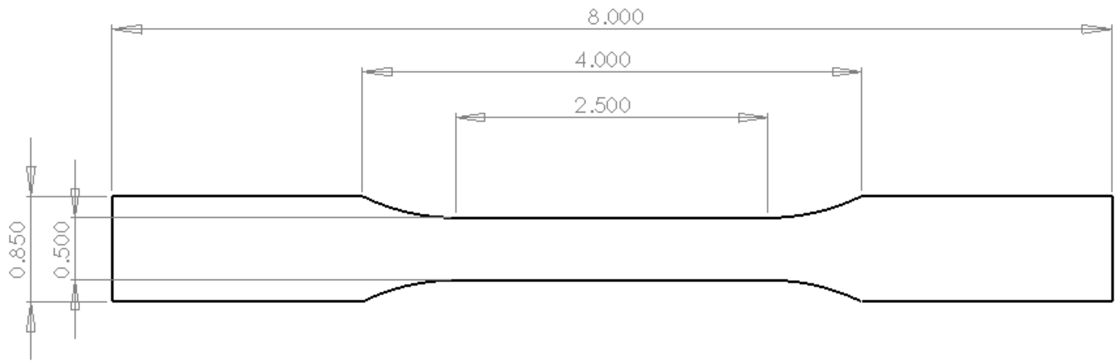

Figure 51: Tensile Test Sample Dimensions (in)

The results of these tests are shown in Figure 52. Tensile strength is the normally most vital attribute of a material when it is used in a role where in plane stress is applied to the material, such as when the material is used as a support or as reinforcement to another structure. Because the forces applied in this plane are very limited in our gondola design, tensile strength was not given a greater weight. The results of the stress test were separated into 5 equal increments over the range of the output. Each material was assigned a score based on the increment in which it failed.

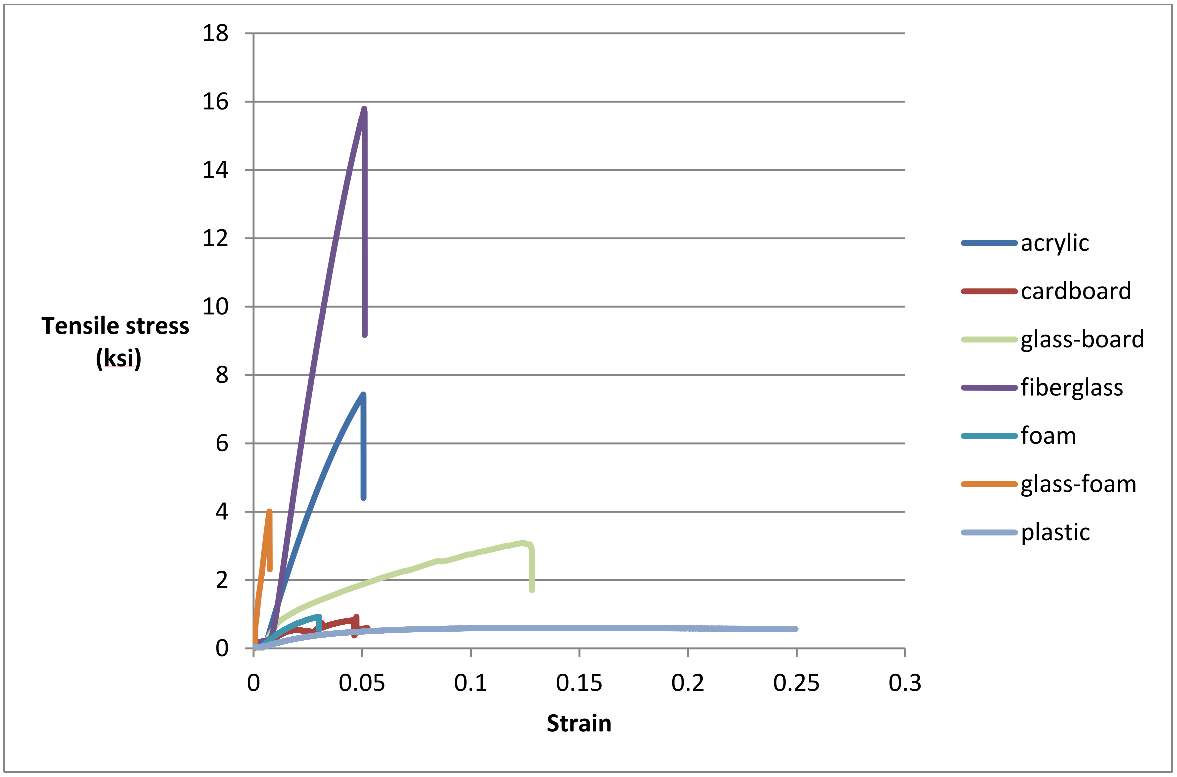

Figure 52: Tensile Test Results

Deflection Strength:

The deflection strength of each material determines how it handles forces normal to the plane of the material. Testing was conducted using the Instron stress testing machine described above. The samples tested were identical 6in by 6in squares. These were placed on two supports and loaded along the centerline using the load cell. The test results are shown in Figure 53. Deflection strength is the most vital attribute of the material when it is used in a role where a load is applied perpendicularly into the material, such as when used as an outer wall or horizontal supporting surface. As this in the majority of the load is applied to the materials mid-plane, this is a very important quality in our chosen construction material. Consequently, it was weighted twice as heavily as other attributes. The results of the stress test were separated into 5 equal increments over the range of the output. Each material was assigned a score based on the increment in which it failed. Fiberglass deflected between the supports at very low pressure and consequently could not be tested. Both cardboard and corrugated plastic were rated based on the strength of their weaker orientation, with the corrugations parallel to the supports. In this configuration, the corrugated plastic failed too quickly to get a reading and was not included.

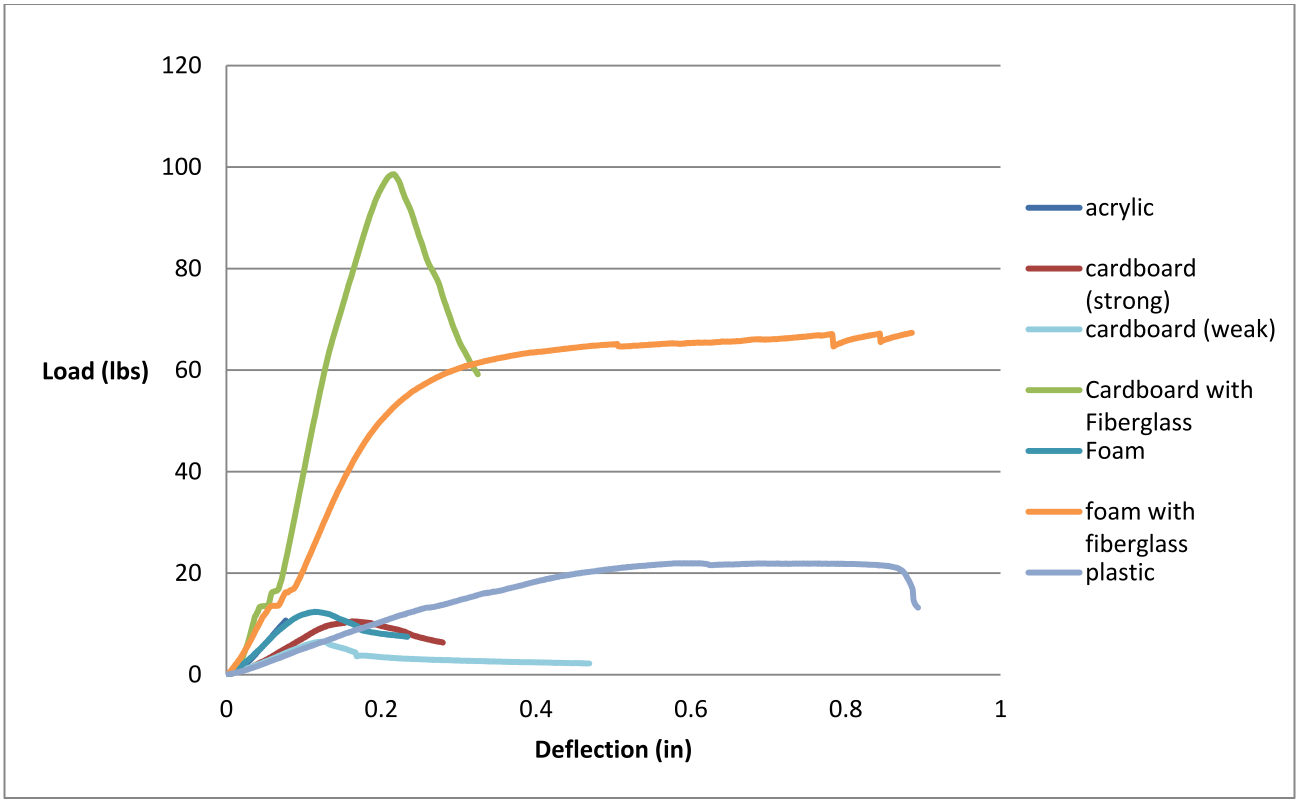

Figure 53: Deflection Test Results

Weight:

The limited lifting capacity of the blimp makes the weight of the gondola the greatest concern, as the gondola will be the largest object and, excepting the batteries, will be the heaviest component. Consequently, it has been given a greater priority than the deflection strength of that material and was weighted three times as heavily as other attributes. Each deflection test sample was weighed before testing and the weights are recorded in Table 10. The score for each material's weight was given based on where it fell between the lightest and heaviest material.

Table 10: Material Weights

Material	Weight (g)	Score (0-5)
Acrylic	142.4	0
Cardboard	13	5
Cardboard with Fiberglass	105	1.44
Foam Core	14	5
Foam Core With Fiberglass	113	1.14
Corrugated plastic	25	4.54
Fiberglass	74	2.64

Appearance:

As the blimp will be on public display at low altitude, the appearance of the gondola is important. However, it is not as important to the function of the blimp as the structural integrity of the gondola and was consequently assigned a smaller weight. The lower weighting is also due to the subjective nature of appearance. In this case, the scores were assigned based on how well it could be made to look even and smooth using paint or left uncoated.

Conclusion:

This analysis showed that the foam core was the optimal material for the majority of the gondola due to its excellent strength to weight ratio, as well as its cleaner appearance.

8.7. Attachment Method Tests

The gondola is secured to the blimp shell via a Velcro strap system. There are three strips of the hook side of Velcro running along the length of the gondola. At any time, at least 8 soft sided Velcro straps that hang from the shell will be attached to the hooked Velcro on the gondola. Pull tests were done using one strip of each material in the same configuration as the Velcro would be in the final version. Using a suitcase scale to measure the force necessary to separate the Velcro, we were able to determine that it takes 7.56 pounds of force to separate the two halves of the Velcro (Figure 54). The standard PSI to separate commercial grade Velcro when in shear is between six and ten PSI. [39] Given that the Velcro strip of connection was a square inch, the measurement of 7.56 PSI is valid.

As there are three connections for each strap and a minimum of eight straps for attachment, this results in twenty four points of contact. In total, a force of 181.44 pounds is necessary to completely tear the gondola away from the shell with all straps attached. As the lifting capacity of the blimp is only eight pounds, the weight of the gondola (with mission module) will be less than this amount. As a result of this weight limit and the strength of the Velcro, the gondola can be held onto the shell with a minimum of two points of contact.

Figure 54: Velcro Pull Test Setup

In order to determine the first point of failure given a structural jerk could be determined given the information about how much force it takes to break the adhesive contact between the Velcro pad and the gondola as well as how much force it takes to break the adhesive contact between the Velcro pad and the blimp shell. The former information can be gained but only through destructive testing of a Velcro pad and a segment of material prepared similar to how the gondola was prepared. The latter information was also obtainable, but this would require destructive testing of the blimp shell itself. Logically, if the Velcro adhesive could not withstand more force than the Velcro connection itself, the adhesive would be useless for its purpose of keeping the Velcro pads connected to anything.

8.8. Summary

In this chapter, we discussed the design of the gondola. Materials testing led to the selection of foam-core for the construction of the gondola. Problems encountered with the Mk. 1 gondola led to design modifications resulting in the Mk. 2 gondola.

Chapter 9

9. Software Design

9.1. Introduction

In this chapter, we discuss the development of the software for the blimp. This includes the establishment of requirements, the development of the software architecture, and testing procedures for the navigation functions. Software was not the primary focus of this project and development was largely directed towards the development of methods to test the most basic system functionality and navigation function. Follow on projects will expand this functionality.

9.2. Software Requirements

In order for the software to perform its goal of testing the system, it needed to fulfill the following requirements.

1. Must control electromechanical components of drive systems
2. Must be able to read the GPS, IMU, and Altimeter
3. Must be able to generate steering instructions based on sensor input
4. Must provide timely control updates to the drive system to achieve system navigation goals

9.3. Software Architecture

The software is divided into four levels:

1. Driver
2. Interface
3. Task
4. Mission

The driver level contains the software for interfacing with the various sensors, servos, and, motors in the system through the Robovero. The interface level utilizes the drivers and contains objects such as motor, servo, tail motor, position sensing, navigation system, etc. for logically and easily reading and controlling peripherals. The task level contains objects for performing complex tasks such as navigating to waypoints and performing mission-specific tasks. These objects instantiate or call the interface level objects as necessary in order to complete the tasks. The mission level consists of a mission object which will instantiate a blimp object with the full set of tasks required to complete a complex mission such as navigating through a series of waypoints, generating and executing a search pattern, etc. The architecture is shown in Figure 55 and each section is explained in detail in the following sections.

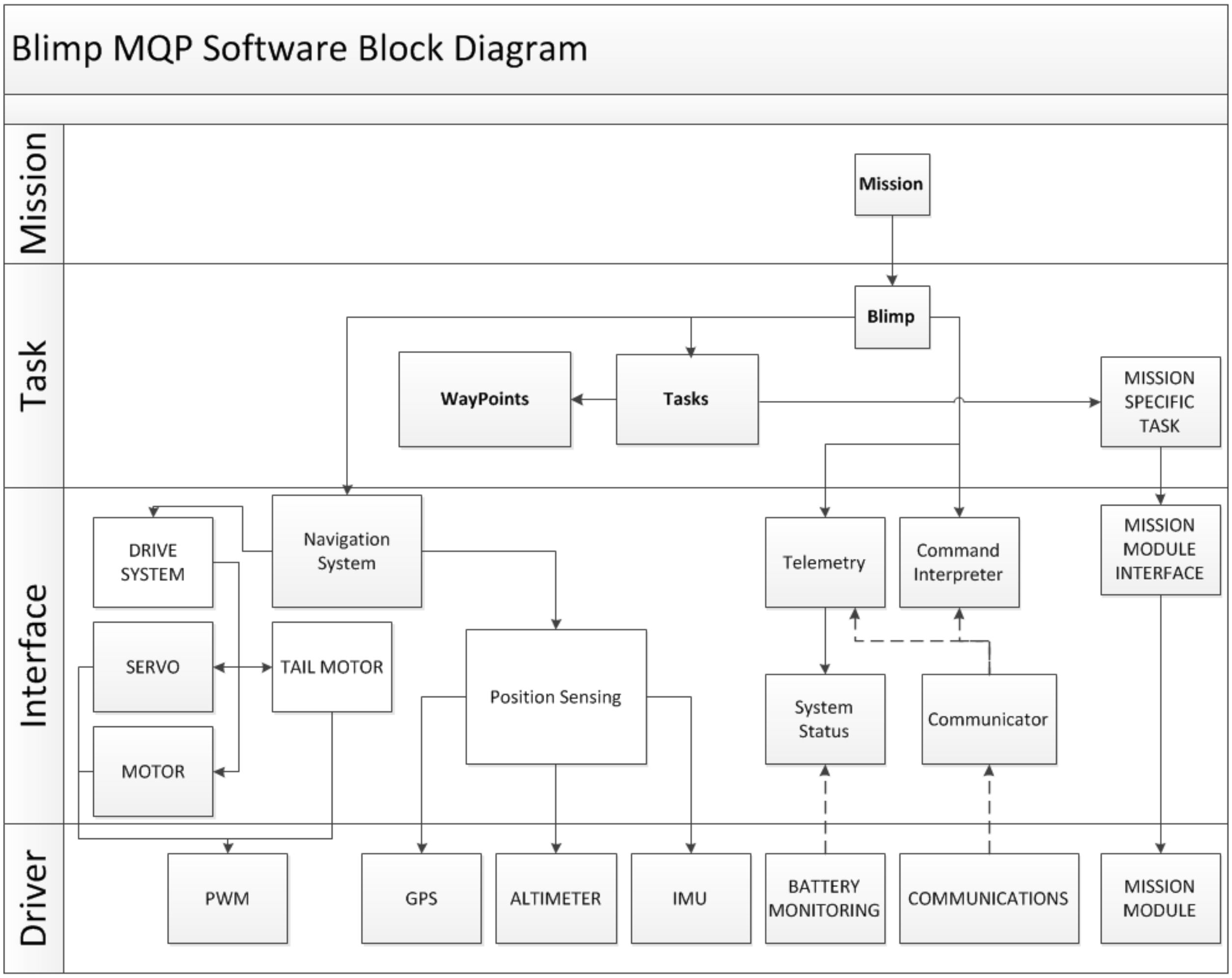

Figure 55: Diagram of Software Architecture

9.3.1. Drivers and Interface

A driver was written for each peripheral. These drivers utilize the API provided by Gumstix for interfacing with the Robovero. The IMU contains three I^2C devices: a 3-axis accelerometer, a 3-axis gyro, and a 3-axis magnetometer (compass). The IMU driver handles the I^2C communications with these devices and provides methods for reading the IMU. The barometric altimeter is also an I^2C device. The barometric altimeter driver reads the device and performs the calibration calculations to provide the temperature adjusted altitude. The motors and servos are controlled by Pulse-Width-Modulated (PWM) signals. A generalized PWM driver was created to generate PWM signals over the necessary duty cycle range and at the correct frequency for controlling the motors and servos. The GPS driver uses the Robovero's UART interface to receive position data from the GPS unit. The communications driver provides a UART interface to the wireless data module used to send telemetry to and receive commands from the base station. Additional drivers can be added for mission specific hardware.

The interface classes utilize the drivers to control individual components or give components the ability to perform higher level actions than simple communications. The PWM driver is used by the servo, motor, and tail-motor classes. Each of these classes is given an output limit and input range corresponding to the capabilities and actions of each motor. For example, motor inputs are 0% to 100% while servo inputs are from 0° to 360°. The drive system class instantiates two motors, one servo, and one tail-motor, representing the entire drive system of the blimp. The position sensing class utilizes the IMU, GPS, altimeter, and airspeed sensor to determine position, speed, heading, and altitude.

9.3.2. Autopilot construction

The autopilot is comprised of the navigation class which instantiates a drive system object and a position sensing object. The navigation class utilizes the position data from the position sensing class as well as the desired position provided by the current navigation task. From this data, the navigation system then calculates the heading and distance to the target coordinate. Based on this heading and distance, it generates control signals to issue to the drive system using a proportional controller.

9.3.3. Task handling

Task classes inherit from an abstract task class. This ensures that each task has an "execute" method which includes the code for executing the task. Tasks can have additional data and helper functions as necessary, depending on what each task requires the blimp to do. The overall mission consists of a list of tasks to be executed in order to complete the mission. These tasks are executed sequentially.

9.3.4. Telemetry

As specified in the system requirements, the blimp must transmit telemetry to the base station. The telemetry is a string of plain-text containing blimp status (i.e. battery voltages and current task/ mission status), position (Latitude and Longitude), altitude, heading, and speed. The blimp transmits this data to the base station via the wireless serial data module.

9.3.5. Ground control

In order to assign and alter missions while the blimp is operating, the ground control station can transmit commands to the blimp via the wireless serial data module. The blimp parses these plain-text commands into function calls which alter the behavior of the blimp.

There is also an emergency remote control override. This consists of a Spektrum DX-6i controller and a six channel receiver in the blimp. One of the channels is used as an override for control of the motors and servos. This override signal acts as the select signal for the RC override system. When the override is engaged, the operator of the DX-6i has complete control of the blimp's drive system.

9.4. Ground Testing

The navigation system of the blimp was tested by attaching the gondola to a dolly and instruction it to navigate to waypoints on the ground as seen in Figure 56. The purpose of these tests was to evaluate the effectiveness of the navigation system at:

1. Determining its position and orientation
2. Calculating distance to target
3. Calculating heading offset to target

Two waypoints were located using a handheld GPS. The waypoints (hereafter referred to as waypoints A and B) were located 50 feet apart. These waypoints were programmed into the blimp system and were marked on the ground with tape. For these tests, the Robovero was controlled via a laptop instead of the Overo. This made it easier to make program adjustments and to modify tests without needing to reprogram the Overo for every change. Using the laptop also made it possible to view the input from the sensors and the output from the navigation programs. The test program consisted of two navigation tasks: navigate to waypoint A, and then navigate to waypoint B. The test started with the gondola located approximately at the location of waypoint B. The gondola was then pushed towards waypoint A, periodically pausing and rotating the gondola. As the gondola was moved, the navigation system printed distance and heading to target data to the console. These reading were compared to the actual measured distance and heading to the waypoint. The accuracy of the navigation was found to be approximately ±3 meters in distance to target and ±5° in heading to target.

9.5. Summary

In this chapter, the design of the software structure of the blimp was discussed. The software was designed in four levels: drivers, interface, task, and mission. This chapter detailed the functionality of each level and the testing methodology used to validate the navigation functions.

Figure 56: Ground testing platform with marked waypoint

Chapter 10

10 Mission Modules

10.1 Introduction

Mission modules are the heart of the Blimp's multi-role capability. Through the use of mission modules, additional, mission-specific hardware can be combined with the blimp platform to add functionality. These modules have a two pound weight limit, must fit in the designated mission module compartment, and can interface with the main blimp systems via the mission module interface. The mission module interface consists of a fifteen pin D-subminiature connector for I/O, a USB connector, and power connections to both the 7.4V and 11.1V buses. The I/O connector contains pins for SPI, I^2C, UART, PWMs, and GPIO. Almost all devices that could be used as a mission module can utilize at least one of these interfaces. By including all of them, most mission modules can be interfaced with the main blimp platform with minimal difficulty. The I/O and USB connectors are wired directly to the corresponding I/O headers on the Robovero®.

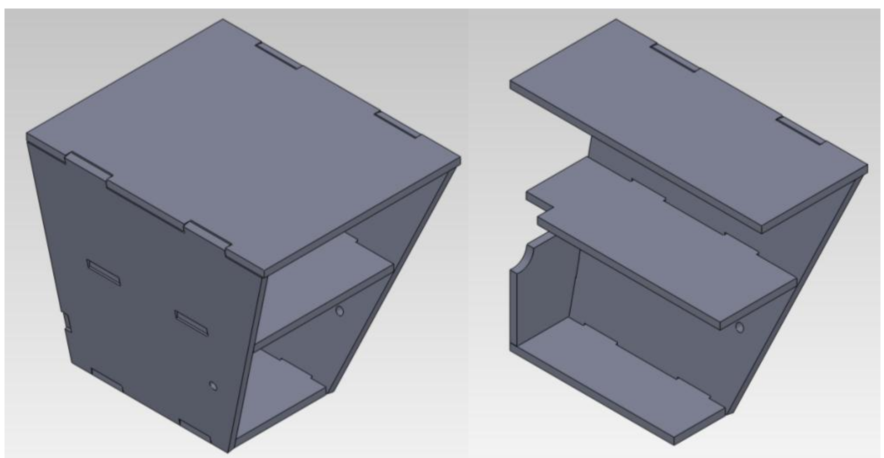

Figure 57: CAD drawing of mission module with cut-away

Three mission modules have been constructed to demonstrate the multi-role capability of the blimp. These modules include the Drop Module, the Video Module, and the Range Extension Module.

10.2 Drop Module

The purpose of the drop module was to allow the blimp to deliver packages to the ground. The drop module can be filled with medical supplies, food, a radio, etc. This can be used during a disaster or search and rescue operation to provide supplies to victims or to deliver flares or other markers to a designated point. In order to accomplish this, the drop module requires a package to contain the load being delivered to the ground and a method to release the package. In the interest of time, we found a commercially available module for this purpose. The drop module consists of an aerodynamically-shaped plastic shell with notches to attach to a servo operated release mechanism. This module uses a single PWM channel to trigger the drop.

Figure 58: Drop Module

10.3 Video Module

The video module is a self-contained mission module for streaming video wirelessly to a receiver on the ground. This can be used for surveillance, event photography, or search and rescue applications. This module is fully encapsulated. No electrical connections to the main blimp platform are necessary. To create the module, we interfaced a commercially available a 640 x 480 CMOS NSTC camera, a commercially available 5.8GHz video streaming chip, and a commercially available 5.8GHz antenna using a proto-board. This module is independently powered by four AA batteries. All of the components were mounted in a project box and attached to an adjustable truss structure (Figure 59).The wireless video streaming has a range of several hundred yards with clear line-of-sight.

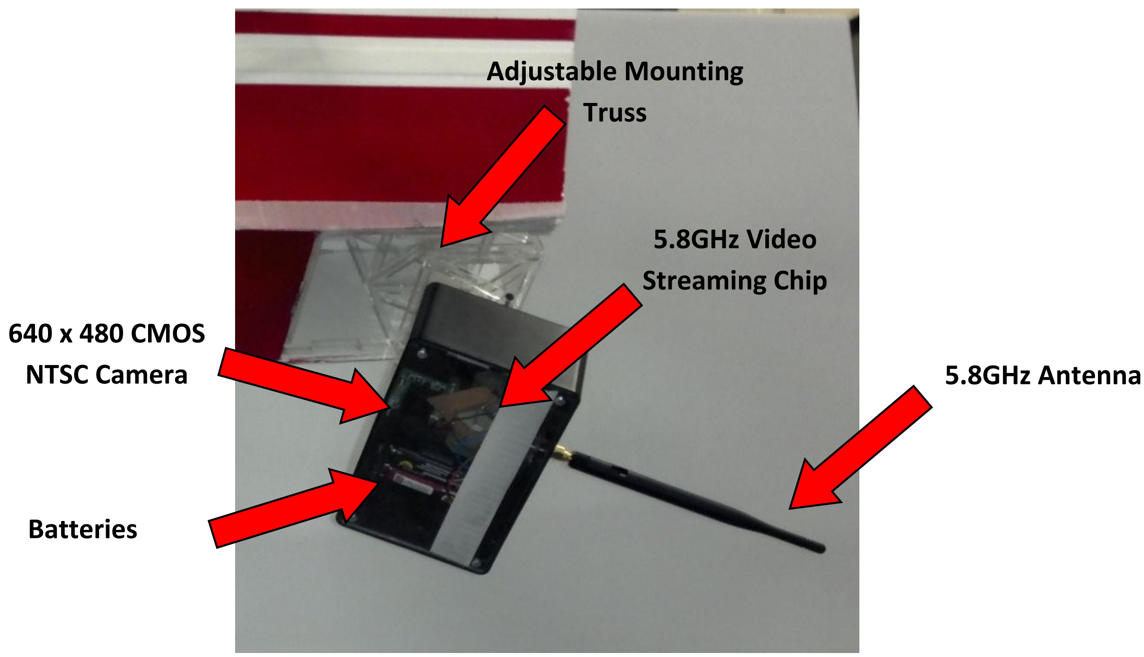

Figure 59: Video Module

10.4 Range Extension Module

The range extension module doubles the battery capacity of the blimp, in order to allow it to remain in the air for a longer period of time. The drive system energy capacity is increased from 10 ampere hours to 20 ampere hours. The control systems energy capacity is increases from 2000 milliampere hours to 4000 milliampere hours. This increase in battery capacity effectively doubles the range of the blimp. The additional batteries are connected directly to the existing 11.1V and 7.4V power buses in the main blimp. As with the main batteries, these connections have series diodes to prevent cross-charging of the batteries.

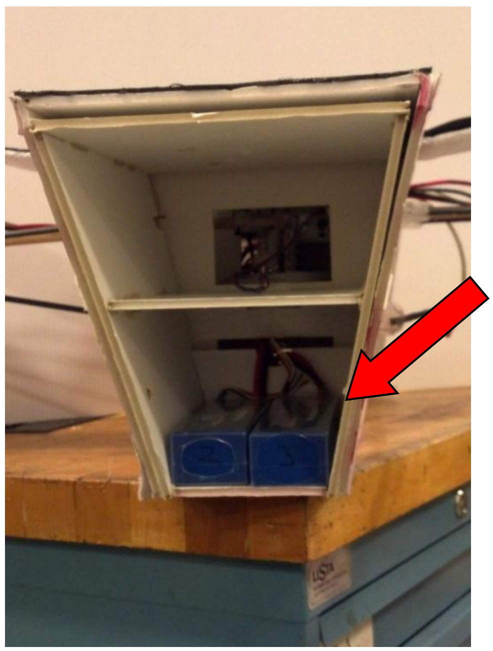

Figure 60: Range Extension Module

10.5 Summary

In this section, we discussed the rational for the mission modules and the interface that is available for the modules to talk to the main platform. We then discussed the three mission modules that were constructed for the initial demonstration of multi-mission capabilities. These were the drop module, vision module, and range extension module.

Chapter 11

11. Project Summary

11.1. Introduction

This chapter summarizes the end result of this project in terms of usable material. The end result of this project was the creation of a hardware platform, electronics system, and software for system control and navigation. A body of test data has also been established regarding a variety of factors involved in the design of the gondola, sensors, and drive system. This includes information on materials for the gondola body and axle, propeller selection, gondola mounting methods, and drive system effectiveness. We have also tested the functionality of our navigation system with a series of ground tests.

11.2. Hardware Evaluation

A body of test data was acquired regarding our design choices for the hardware. After our engines were selected, we conducted tests to determine the effects of propeller pitch and diameter on the thrust output under a variety of wind speeds. By this method, we developed thrust ratings for hobby-scale propellers and selected a propeller appropriate to our needs.

Similarly, tests were undertaken to determine the optimal material for our gondola and axle. Gondola materials were tested for deflection under three point bending and tensile strength. This established strengths for a variety of uncommon materials, including several paper/fiberglass composites. We also conducted two point bending tests on several different axle materials.

The blimp platform proved highly effective under our Standard Operating Conditions (S.O.C.), though there were significant reliability problems with our selected motors. It was shown during RC flight tests (see Appendix J: Third Flight Test and Results) that the modified drive system was highly effective in light winds as designed. It was capable of making turns within the area specified in our system requirements for holding position. It could also hold position and maneuver in 5 knot winds as specified. Unfortunately, air testing was hindered greatly by repeated failures in the motor shafts of our main drive engines. The gyroscopic forces on the motor shafts when the axle pivoted led to shaft failures. The shafts failed repeatedly at the point of attachment for the shaft C-clamp. The shafts were composed of soft iron with a thin coating of aluminum on the outside. At the time off this writing, we have purchased motors with solid shafts, but have not yet been able to evaluate their effectiveness.

Figure 61: Axle Failure

11.3. Electronics Evaluation

The electronics that were purchased and designed for this project functioned as specified; however, due to time restrictions and supply problems, not all of the original goals for the electronics system were able to be met. The power distribution system to the altimeter and GPS were fully functional and experienced no failures over 4 months of use. Similarly, the separate power distribution boards for the 7.4 V and 11.1 V systems functioned without failure over the same time period. The multiplexer board itself worked without incident; however the system had many problems with wires coming loose between tests, causing control failures. While these were sometimes problematic to troubleshoot, the need to adjust the system precluded permanent attachment.

The communication system was not fully implemented due to a lack of time for troubleshooting and difficulties with the hardware on the ground station end of the system. The USB to serial adapter that was purchased with the system was non-functional and required replacement, delaying testing and implementation. As the system was not flight critical, efforts within our limited time frame were focused in other areas.

11.4. Software Evaluation

Due to time restrictions, the software design was not fully tested. However, the aspects that were implemented were tested with the gondola separated from the shell. The lowest layer, the driver layer, was fully tested. The Robovero was shown to be capable of driving each motor at a desired percentage of its maximum speed. It was also demonstrated to be capable of reliably setting the angle of the servo. The barometric altimeter and built in magnetometer were successfully configured (as seen in Appendix G: Debugging Reports) using a driver written for the I^2C bus of the Robovero. Finally, the driver for the GPS was able to successfully read and interpret the NMEA format strings output by the GPS module.

The interface layer was limited to parsing the input from the navigation system to the motors and output from the drivers to the Robovero. The interface to the motors successfully parsed the input from the navigation system to the motors and converted them to the correct output range of the PWM for each motor. The GPS interface parsed the NMEA string to extract the relevant information. The magnetometer interface was able to parse the output from the I^2C driver to get a compass heading to an accuracy of ± 5 degrees. Similarly, the barometric altimeter achieved an accuracy of ±2 feet. Altitude measurements are taken relative to the altimeter's starting altitude.

Finally, our navigation system was able to successfully determine the bearing and range to a given GPS waypoint and could navigate to within 2m of the goal position. A proportional controller was implemented to convert the errors between goal heading and actual heading to determine the correct motor outputs; however, it was not fully tested or tuned due to time constraints.

The upper layers, task and mission, were designed to encapsulate all functionality of the blimp. However, due to time constraints, they were only tested on very simple missions (navigation between two waypoints on the ground). The wireless communications interface and instruction interpreter were also disregarded due to time constraints.

Chapter 12

12. Future Work

12.1. Introduction

While this project has created a basic platform, there is still much room for improvement and expansion of capabilities. This section describes potential future projects to be undertaken using this platform.

12.2. Power Efficiency Enhancements

In the process of creating the platform, several possible improvements to the electrical systems were noted. The Schottky diodes used for battery cross-charging protection result in a loss of about 0.4 volts. This reduces the maximum capable speed of the motors and tail rotor. If the diodes could be replaced by an equivalent system with a lower voltage drop, than this reduction in capability can be avoided. The propulsion systems could be replaced with more efficient systems that would allow the platform to last longer using less capable batteries. As discussed in Section 7.6, the best solution would be to replace the diodes with ideal diode controllers. These were not implemented in this iteration of the project due to time and budget constraints. Additionally, the 11.1V and 7.4V power buses should be replaced with printed circuit boards.

12.3. Communications System

Due to time limitations, the communications system that was initially purchased was determined to be a low priority and has not yet been installed. Since the ability to transmit telemetry to and receive data from a ground control station was one of the original goals of the project, implementing the communication system and the corresponding software could be a goal for future work. The current communication system utilizes a prebuilt radio module and has a theoretical range of several hundred yards with requisite bandwidth to transmit telemetry with sufficient margin for error. If the radio could be upgraded to better range and bandwidth, the platform would be able to communicate much more easily with the base station and would be able to communicate additional information, such as images, video, or additional data from mission modules. The ground station is currently planned to be implemented through a text based command interface; however, there are various open source projects that can provide a much more intuitive user interface if utilized.

12.4. Sensor Improvements

Sensors could also be upgraded to a higher resolution, allowing the blimp to have a greater knowledge of its location and orientation. This includes potentially upgrading to a WAAS enabled GPS or other A-GPS technologies which would have higher accuracy. If the autopilot were able to determine wind speed and wind direction, it could plan routes that would allow for more efficient movements. An example of this movement type would be moving into position so that the motors can be deactivated and the winds will push the platform to the desired waypoint. Additional sensors could be added to increase the platforms awareness of the wind conditions within its environment. These sensors could include the implementation of an airspeed sensor or the integration of the existing three-axis accelerometer and three-axis gyroscope into the navigation system.

12.5. Gondola Redesign

The original gondola was designed with only minimal concern for aerodynamics, being more focused on strength and ease of fabrication. As such, the gondola is structurally sound; however, it is not a very efficient shape for flight. If the gondola were to be redesigned for a more streamlined shape, it could be possible to reduce the effect of wind upon the platform's orientation during flight. It may also be possible to improve the axle and servo mounting mechanisms, possibly incorporating bearings and more rigid fixtures.

12.6. Drive System Improvement

There are several possible methods of improving the drive system. Control surfaces could be added to the platform's tail to experiment with their effect on pitch and yaw control. Implementing such a control scheme may allow for a more precise or responsive handling. Experimentation with alternate motors and propellers may also prove useful. The motor mounting system could be redesigned to be lighter and to better restrict motor oscillation. Finally, modifying the propulsion system to create independently pitching motor mounts has been discussed as a method of improving agility and stability.

12.7. Collision Avoidance

The platform currently has no obstacle avoidance and assumes that the individual programming the list of waypoints is 'competent' and will program a path that avoids potential collisions. This could be changed such that the platform has the ability to sense its surroundings and to take action to prevent collisions on its own. Stereoscopic imaging capability would allow the platform to detect the terrain and plan its movements accordingly, as well as locate its position given various known landmarks.

12.8. Autopilot Improvements

A major potential future undertaking would be the improvement of the navigation system using the current sensors. The current proportional only controller leaves significant room for improvement. Possible expansions of this system include implementing a full PID controller or a PD^2 controller, both of which have been used in other projects. Possible alterations of the control systems to use an inverse optimal approach like the one used by the Kyoto University team.

12.9. Android Phone Based Control

It has been proposed that the Blimp's current processor and sensor architecture could be replaced by an android phone. Using the USB host of the phone, it could be used to control the

Robovero with little to no modification. This would allow the system to take advantage of the Android's powerful processor, advanced wireless communications capabilities (WIFI, 3G/4G, Bluetooth, etc.), and its integrated sensor suite which includes a GPS, an IMU, and a barometric pressure sensor.

12.10. Mission Modules

Mission modules give the platform is multirole capabilities and versatility. During the course of the project, the team developed the range extension module, the camera module, and the drop module. Some of the roles that the blimp could fulfill, given an appropriate mission module, include:

- Search operations
- Advertising
- Disaster relief surveying
- Reconnaissance
- Radio or WIFI repeater for emergency communications
- Public address system platform
- Event photography or recording
- Swarm control station
- Navigational Aid
- Weather or environmental observation
- Alternative energy generation

12.11. Summary

In this chapter, several possibilities for future work were discussed. These possibilities include: power efficiency enhancements, communications system implementation, sensor improvements, gondola redesign, drive system improvements, collision avoidance, autopilot improvements, Android phone based control, and design of additional mission modules.

Chapter 13

13. Conclusions

In this project, an autonomous lighter-than-air platform was designed and constructed for the purpose of enabling development of navigational controllers and providing multi-mission capability through modularity. This system is a basic platform with the potential to be applied to many fields through the addition of specialized hardware and software. Through the improvement of the basic platform and the creation of additional mission modules, the utility of this project is virtually limitless. Just a few of these possibilities are discussed in the Future Work section of this paper.

Although the original goals of this project were not fully met, the basic platform is in place. With more work, this platform could be brought to its full potential as a low-power, high-endurance aerial asset. With its applications only limited to the available mission packages, this project could be a valuable resource for a wide range of tasks. This project can be modified to fit the needs of almost any situation.

Small-scale outdoor blimps are virtually unprecedented. The difficulty of maintaining position and navigating in even the slightest winds is no small feat for a lighter-than-air vehicle. This project came close to designing a system capable of such navigation. With additional time and effort put into the navigation system, this project could succeed. Time limitations and unforeseen hardware problems prevented this project from fulfilling all of its goals in time, but given additional work, those goals could be met and even surpassed.

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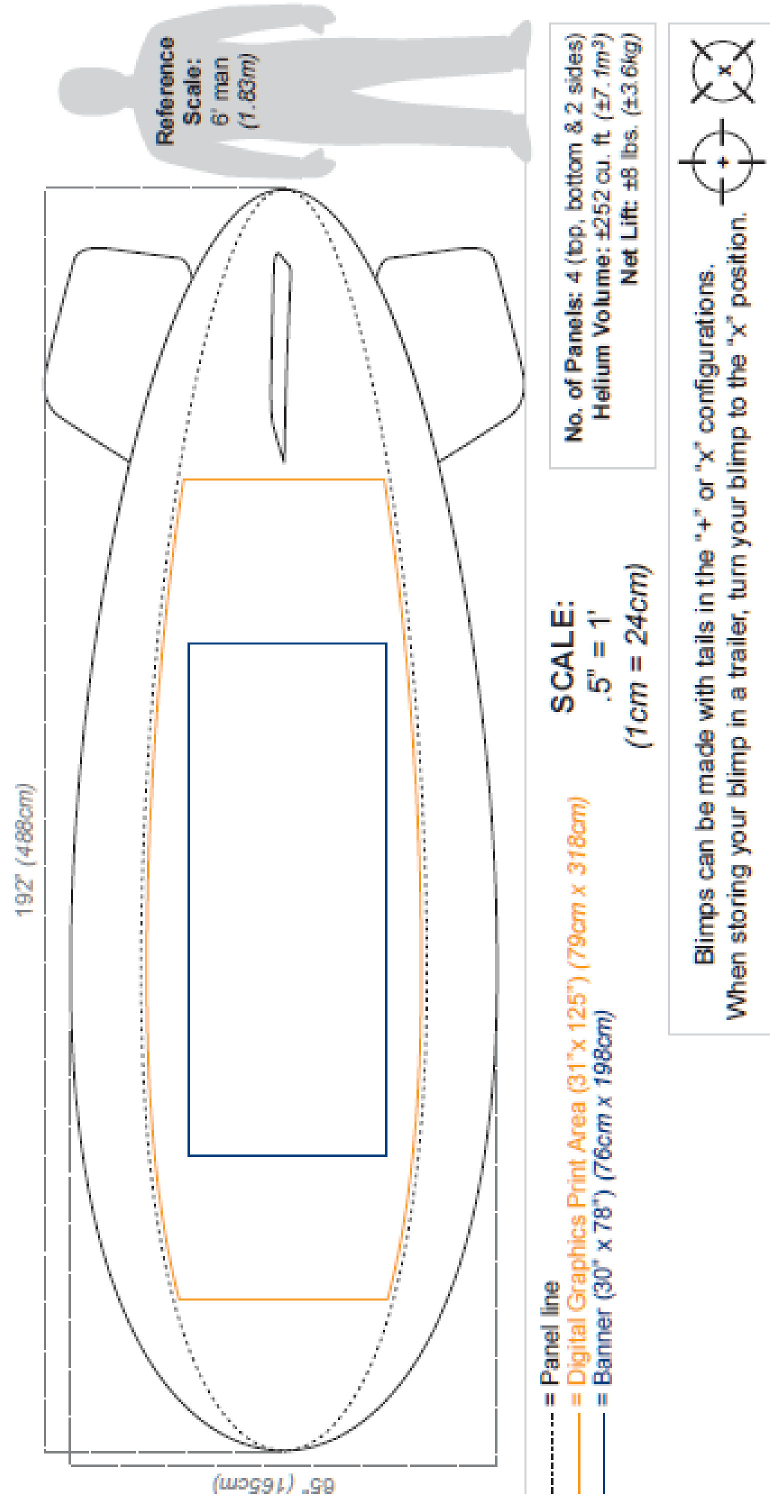
Appendix A: Shell Specification Sheet



Appendix B: Initial Fill Procedures

B.1. Required Personnel:

Requires 3 persons in the following roles

1) Control tank valve
2) Hold fill hose
3) Monitor blimp

B.2. Fill Checklist:

1) Sweep floor
2) Check for Pointy objects on the ceiling
3) FOD walk – second check for debris on floor
4) Lay down drop cloths – no shoes on drop cloths
5) Lay down blimp
6) Attach thin line to built in points and to 7.5 lbs of weights
7) Two persons will confirm that the mass relief valve is closed
8) Clear tank nozzle
9) Attach fill hose to tank
10) Attach fill hose to blimp

From this point on any call of "stop" will result in the closing of valve

11) Person two holds hose in blimp
12) Person one puts hand on valve
13) Person three calls start
14) Person one cracks tank valve
15) Person three confirms clear and signals to increase fill speed
16) Blimp fill speed increases, with flow speed regulated upwards by person three and downward by any team member
17) At person three's call of "slow", the valve is set back to the cracked position
18) Once the wrinkles are approximately 90% gone, person three will call "stop"
19) After 15 minutes, the person three will call "slow".
20) Once the weights can be easily lifted, person three will call "stop"
21) Person two will remove the fill hose and cap the fill plug
22) Person one will re-cap the tank.

B.3. Storage

1) The blimp will be tied down using the built in fill points to more than 8 pound of weight
2) The blimp will be protected with a tarp
3) There will be a paper with safety, project member, and advisor information visible in the vicinity of the blimp

Appendix C: Refill Procedures

C.1. Required Personnel:

Requires 2 persons in the following roles:

1) Control tank valve and hold fill hose
2) Monitor blimp

C.2. Refill Checklist:

1) Check for Pointy objects on the ceiling
2) Attach thin line to built in points and to more than 8 lbs of weight, with a strain gage in between
3) Two persons will confirm that the mass relief valve is closed
4) Clear tank nozzle
5) Attach fill hose to tank
6) Attach fill hose to blimp

From this point on any call of “stop” will result in the closing of valve

7) Person one holds hose to blimp and puts hand on valve
8) Person two calls start
9) Person one cracks tank valve
10) Person two confirms clear and signals to increase fill speed
11) Blimp fill speed increases, with flow speed regulated upwards by person two and downward by any team member
12) At person two’s call of “slow”, the valve is set back to the cracked position
13) Once the wrinkles are approximately 90% gone, person two will call “stop”
14) After 15 minutes, the person two will call “slow”.
15) Once the strain gage reads 7.9 lbs, person two will call “stop”
16) Person one will remove the fill hose and cap the fill plug
17) Person one will re-cap the tank.

Appendix D: Static Flight Procedures

1) The blimp will be tied by one line each to the three main installed attachment points.
2) These lines will be attached through one quick link per line to the ground.
3) A minimum of two 100 foot lines will be run from the quick link to the ground.
4) These lines will be attached on the ground to weights greater than 8 pounds staked to the ground or to fixed points.
5) The attachment points on the ground will be located on the midpoints of the sides of a square 50 feet in diameter, with the required two lines being diametrically opposed. The outer edge of this square shall be 50 feet from the nearest obstacle.

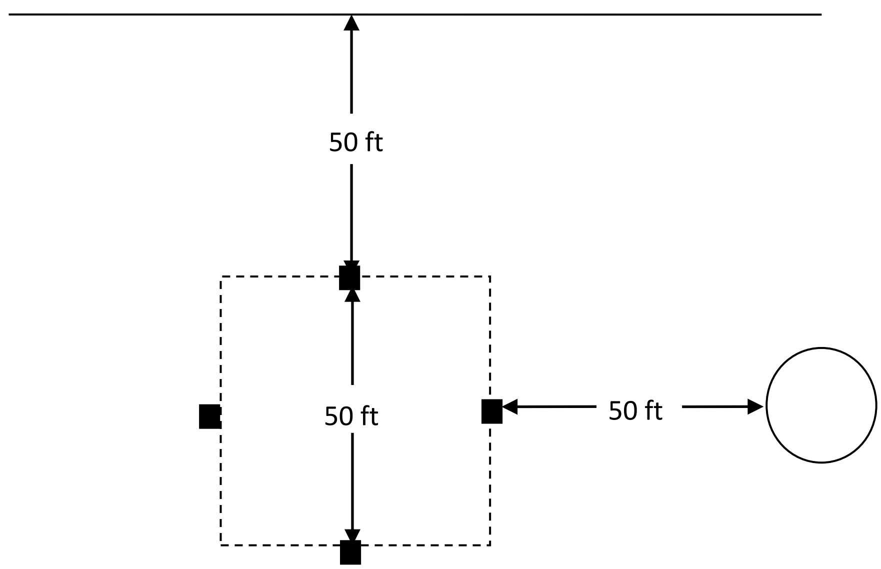


Figure 62: Layout of Anchor Points for Static Display

Appendix E: Ground Testing Procedures

E.1. Introduction

This document describes the generalized procedures for testing systems contained in the gondola while not attached to the shell. This includes the drive system, with the exception of the tail rotor, all sensor systems, and the processor subsystem. Please note, all of these testing set-ups are designed for use with a laptop in place of the Gumstix processor.

E.2. Hardware set-up

The gondola should be secured to a stationary or mobile platform as required for the testing to be conducted. For tests of the drive system, the gondola should be secured to its platform with a minimum of one strap or rope. A significant amount of weight placed on top of the gondola is also acceptable if the gondola will be stationary during the test. Acceptable platforms for mobile testing include movers' dollies, as shown in Figure 63, and rolling chairs. A mover's dolly should be the only platform used if the gondola will be moving under its own power during the test. The gondola will never be held while the drive system is powered.

Figure 63: Ground Testing Setup Example

E.3. Drive Motor Calibration

Calibration of the drive motors is a necessary step prior to any testing involving the drive motors. Calibration must be undertaken under manual control. The procedure listed below outlines the required steps for calibrating both the main drive motors and tail rotor.

1. Power on DX6i controller
2. Set to controller manual mode

3. Power on 11.1V system
4. Press throttle to full until tones sound
5. Press throttle to stop until tones sound
6. Increase throttle until propellers start moving.
7. Trim until both motors start simultaneously
8. Switch on tail rotor ESC switch
9. Press rudder to full left until confirmation tones sound
10. Press rudder to full right until confirmation tones sound
11. Center rudder until confirmation tones sound
12. Wait for ESC ready tones
13. Test tail rotor function

E.4. Test Type 1: Sensor and Processor Systems Only

Uses:

This type of testing is useful for sensor and algorithm debugging when output to the motors is not required. This included testing sensor reliability, accuracy, and interaction.

Procedure:

1. Place blimp into testing setup if desired
2. Attach 7.8V battery to 7.8V power board
3. Attach USB from computer to Robovero
4. Power on 7.8V system using switch
5. Proceed to test

E.5. Test Type 2: Drive Systems Only

Uses:

This test is intended primarily to test hardware functionality, such as a replacement motor or an alteration to the multiplexer circuit.

Procedure:

1. Place blimp into testing setup and secure
2. Attach one or more 11.1V battery to 11.1V power board
3. Turn on DX6i controller
4. Set controller to manual mode
5. Power on 11.1V system using switch
6. Calibrate drive motors
7. Proceed to test

E.6. Test Type 3: Drive, Processor, and Sensor Systems

Uses:

This test is intended as a full scale test of the blimp's ability to maneuver based on the input to the processor from the sensor system.

Procedure:

1. Place blimp into testing setup and secure
2. Attach 7.8V battery to 7.8V power board
3. Attach one or more 11.1V battery to 11.1V power board
4. Turn on DX6i controller
5. Set controller to manual mode
6. Attach USB from computer to Robovero
7. Power on 11.1V system using switch
8. Calibrate drive motors
9. Power on 7.8V system using switch
10. Proceed to test

Appendix F: Mechanical Engineering Requirements

Daniel Lanier

In fulfillment of the requirements for the degree of mechanical engineering, I have performed several aspects of this multi-disciplinary project in line with the tasks incorporated into a mechanical engineering MQP.

1. Air-resistance calculations in section 5.3
2. Propeller testing and analysis in section 6.6
    2.1. Designed and built test setup
    2.2. Conducted experiments
    2.3. Analyzed data to determine proper propeller
3. Gondola material analysis in section 8.4
    3.1. Designed and ran tests
    3.2. Developed fixtures for assembly
4. Axle material analysis in section 6.5
    4.1. Designed and ran tests
    4.2. Fabricated and installed axels
5. Drive system analysis in section 6.1-6.4
    5.1. Determined force vectors for each drive system type
    5.2. Created theoretical designs for each to evaluate potential complexity and weight
6. Main Motor mountings
    6.1. Created CAD models

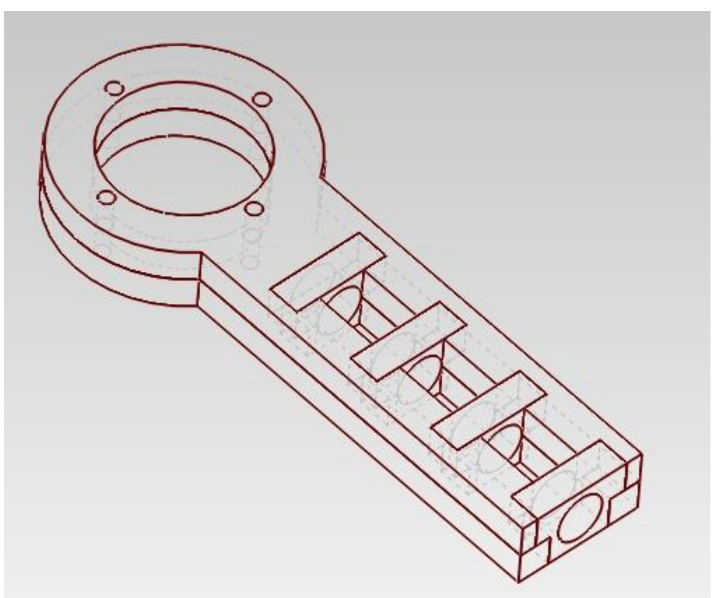


Figure 64: CAD of motor mounts

6.2. Fabricated Motor mounts and tested under load

7. Tail rotor mounting plate

7.1. Created CAD Designs

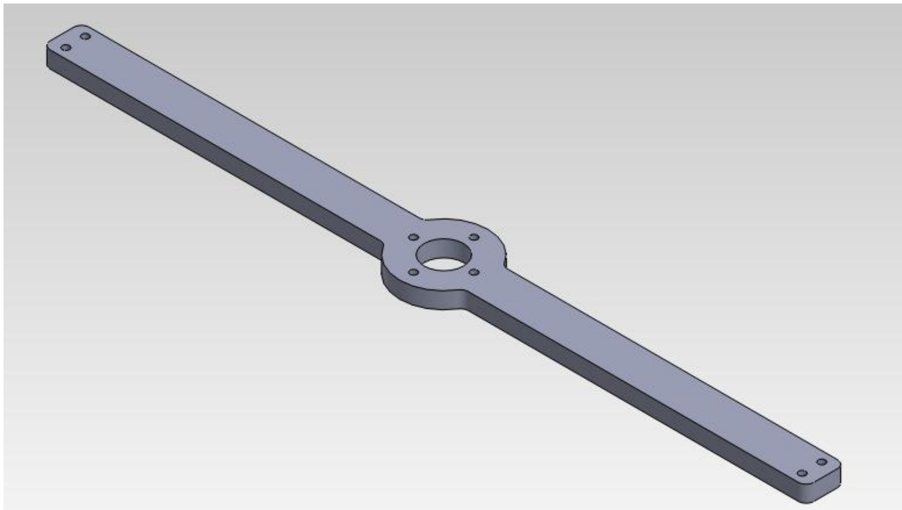


Figure 65: Tail Rotor Mounting Plate CAD Design

7.2. Fabricated plates and tested deformation under load

8. Mission module attachment plate

8.1. Created CAD designs

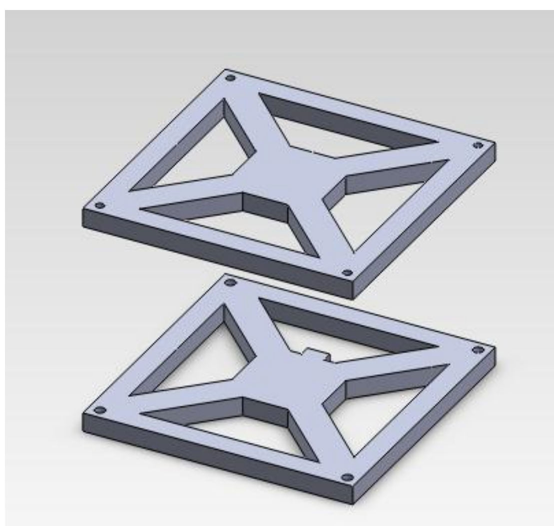


Figure 66: Mission Module Attachemnt Plate Models

8.2. Fabricated mission module attachment point and tested deformation under load.

9. Created vision module support structure

9.1. Created CAD designs

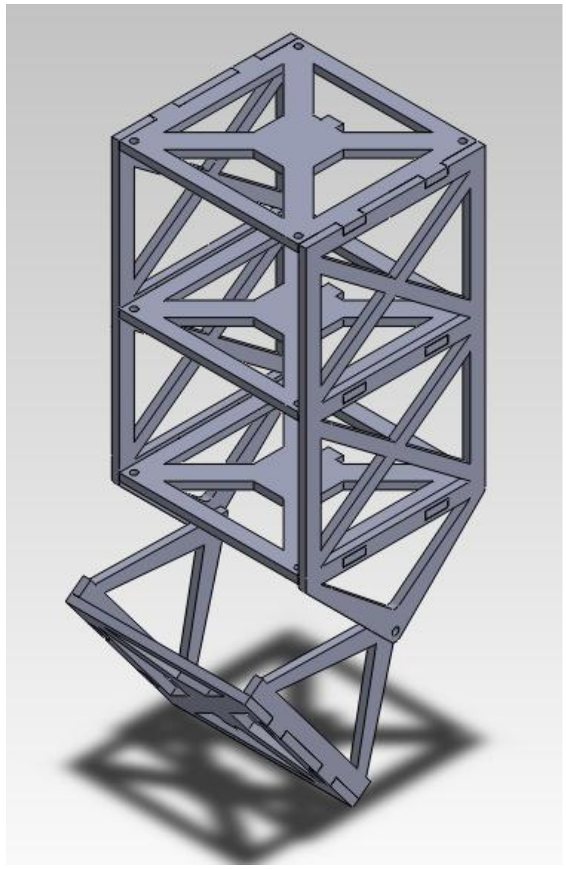


Figure 67: CAD Design of Vision System Mounting Braces

9.2. Fabricated and tested structure

10. Oscillation reduction bracing design and fabrication in section 6.8
11. Roll prevention bracing design and fabrication in section 6.9

Appendix G: Debugging Reports

G.1. GPS

The GPS (D2523T) interfaces with the rest of the system via a 9600 baud UART connection. Once the GPS is activated, it begins transmitting data over this connection in the form of NMEA strings. In order to use this GPS with the blimp system, it was connected to one of the UART ports on the Robovero. The Robovero API provides code for reading from its UART ports; however, some difficulties were encountered when trying to read the GPS. The Robovero was either receiving no data at all or random garbage data when it tried to read the GPS. In order to solve this problem, several steps were taken:

1. Check UART send pin on GPS with oscilloscope to make sure it is transmitting.
2. Check UART receive pin on Robovero to make sure the signal is making it to the Robovero.
3. Check Robovero API UART code to make sure it is working properly.

Steps 1 and 2 were completed by connecting an oscilloscope to the UART pins on the GPS and Robovero. By observing and comparing these signals, it was determined that the GPS was transmitting properly and there was no data loss between the GPS and the Robovero. This meant that the problem was most likely in software on the Robovero.

Step 3 involved examining the Robovero's API and looking at documentation and code examples regarding UART receiving. Official documentation on the Robovero is very limited; however, there are many forums in which developers discuss their problems with the Robovero. These forums are often a good place to look for solutions. Several discussions of UART receiving were found, but none provided useful solutions to our problem.

The API provides a simplified method of controlling the Robovero's peripherals. In the case of UART receiving, the UART channel is initialized with the "UART_Init" method, a receive buffer is initialized then the "UART_receive" method is called with the arguments: UART channel, receive buffer pointer, receive buffer length, and transfer block type.

The problem was eventually found to be with the "UART_configstruct" used by the API during initialization of the UART channel. Originally, the default configuration structure was being used. When a new configuration structure was instantiated with its baud rate explicitly set to 9600, the Robovero was able to read the data from the GPS.

After the GPS was issue was solved, some observations were made for future improvements. The GPS outputs NMEA strings continuously, this means that in order to read a specific message, you must read a large block of data, then post-process it to find the message of interest. This greatly slows down the process of gathering data from the GPS. It would be very useful if the GPS could be configured to output the desired string only when requested to by the Robovero. This would speed up the process of collecting GPS data and eliminate the need for a large receive buffer. The receive buffer would only need to be as long as the maximum length of the desired message rather than as long as the maximum length of the entire block of messages transmit by the GPS. It would also eliminate the need to search through the receive buffer for the desired string before parsing it.

G.2. Altimeter

The barometric altimeter (BMP085) interfaces with the Robovero over an I^2C bus. After connecting the altimeter to the I^2C bus, attempts to write configuration data to and read temperature and pressure values from the device failed. This is the same I^2C bus used by the Robovero's integrated IMU so it was known that the I^2C was functioning properly. This meant that the problem was either with the wiring of the altimeter to the bus, the software for the altimeter, or the altimeter hardware itself.

First, the wiring between the altimeter and the Robovero was examined. By observing the signals at both ends of the data and clock wires, it was determined that there was signal distortion between the altimeter and the Robovero. The wiring was redone and the signal distortion problem was solved. However, writing to and reading from the altimeter was still not functioning.

The next step was to re-examine the altimeter's software. It was found that the Robovero was only reading the first 8 bits of the 16 bit registers on the altimeter. A mathematical error was also found in the temperature compensation algorithm of the altimeter. These errors were corrected and data was successfully read from the altimeter.

G.3. Gumstix Programming Debugging Report

Upon beginning work with the Overo Water, several difficulties were encountered. First, problems were encountered when attempting to install additional required software packages on the Overo. One of the benefits of using a controller with an operating system is that software can be added without having to re-flash the entire kernel. The standard method of installing software is to use the package manager, opkg, which automatically finds the requested software on the Gumstix repository, downloads the necessary files, and installs the requested software as well as any dependencies. As the Overo Water does not have WIFI and the Robovero does not have an Ethernet connection, this method of installing software was not possible. Instead, packages had to be manually downloaded from the Gumstix repository to a host computer, copied to the Overo, and then installed with the package manager. This is a very tedious process, especially for packages with many dependencies. Initially, the only way to copy files from a host computer to the Overo was by using a microSD card to transfer the files. To facilitate file transfer, lrzsz, software package for sending/ receiving files over a serial connection, was installed on the Overo. With this software, it is possible to utilize the z-modem protocol to transfer files between the host computer and the Overo via the serial connection through the Robovero.

Second, the most significant problem encountered was the result of a poorly documented quirk of the Robovero. The Robovero can be controlled by either an external host computer or by an Overo mounted directly on the Robovero. The host computer connects to the Robovero via a USB connection. This connection allows control over the Robovero and a command line interface with the onboard Overo. Unfortunately, while the host computer is connected to the Robovero, it has exclusive control of the Robovero preventing the Overo from connecting to any of the Robovero peripherals. This makes it nigh impossible to test code on the Overo. Two solutions to this problem were presented on Gumstix forums[1]:

> *"How are you communicating with the Overo? If you have a USB cable connected, the Overo will not have access to RoboVero. Two options spring to mind:*
>
> > *1) Connect to the Overo using wireless as per Mike's instructions in this thread.*
> > *2) Use a different expansion board to host RoboVero for development then mount the Overo directly on RoboVero to deploy. This way you can have USB console access to the Overo which can control RoboVero."*

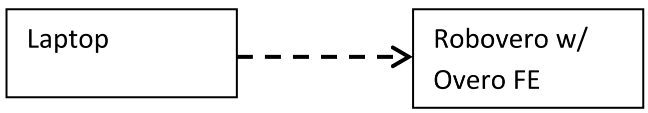
The first proposed solution required purchasing an Overo model with built in WIFI. This would have been significant expenditure, but it would have made it possible to have shell access to the Overo while it was running on the Robovero. This would have allowed real-time debugging and program modification while the Overo was running. It would also have had the added benefit of making it easier to install software as previously mentioned. Solution two was much less expensive, and only slightly less convenient. It was still possible to perform real-time debugging and program modification while the Overo is running; however, without an internet connection, the minor inconveniences would still exist. The user on the previously mentioned forum had success with option 2:

[1] http://old.nabble.com/RoboVero-td32127005.html#a32127005

"Option 2 works fine, I can access the RoboVero now. Thanks for your help."

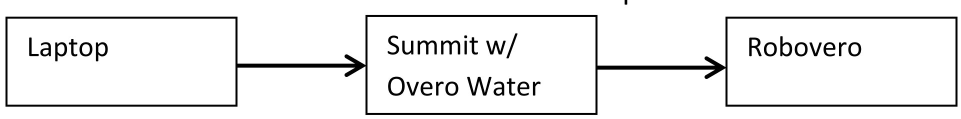
To fully implement the first solution, the following steps would have had to been taken:

1) Purchase a Gumstix Overo FE ($229.00) (https://www.gumstix.com/store/product_info.php?products_id=256)
2) Configure WIFI as described in the Gumstix wiki (http://wiki.gumstix.org/index.php?title=Overo_Wifi)
3) Connect to Gumstix wirelessly and control Robovero from Gumstix



To fully implement the second solution, the following steps would have had to been taken:

1. Purchase a Gumstix Summit expansion board ($49.00) (https://www.gumstix.com/store/product_info.php?products_id=215)
2. Use Overo Summit to host Robovero for development



3. Connect Overo directly to Robovero for deployment

In the end, solution two was chosen because it was significantly less expensive and was only slightly less convenient than option 1. It was implemented successfully and without incident.

Appendix H: First Flight Test and Results

Date: 11/18/2011

Introduction

In order for the autopilot to function, it needed to be able to assert control over the position of the blimp using the thruster system. To determine the blimp's degree of maneuverability, and thus the effectiveness of the thruster system, a series of both ground and air tests were run using manual control of the blimp. The blimp is legally required to be controllable by a remote pilot and the testing sought to determine the difficulty in remotely operating the blimp.

For the ground testing, the gondola was attached to a platform with four freely rotating casters. This simulated maneuvering on a flat plane with no vertical stabilization. In order to determine the aerial maneuvering characteristics of the blimp, the platform was flown under remote control inside a gymnasium. This allowed the evaluation of the blimp's maneuverability without the interference of wind.

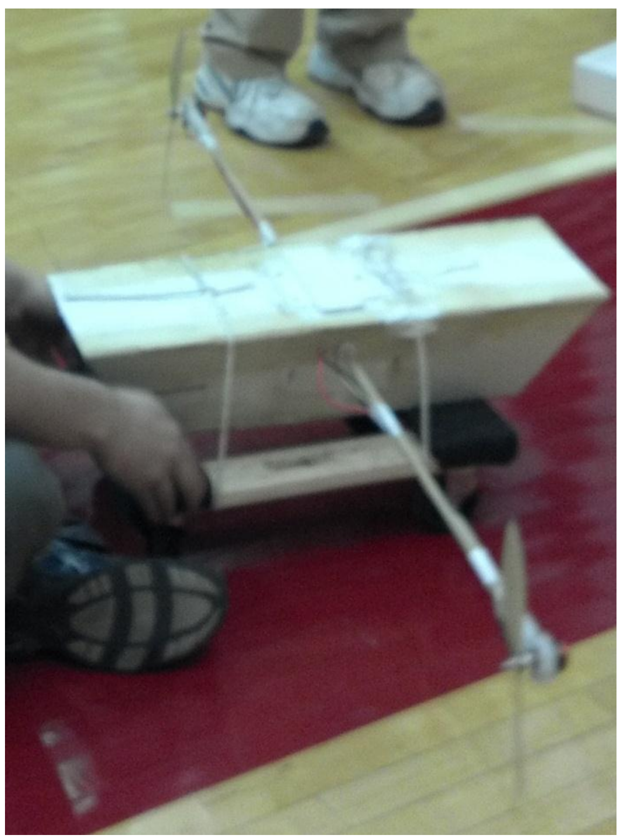


Figure 68: Ground Test Platform

Test 1: Ground-Straight Line Drive

Design:

In this test, the two motors were held level and given power at the same rate until the cart began moving. The goal was to break static friction on the wheels and proceed in a straight line. This test was designed to illustrate the complexity of maintaining a balance between the two motors and the ability of the motors to accelerate the platform.

Results:

When power was applied, friction broke unevenly, resulting in unintended launch angles. Even when these were corrected, evenly applied thrust did not result in a straight vector and constant corrections were required to maintain a straight course. When the test was repeated on a smoother surface, the corrections were less pronounced but the required power on each motor was not equal and a straight path was difficult to maintain.

Conclusions:

Differences between friction on each wheel, differing initial speed controller settings, and inconsistencies between the propellers led to the need for constant corrections to maintain a consistent heading. This may also be due to the lack of vertical stabilization on the cart, a conclusion which is reinforced by the aerial straight line drive test.

Test 2: Ground-Full Power Fixed Test

Design:

In this test, the two motors were held level and given power at the same rate while the cart was held in place. The goal was to determine the behavior of the motors at high power without needing to worry about collisions.

Results:

When power reached approximately half on either motor, that motor began oscillating on its axle. These oscillations were significant enough that the motors could not be brought to full power without striking the floor.

Conclusions:

There is a significant imbalance in the propellers, leading to oscillation when they were run up to near full speed. This will need to be corrected by balancing the propellers. Additionally, braces from the gondola to the axle will limit the range of the deflection.

Test 3: Aerial-Ascent and Descent

Design:

This test was designed to evaluate the blimp's ability to control its altitude. The propellers were tilted upwards and powered equally until the blimp gained altitude. The propellers were then tilted downwards and powered equally until the blimp lost altitude.

Results:

The blimp ascended and descended as soon as minimum power was applied. A slight pitch was induced during this maneuver, which cleared as soon as vertical movement stopped.

Conclusions:

The blimp can change altitude using its directed thrust system with no difficulty. This system for controlling altitude is effective. The pitch appears to have been due to the effects of the stabilizers and will require monitoring in the navigation algorithms.

Test 4: Aerial- Single Engine Ascent and Descent

Design:

This test was designed to evaluate the blimp's ability to control its altitude using only a single engine. This would mimic attempting the descent portion of a descending turn or an emergency descent after engine failure. The propellers were tilted upwards and powered one at a time until the blimp gained altitude. The propellers were then tilted downwards and powered one at a time until the blimp lost altitude.

Results:

The blimp ascended and descended as soon as minimum power was applied. A pitching motion was induced during this maneuver, though less than with both engines, which cleared as soon as vertical movement stopped. Additionally, a slight turn away from the powered engine was induced, as well as a very slight roll.

Conclusions:

The blimp can change altitude using only one motor of its directed thrust system with no difficulty. This system for controlling altitude is effective, even when only a single engine is used. The roll may become more significant at higher power levels and should be monitored.

Test 5: Aerial- Straight Line Level Flight

Design:

This test was designed to evaluate the blimp's ability to fly in a straight line. It evaluated the ability of the motors to accelerate the blimp, the blimp's behavior when power is applied, and the blimp's ability to hold a straight course.

Results:

The blimp moved forward in a straight line when given minimum power on each motor. The continuous application of power until the motor oscillation described above occurred (roughly half power) resulted in a significant acceleration, though exact speed measurements were not taken. The trajectory of the blimp did deflect slightly to the right at higher motor powers. When power was applied, the blimp pitched upwards slightly, but corrected back to a flat trajectory once it gained speed with only a slight increase in altitude.

Conclusions:

The blimp can perform this most basic maneuver with limited difficulty, but the motor oscillation prevented it from doing so at its full capacity. This necessitates correction of the oscillation or the limitation of axle deflection to allow greater forward movement speeds. The stabilizing effects of the tail fins and the blimp body were evident from the differences between the behavior of the blimp and the independent gondola in ground testing. The slight right turn induced at higher powers may be due to a performance difference between the two propellers and programming differences between the speed controllers. A controller that handled mixing the inputs between the two motors could remove this problem by allowing trimming to remove the difference. The lack of pitch variation does confirm that the platform is stable under acceleration, alleviating previous concerns.

Test 6: Aerial- Level Turns with Both Vertical Stabilizers

Design:

This test was designed to evaluate the blimp's ability to execute a turn with both vertical stabilizers in place. This tested the ability of the motor configuration to generate a turning moment against the resistance of both stabilizers. The test consisted of powering each motor independently with the other at zero power until the blimp began turning.

Results:

When given the most power possible without inducing motor oscillation, the blimp proved unable to execute a 180° turn in less than the length of the gymnasium. Any power applied to either engine created a forward trajectory with a slight variation away from the powered engine.

Conclusions:

The inability to alter its heading in place will be a distinct limitation when the platform needs to hold position in changing winds or setting a course. The need to turn place is a key characteristic of the platform and the inability to do so will need to be rectified before the platform can be put to outdoor use. The damping effect of the stabilizers was too great to turn against. Adding additional turning force or removing the stabilizers may prove effective in decreasing the blimp's turning radius.

Test 7: Aerial- Level Turns with One Vertical Stabilizer

Design:

This test was designed to evaluate the blimp's ability to execute a turn with a single vertical stabilizer. This tested the ability of the motor configuration to generate a turning moment against the resistance of only a single stabilizer and evaluated if there was an improvement versus having both stabilizers in place. The test consisted of powering each motor independently with the other at zero power until the blimp began turning.

Results:

When given the most power possible without inducing oscillation, the blimp's turning radius did improve. It was now able to execute a 180° turn in less than the length of the gymnasium, though it still moved forward significantly more than it turned. The blimp could still maintain a straight line course.

Conclusions:

While removing one vertical stabilizer decreased the turning radius of the blimp, it was still unable to rotate in place. This would indicate that the vertical fins provide a significant resistive force to turning.

Test 8: Aerial- Level Turns with Vertical Stabilizers Removed

Design:

This test was designed to evaluate the blimp's ability to execute a turn with no vertical stabilizers. This tested the ability of the motor configuration to generate a turning moment with only the blimp shell providing resistance and evaluated if there was an improvement versus having stabilizers in place. The test consisted of powering each motor independently with the other at zero power until the blimp began turning.

Results:

When given the most power possible without inducing oscillation, the blimp's turning radius improved significantly. It was now able to execute a 180° in less than half the length of the gymnasium. Unfortunately, the blimp's ability to hold to a straight trajectory was compromised and lateral drift became evident.

Conclusions:

While removing all vertical stabilizers produced a smaller turning radius, it led to significant difficulties with straight line flight. Removing both stabilizers is therefore not a viable method for improving maneuverability and another alternative will be needed.

Appendix I: Second Flight Test and Results

Date: 12/8/2011

Introduction

After the installation of the tail rotor, it was necessary to determine the effect that the tail rotor had on the blimp's maneuverability. To this end, the blimp's turning radius was evaluated while performing a variety of maneuvers with a variety of control inputs from both the main rotors and the tail rotor. Additionally during this testing, the motors were brought to full power in order to determine the effect of the newly installed bracing on the propeller's stability.

As the blimp was prepared, we also conducted outdoor testing during this test session. The weather conditions were not optimal for flight, with winds at 23mph, gusting significantly higher. However, we attempted to maintain controlled flight.

Test 1: Indoor – Turning without Tail Rotor

Design:

In this test, the blimp was moved to altitude, the main motors were held level, and a single motor was given power until the blimp executed a turn. The goal was to create the tightest turn possible with the given control inputs. This test was designed to establish a baseline turning radius without the input of the tail rotor.

Results:

The blimp turned in a manner similar to our previous tests, with a turning radius greater than 50 ft. Any power applied to either engine created a forward trajectory with a slight variation away from the powered engine. Both propellers could be brought to full power without deflection greater than 2 inches. The propellers oscillated slightly at around half power; however they stopped above this point, indicating resonance at this point.

Conclusions:

This turning method would be insufficient to our needs. While the main drive motors can generate significantly more thrust that our tail rotor, they are unable to apply a sufficient turning moment. Additionally, the forward speed generated in this turning method increases the stabilizing effects of the tail fins, generating a moment that counteracts the turning moment produced by the main engines. The bracing appears to be effective at reducing propeller oscillations, as we can now reach full power without inducing dangerous oscillations.

Test 2: Indoor – Turning with Tail Rotor Only

Design:

In this test, the blimp was moved to altitude, the main motors were shut down, and the tail rotor was given power until the blimp executed a turn. The goal was to create the tightest turn possible with the given control inputs. This test was designed to determine the degree of improvement in the turning radius of the blimp when the tail rotor was used.

Results:

When the tail rotor was given power, the blimp was capable of executing a slow turn in place. Power output and turning speed vary between left and right turns.

Conclusions:

The slow speed of the turn and weak nature of the thrust from the tail rotor mean that, while it can be used to pivot, there is a risk that it will not be adequate for outdoor operations. Further testing is required to determine whether or not this system is capable of making turns in an outdoor environment without assistance from the main engines.

Test 3: Indoor – Turning with Tail Rotor and Main Engines

Design:

In this test, the blimp was moved to altitude, a single main motor was turned on, and the tail rotor was given power until the blimp executed a turn. The goal was to create the tightest turn possible with the given control inputs. This test was designed to determine the degree of improvement in the turning radius of the blimp when the tail rotor was used in conjunction with differential thrust in the main engines.

Results:

The blimp turned in a radius significantly smaller than without the tail rotor, but did not turn in place. By varying the angle of the propellers, various effects were added to the turn, including diving and climbing while turning. It also became possible to execute a turn in place by using the main thrusters to slow the blimp and differential thrust and the tail rotor to turn it. When power was applied differentially to the main motors while they were in a tilted configuration, the blimp made rolls that varied up to approximately 15 degrees, depending on the difference in thrust between the two main propellers.

Conclusions:

In this configuration, the blimp was able to turn powerfully within a small radius. The roll is of concern, but can be controlled by balancing the output of the main engines when they are tilted. This appears to be the optimal turning method if maintaining position precisely is not required.

Test 4: Outdoor – Maintaining Straight Line Flight

Design:

In this test, the blimp was brought outside and launched. The goal was to steer the blimp across the quad in a straight line. Several attempts were made and the ability to abort was provided through the use of a tether. As with previous tests, control was provided through a hobby remote control transmitter and each team member attempted to pilot the blimp for the test.

Results:

The wind conditions during this test rendered straight line flight impossible. Varying wind direction made it impossible to keep the nose of the blimp into the wind. Turning using only the tail rotor was completely ineffective and the blimp drifted significantly during turns made with both differential thrust and the tail rotor.

A straight line trajectory was briefly possible during periods where the wind was coming from a single direction and there were no gusts. This was accomplished by facing directly into the wind and giving power to the engines equally and using differential thrust to compensate for slight drift.

Conclusions:

Wind conditions dictate the degree of maneuverability of the blimp almost completely. While it could maneuver in a straight line into the wind, crossing the wind at all resulted in significant drift. Additionally, this test showed that the blimp has low enough forward drag and sufficient power to fly into a high wind. However, this test has also reinforced the necessity of setting a maximum operating wind speed, due to the high wind's effect on turning and maneuvering in cross-winds.

Test 5: Outdoor – Maintaining Position

Design:

In this test, the blimp was launched outside, powered to roughly 5 meters off the ground, and controlled to remain in position above its launch site.

Results:

The blimp demonstrated excellent ability to control its altitude. However, as seen in the previous test, crossing and variable winds made it almost impossible to hold position. The changing and crossing winds made it difficult to keep the blimp's nose into the wind and none of the team members who attempted it could vary the motor power quickly or accurately enough to compensate for the changes in wind speed. In especially wide variations, the team member controlling the blimp was prone to over compensating. Several near collisions with various objects around the quad led to the termination of the test before a hover could be successfully achieved.

Conclusions:

Similar to the previous test, the wind proved too significant and variable to accomplish the goal of the test. It was theorized that a computer, with faster reaction speed and better perception, attached to an airspeed sensor or accelerometer might be better able to compensate for changing wind speed without over correcting. Additionally, more experienced pilots might be able to anticipate the wind or the blimp's reactions better and thus hold position more closely. This test will need to be attempted again in calmer wind conditions.

Appendix J: Third Flight Test and Results

Date: 12/9/2011

Introduction

After the previous series of outdoor tests, it was determined that outdoor testing would need to be repeated on a day with calmer wind conditions. The weather conditions during this test were close to our described standard operating conditions, with winds from 0 to 7 mph, with few gusts. The tests began with the repetition of the previous test series and then moved into tests of more advanced maneuvering capabilities. This test also gave the team practice operating the blimp under manual control.

Test 1: Straight Line Flight

Design:

In this test, the blimp was brought outside and launched. The goal was to steer the blimp across the quad in a straight line. Several attempts were made and the ability to abort was provided through the use of a tether. As with previous tests, control was provided through a hobby remote control transmitter and each team member attempted to pilot the blimp for the test.

Results:

The blimp was able to easily maintain a straight, level trajectory in multiple crossings of the quad. The greatest problem was correcting for crosswinds. This was done through a slight application of differential thrust, with the additional of the tail rotor in case of significant crosswinds. This resulted in either a slight "crabbing", a sideways motion, or a movement pattern that was slightly curved. In calm conditions or into the wind, the blimp maintained a straight path with minimal corrections needed. There were several incidences of turning or sudden downward movements due to the tether reaching its extents and pulling the blimp downwards. At only 1/3 power, the blimp was capable of outpacing the person holding the tether.

Conclusions:

While within standard operating conditions, the blimp's performance did not differ significantly from the pattern which we established during the indoor tests. Standard (mixed tail rotor and differential) turning was capable of compensating for drift, with minimal deviations from course. The degree of deviation could be reduced through the implementation of a computerized control system that can correct more quickly and accurately for drift. The main limit to our maneuverability was our tether. In the future, a longer tether will allow us to maneuver without this restriction.

Test 2: Maintaining Position

Design:

In this test, the blimp was launched outside, powered to roughly 5 meters off the ground, and controlled to remain in position above its launch site.

Results:

Once the blimp was facing into the wind, almost no power was required to hold the blimp in place. The slightest application of power generally resulted in forward motion in anything but the strongest wind. However, even light crosswinds pushed the blimp out of position and required correction.

Conclusions:

Similar to the previous test, the wind was our largest obstacle, but the goal could still be accomplished under manual control. It was theorized that a computer, with faster reaction speed and better perception, attached to an airspeed sensor or accelerometer might be better able to compensate for changing wind speed without overcorrecting. The tether again proved a problem when it began pulling the blimp downwards or turning it before the pilot could correct sufficiently. This can be rectified by using a larger tether in a space with more room to correct in.

Test 3: Turning

Design:

In this test, the blimp was launched, steered to a clear space, and was directed to turn. All three turning methods (differential, tail rotor only, and combined differential and tail rotor) were tested in this method, in both directions. Our testing area is shown in Figure 69.

Figure 69: The Dimensions of the Testing Area
Source: Google Maps

Results:

Differential turning produced more forward motion than rotation, as seen in the indoor tests. The blimp was able to make a 180° turn within the area of the quad in no wind conditions, but the blimp drifted outside this area while wind was present. Using this method, the blimp executed turns even in crosswinds, though not in a radius that is usable in any remotely confined space.

Turning using the tail rotor only, the blimp rotated in place. However, it could only do this in no wind conditions. In situations where a moderate amount of wind was present, the tail fins created too great of a stabilizing influence to turn against. The tail rotor could be used to face the blimp into the wind, but not in any other direction. Additionally, the blimp drifted with the wind while this turn was in progress.

The combination of differential thrust and the tail rotor produced the fastest and tightest turns of the three combinations. The blimp was capable of making a 180° turn in less than 25ft, quickly enough that there was no significant drift during the turn. There was a slight roll induced by the tail rotor, but this settled after the turn.

Conclusions:

The mix of differential thrust and input from the tail rotor produced the optimal turn for our purposes. The turn was fast enough that significant drift did not occur in the process and small enough to be feasibly useful. The slight roll will mean that our position sensing algorithms will need to account for this behavior when determining heading.

Test 4: Turning while changing altitude

Design:

In this test, the blimp was launched, steered to a clear space, and was directed to turn. The turns were executed while the two main thrusters were in a climbing configuration. This configuration was the propellers angled upwards between 45 and 90 degrees. The test was repeated multiple times, with a variety of power and angle settings.

Results:

These settings produced a much sharper turn and a much greater roll than the previous test. There was also a climb during this time. The angle of the props determined the angle of the roll and degree of climb. A 45° angle on the propellers resulted in a significant roll, between 30 and 45 degrees, but also a hard turn, almost in place. The climb during this maneuver was fairly significant, with the blimp taking a steep fore-aft pitch. A steeper propeller angle resulted in a steeper bank, a tighter turn, and less climb. The gondola also rocked from side to side relative to the shell when uneven upward thrust was provided.

Conclusions:

In this configuration, the blimp was able to turn powerfully within an even smaller radius by pointing the main engines in the direction of the turn with a bank. This lends their considerable thrust to the turning effort. Programming a computer to execute this maneuver however, may be problematic. The roll compensation in the heading sensing program will need to work with even greater rolls. The blimp will also need to be able to detect its degree of roll and balance the power to the two main engines to maintain the bank as needed and return the blimp to level flight when the maneuver is complete. The rocking of the gondola from uneven thrust also illustrated that the strap based attachment system was inadequate, allowing the gondola to shift on the blimp. This will need to be rectified in the future to improve control under uneven upwards thrust and remove the possibility of the gondola rocking until the propellers come in contact with the shell.

Test 5: Braking and Reversing

Design:

In this test, the blimp was given a forward velocity. The propellers were then reversed (turned to face 180° from forward) and given power until the blimp stopped. Power application continued until the blimp was moving in the reverse direction.

Results:

While the blimp was able to stop in a very short distance, estimated to be less than 3m, from high speed, stopping from this speed required very significant power and led to a sharp drop in the nose of the blimp. A gradual reduction in forward power and the gradual application of reverse power produced significantly better results, with the blimp slowing to a stop with limited drop of the nose under breaking. Reversing met uniformly with failure, as the slightest cross-breeze or uneven application of thrust would result in air catching on the stabilizers and spinning the blimp around. No team member could successfully reverse the blimp in an outdoor environment.

Conclusions:

Assuming the need to reverse is know in advance, the blimp performs quite well under braking. In sudden braking it fairs more poorly, however in this test some of that poor performance may have had to do with forces on the tether. Reversing may be possible with computer control, with its superior response time; however it proved extremely difficult under manual control.

Test 6: Sudden Changes in Power Output

Design:

In this test, the blimp was given a rapid forward trajectory and suddenly given a rapid change in commands. The new command set was to turn hard left with the main engines at full power and pointed up.

Results:

While executing the change, the gondola rocked severely relative to the shell. The right propeller, which was at full power due to the controller settings, impacted the shell. This induced a significant shearing force in the motor axle, causing it to shear in plane with the propellers. Either this impact or the impact of the propeller with the ground also warped the collet holding the propeller in place. The propeller flew a significant distance before hitting the ground, where it ricocheted at least 15ft before hitting a fence.

Conclusions:

This incident very nearly caused a rupture of the blimp shell and possibly the loss of the project. The ability of the gondola to move relative to the shell led directly to this accident and impairs the ability of the blimp to simultaneously climb and turn, thus it must be rectified before any further flights are made.