Guidance, Navigation and Control of a Fly-By-Wire Transport Category Airship Designed for Hover Cargo Delivery

Harshad H. Lalan
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GUIDANCE, NAVIGATION AND CONTROL OF A FLY-BY-WIRE TRANSPORT CATEGORY AIRSHIP DESIGNED FOR HOVER CARGO DELIVERY

by

Harshad H. Lalan

A Thesis Submitted to the Graduate Studies Office In Partial Fulfillment of the Requirements for the Degree of Master of Science in Aerospace Engineering

Embry-Riddle Aeronautical University Daytona Beach, Florida Spring 2011
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Harshad H. Lalan

This thesis was prepared under the direction of the candidate's thesis committee chairman, Dr. Richard "Pat" Anderson, Department of Aerospace Engineering, and has been approved by the members of his thesis committee. It was submitted to the Department of Aerospace Engineering and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering.

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Department Chair, Aerospace Engineering

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ACKNOWLEDGEMENTS

This thesis arose in part out of the last two years of research that has been done on Airship Control Systems at Eagle Flight Research Center. I have worked with a great number of people, whose contributions in assorted ways to the research and making of the thesis deserve special mention. It is a pleasure to convey my gratitude to them all in my humble acknowledgment.

First, I would like to thank Dr. Anderson for his advice, supervision and crucial contribution which have made him a backbone of this thesis. I owe my deepest gratitude to Dr. Reinholtz for all of his advice and knowledge, which have played a major role in completing this thesis. I would also like to thank Prof. Eastlake for guiding me throughout the research process.

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I dedicate this thesis to my mother and father.
ABSTRACT

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Title: Guidance, Navigation and Control of a Fly-By-Wire Transport Category Airship designed for Hover Cargo Delivery

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Degree: Master of Science in Aerospace Engineering

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The purpose of this thesis is to develop fly-by-wire pilot controls for a transport category airship propelled with six thrust vectoring engines, and to develop control laws to maintain position, heading, and attitude during hover and cargo operations. Owing to the large body area, most airships require that they be pointed into the wind to maintain their position. This research aims at controlling an airship attitude and position during hover cargo delivery, irrespective of the wind direction.

Control laws were developed for two primary modes of the airship: Flight (High Speed Mode) and Hover (Cargo Delivery Mode). Different sets of pilot controls were developed for each mode, oriented towards reduced pilot work load and simplicity of operation. A proof of concept sub-scale model of the airship was built and flown in an indoor hangar environment. An Attitude Heading Reference System (AHRS) system was implemented using Inertial Measuring Unit (IMU) and a Magnetometer. Indoor positioning of the airship was achieved using target LEDs, and applying robotic vision techniques such as motion detection, color blob analysis, and stereo vision. The developed control laws were tested during indoor flight tests, and conclusions were drawn regarding their feasibility.
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<table>
<thead>
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<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERAU</td>
<td>Embry-Riddle Aeronautical University</td>
</tr>
<tr>
<td>AHRS</td>
<td>Attitude Heading Reference System</td>
</tr>
<tr>
<td>BE</td>
<td>Bow Engine</td>
</tr>
<tr>
<td>CG</td>
<td>Center of Gravity</td>
</tr>
<tr>
<td>CSB</td>
<td>Control System Block</td>
</tr>
<tr>
<td>CV</td>
<td>Center of Volume</td>
</tr>
<tr>
<td>ERAU</td>
<td>Embry-Riddle Aeronautical University</td>
</tr>
<tr>
<td>GPS</td>
<td>Ground Positioning System</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>IMU</td>
<td>Inertial Measuring Unit</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>PA</td>
<td>Port Aft</td>
</tr>
<tr>
<td>PF</td>
<td>Port Forward</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional, Integral and Derivative</td>
</tr>
<tr>
<td>SA</td>
<td>Starboard Aft</td>
</tr>
<tr>
<td>SF</td>
<td>Starboard Forward</td>
</tr>
<tr>
<td>TE</td>
<td>Tail Engine</td>
</tr>
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</table>
## NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>$\alpha$</td>
<td>Angle of attack</td>
</tr>
<tr>
<td>$f_c$</td>
<td>Focal Length</td>
</tr>
<tr>
<td>$c_c$</td>
<td>Principal Point</td>
</tr>
<tr>
<td>alpha_c</td>
<td>Skew Coefficient</td>
</tr>
<tr>
<td>$k_c$</td>
<td>Distortions</td>
</tr>
<tr>
<td>$x_n$</td>
<td>Normalized (pinhole) image projection</td>
</tr>
<tr>
<td>$d_x$</td>
<td>Tangential Distortion Vector</td>
</tr>
<tr>
<td>KK</td>
<td>Camera Matrix</td>
</tr>
<tr>
<td>O</td>
<td>Origin</td>
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1. INTRODUCTION
The purpose of this thesis is to develop fly-by-wire pilot controls for a transport category airship. Airships in general have a large surface area, and, as a result, are very hard to control in windy conditions. Today, one of the most sought-after applications of airships is to use them for transporting cargo over long distances and harsh terrain. While loading/unloading certain cargo, it’s essential that the airship maintains its position and direction, irrespective of the weather conditions. This research focuses on developing control laws to control such an airship and test these control laws on a proof-of-concept sub-scale model. A brief history of airships and various systems used in this thesis is provided below.

1.1 History of Airships

1.1.1 Birth of Lighter-than-air Flight
Any history of the airship must start with the birth of lighter-than-air travel. This leads us to Roger Bacon, an English scholar of the 13th Century. He set forth a strategy for human powered flight that involved lifting a man with a structure “filled with the thin air of the upper atmosphere, or with liquid fire, thus rising high into the heavens.” This is the first recorded theory for lighter than air travel.

In 1783, two French brothers, Jacques Etienne and Joseph Michel Montgolfier, invented the hot-air balloon and sent one to an altitude of 6,000 ft (1,800m). Later that year, the French physicist Jean Pilatre de Rozier made the first manned balloon flight. While balloons could travel to high elevations, they could not travel on their own propulsion and were at the mercy of the prevailing winds. The attempt to control the direction and velocity of these balloons led to the birth of the “Airship.”

1.1.2 Birth of Airships
An Englishman named Baron Scott first laid down an airship design in 1789. The design included two ballonets that could inflate and deflate to control the attitude of the airship. In 1843, Monk Mason of Great Britain made a model of an airship powered by a clockwork engine, and
attained speeds of several miles per hour. An Austrian named Paul Haenlein built the first full sized powered dirigible ship and flew it on December 13th, 1872. A year later, Count Ferdinand von Zeppelin designed the first airship with separate gas cells, all filled with hydrogen. This became the trademark of Zeppelin designs until the last ship was produced. The first airship he built, LZ1, was a failure. The twin 16 HP engines did not have enough power to overcome strong winds. The second airship, LZ2, was better designed, and had an even more powerful propulsion system. LZ2 was destroyed in an overnight storm. LZ3 was the first successful airship, and flew on October 9th, 1906. The LZ3 was designed based on lessons learned from the mistakes of LZ1 and LZ2 and received orders from the German military. Zeppelins were used in the First World War as the first long range bombers. The Zeppelins were also used extensively for transportation of armament to German troops at the frontline. At the end of the First World War, the Zeppelins were destroyed or given as war reparations.

1.1.3 The Golden Age
The golden age of the airship started after the First World War, when many of the allied nations decided to invest in building airships. The golden age is marked by some of the very famous airships such as the Shenandoah, the Los Angeles, the Graf Zeppelin, the Akron, the Mason, and the Hindenburg. The Shenandoah was a US navy aircraft career of the sky and the first rigid airship built in the United States. The Shenandoah was destroyed in a storm killing 14 crewmen. The Los Angeles was then the only airship under the US arsenal after the Shenandoah was destroyed. The Los Angeles used Helium for safety and was the only airship to survive until decommissioned in 1939. The Graf Zeppelin (LZ128) made its first flight on September 18th, 1928. It was the first airship to go around the world in 21 days, and logged more than one million miles of flight. The success of LZ128 led to the development of even bigger airship, the Hindenberg. The Akron and the Mason were two military airships, built by Goodyear and Zeppelin respectively. The USS Akron served as a flying aircraft carrier, launching Sparrowhawk biplanes. On May 6th, 1937, the Hindenburg burst into flames while landing at Lakehurst, New Jersey. The accident killed 35 people, marking the end of the Golden Age of airships. Although the disasters of airships are highlighted, non-rigid airships have by far the best safety record of any type of flying vehicle.
1.1.4 Modern Use of Airships
Because lighter-than-air gas provides the lift in an airship or blimp, rather than a wing with an engine as in an airplane, airships can fly and hover without expending fuel or energy. Furthermore, airships can stay aloft anywhere from hours to days; much longer than airplanes or helicopters. These properties make them ideal for such uses as covering sporting events, advertising, and some research, such as scouting for whales.

Recently, there has been renewed interest in using rigid airships for lifting and/or transporting heavy cargo loads—like ships, tanks, and oil rigs—for military and civilian purposes. Modern airships, such as the Zeppelin NT and CargoLifter, use lightweight, carbon-composite frames that allow them to be huge, light and structurally sound. There has been a large standing need in both commercial and governmental applications for airships that can pick up very large, indivisible objects and transport them over long distances. In certain areas, such as Alaska and Canada, harsh arctic conditions and the lack of transportation infrastructure frustrate development. Airships represent a unique solution to many of these transportation challenges.

1.2 Fly-By-Wire Control Background
A fly-by-wire system is an electronic interface that substitutes the traditional mechanical and hydraulic flight controls. Instead of mechanical linkages between the pilot controls and actuators, the pilot commands are converted into digital signals transmitted by wires to the actuators. Fly-by-wire systems considerably reduce weight and complexity.

Controlling actuators using electronic signals was first tested in the 1950s. The first non-experimental aircraft to fly with a fly-by-wire flight control system was the Avro Canada CF-105 Arrow in 1958. [1] The first digital fly-by-wire aircraft to fly was an F-8 Crusader in 1972, which was modified by NASA as a test aircraft. The same concept was employed by the USSR in the Sukhoi T-4, and by the United Kingdom in the Hawker Hunter. During 1984, the Airbus
A320 became the first airliner to fly with an all-digital fly-by-wire control system. In 2005, the Dassault Falcon 7X became the first business jet to use a fly-by-wire flight control system.

1.3 Stereo Vision Background
Stereo vision is one of several techniques in which we recover depth information from two images that depict the scene from different perspectives. The theory of depth from stereo has been well understood for years, while the engineering challenge of creating a practical stereo sensor has been formidable. Stereo vision has a lot of applications in automated systems and robotics. It is mostly used for range sensing, object recognition, contour maps, etc. There is no standard formulation of how computer vision problems should be solved. There are many methods available for solving various well-defined computer vision tasks, where the methods often are very task specific and seldom can be generalized over a wide range of applications. Many of the methods and applications are still in the state of basic research, but more and more methods have found their way into commercial products.
2. SCOPE AND APPLICABILITY

2.1 Sign Conventions

A positive sense of directions and rates are specified and used throughout the design process. As far as practically possible, the same conventions have been kept as used for general aviation. The following figure shows the positive sense of direction, rates and surface deflection. From the figure looking out the cockpit: a roll to the right, pitch up, and yaw to the right are considered positive.

The X, Y, and Z axis meet at the Center of Volume (CV) contrary to the Center of Gravity (CG), which is normally used for general aviation airplanes. Since the propulsion system will be thrust vectored, their positives are also defined. The thrust of the tail lateral propeller is considered positive in the '+Y' axis direction. The following figure shows the positive sense for the engine swivel in the XZ plane.
The following figure defines the datum used. From the figure, the XY Datum is defined as 100 feet below the bow stern center line. The YZ Datum is located at the nose of the airship and the XZ Datum passes through the center of the airship.
2.2 Structural Setup

The following tables list some of the basic dimensions of the proposed Single-Hull Airship, and those of the proof-of-concept model.

**Table 1: Dimensions for the Single-Hull Configuration**

<table>
<thead>
<tr>
<th></th>
<th>Metric</th>
<th>English</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>168.25 m</td>
<td>552 ft</td>
</tr>
<tr>
<td>Maximum Diameter</td>
<td>33.53 m</td>
<td>110 ft</td>
</tr>
<tr>
<td>Total Volume</td>
<td>112,049.76 m$^3$</td>
<td>3,957,000 ft$^3$</td>
</tr>
<tr>
<td>Total Weight</td>
<td>50 metric tons</td>
<td>110.231 lb</td>
</tr>
<tr>
<td>Max Payload Weight</td>
<td>60 metric tons</td>
<td>132,277 lb</td>
</tr>
</tbody>
</table>

**Table 2: Dimensions for the Sub-Scale Model**

<table>
<thead>
<tr>
<th></th>
<th>Metric</th>
<th>English</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>4.27 m</td>
<td>14 ft</td>
</tr>
<tr>
<td>Maximum Diameter</td>
<td>0.6 m</td>
<td>2 ft</td>
</tr>
<tr>
<td>Total Volume</td>
<td>1.25 m$^3$</td>
<td>44 ft$^3$</td>
</tr>
<tr>
<td>Total Weight</td>
<td>2950 grams</td>
<td>6.5 lb</td>
</tr>
<tr>
<td>Max Payload Weight</td>
<td>453.6 grams</td>
<td>1 lb</td>
</tr>
</tbody>
</table>

On the full scale proposed airship, the envelope and the engines are supported by a triangular internal frame as shown in figure 4. For the sub-scale model, the same triangular concept is used to support the motors, but, to simplify the building process; the envelope is placed inside the triangular structure.

![Figure 4: Engine Location in the YZ plane](image-url)
2.3 Propulsion Setup

A total of six engines are required to meet all maneuver and power needs of the airship. The general arrangement of these six engines is shown in figure 5 and their labels are shown in table 3.

![Figure 5: Engine ID and Locations](image)

### Table 3: Engine Identification

<table>
<thead>
<tr>
<th>Engine No.</th>
<th>Engine ID</th>
<th>Engine Location</th>
<th>Swivel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PFE</td>
<td>Port Forward</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>SFE</td>
<td>Starboard Forward</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>PAE</td>
<td>Port Aft</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>SAE</td>
<td>Starboard Aft</td>
<td>Two-Axis Gimbals</td>
</tr>
<tr>
<td>5</td>
<td>TE</td>
<td>Tail</td>
<td>Single-Axis Gimbals</td>
</tr>
<tr>
<td>6</td>
<td>BE</td>
<td>Bow</td>
<td></td>
</tr>
</tbody>
</table>

As shown in the above table, two types or engines are used on this airship:

1) Main Engine X 4

2) Tail/ Bow Rotor
The four main engines are located at 25% and 75% of the length of the airship hull. The further away the engines are from the CG of the airship, the more effect their thrusts have on the airship moment. This helps provide quick and very effective control of pitching and yawing moments. On the other hand, the large structure also results in the bending and warping of the structure. This results in error in the effective trust lines of these engines. For the purpose of this study, this effect is ignored.

Each engine is a pusher type of system, as opposed to a puller system. Hence, the propellers in the figures are shown facing aft. In this configuration, a single propeller engine is mounted in a dual gimbals system. This configuration allows using one propeller setup to provide thrust in all directions. This reduces mechanical complexity while improving maneuverability. Figure 6 shows the two-axis gimbals as applied on the sub-scale model.

Figure 6: 2 Axis Gimbals System
2.4  Pilot Controls
The pilot controls are designed to provide maximum control of the airship while minimizing pilot load. The controls are designed to be simple and intuitive. A Saitek Aviator Joystick was used to control the airship, as shown in figure 7. The airship controls in hover and low speeds depict that of any conventional helicopter and at high speeds; the airspeed controls depict a conventional aircraft. As a result, there are two basic modes of the airship that will be discussed in detail in later sections.

![Figure 7: Saitek Aviator Joystick](image)

2.5  Mission Profile
The proposed airship is designed to have a cruising speed of 55 knots and a maximum forward speed of 75 knots. During cargo loading/unloading, it should be able to withstand winds of 20 knots in all directions. These requirement forms the basis of the control law design. This mission profile is best illustrated by figure 8.
2.6 Model Assumptions

The following assumptions were made for the purpose of this study.

1) The sub-scale model will be flown in an indoor hangar environment where the airspeed will never be more than 20 knots. Hence, all the aerodynamics effects will be ignored including envelop shape, control surface effects, etc.

2) The model will be assumed to be rigid, thus ignoring the warping and bending of the structure.

3) Ballonets will not be installed and their effects will be ignored.

4) Helium pressure will be arbitrary, and will not be actively controlled.

5) Effects of temperature and altitude on the helium lift will be ignored.

6) Control laws are designed for a slightly negative buoyant airship.
3. METHODS

3.1 Top Level Design

The general structure of the entire system is shown in figure 9.

![Figure 9: Top-Level System Architecture](image)

The Control System is implemented in the Simulink environment. It receives attitude information from the on-board Attitude Heading Reference System (AHRS). The 3D position of the blimp is provided by the stereo-camera system. The user commands are received through the joystick. The Graphical User Interface (also implemented within Simulink) displays blimp position, attitude information, engine positions, and power settings to the user. The servo and motor control laws are transferred to the blimp wirelessly.

Each of the above sub-systems and their processes are discussed in detail in the following sections.
3.2 Control System Block (CSB)

The primary objective of the Top Level Control System Design was to accommodate the specific mission profile requirement described in section 2.5. To meet the forward velocity requirements, thrust from all engines is required to overcome the airship drag forces. During cargo operations, the hardest task for the airship is to maintain its position during strong cross winds. Owing to these requirements, three different regime of airship operations are considered as shown in table 4.

<table>
<thead>
<tr>
<th>Table 4: Airship Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-20 \text{ knots} \geq \text{airspeed} \geq 20 \text{ knots})</td>
</tr>
<tr>
<td>(20 \text{ knots} &gt; \text{airspeed} &gt; 35 \text{ knots})</td>
</tr>
<tr>
<td>(\text{airspeed} \geq 35 \text{ knots})</td>
</tr>
</tbody>
</table>

The control laws are primarily written for low speed and high speed regime only. In the transition speed regime, both the low speed and high speed regime control laws are used. The effectiveness of low speed/high speed control laws in the transition regime depends on the indicated airspeed and is governed by the lookup table 5.

<table>
<thead>
<tr>
<th>Table 5: Mode Selection Lookup Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airspeed(knots)</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>-20</td>
</tr>
<tr>
<td>-15</td>
</tr>
<tr>
<td>-10</td>
</tr>
<tr>
<td>-5</td>
</tr>
<tr>
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<td>35</td>
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<td>40</td>
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</tbody>
</table>
For the sub-scale model, airspeed is irrelevant as mentioned in section 2.6. Hence the change of modes is governed by a manual switch, as opposed to being airspeed dependent. Also, the transition block is not implemented for the subscale model.

The following figure shows the implementation of the Control System Block as discussed. The FCS block includes three main sub-systems:

1) Low Speed Mode Sub-system (orange)
2) High Speed Mode Sub-system (cyan)
3) Mode Selector (green)

Figure 10: CSB Top-Level Design
3.2.1 Low Speed Sub-system (CSB)

This sub-system has various controls for airship at low speeds and hover mode. At low speeds, there is not enough dynamic pressure on the control surfaces to provide control power. Hence, the fins are locked out. All the control actuation is provided by the four main engines, the tail, and the bow engines. The following figure shows the basic logic implied by this sub-system.

![Diagram](image)

**Figure 11: Low Speed Control Logic**

The pilot controls in this mode mimic the controls of a helicopter. The basic maneuvers augmented by joystick in this mode are shown in figure on the following page. In this mode, autopilot is engaged for pitch stabilization and roll stabilization. Hence, the airship maintains level attitude at all times.
In this mode, all the main engines point in the positive Z direction by default. Following joystick command, all motors point thrust in the same direction at a fixed thrust rating.

### 3.2.2 High Speed Sub-system (CSB)

The high speed control laws are applied at speeds higher than 35 knots and partially implemented during the transition regime (20 knots to 35 knots). The high speed control laws are designed to make the airship behave and control like an airplane. In high speed mode, the engines are primarily used for forward thrust and fins are used for actuation as shown in the logic diagram on the following page. In this mode, all motors point thrust in positive X direction by default. Roll and pitch stimulation is achieved by differential thrust.
To test the high speed control laws at low speeds using the sub-scale model the fin actuation is generated by differential engine thrust. For example, to achieve pitch up attitude the two forward engines are rotated along Z axis while keeping the rear engines pointing in the positive X direction.
3.2.3 Roll Stabilization

In low speed mode, no pilot input is available to change the roll attitude of the airship. In high speed mode, roll stabilization can be manually turned on/off. For roll stabilization, the controller receives airship bank angle from the processed IMU data. Figure 15 shows the controller logic. The gain values shown in figure 15 were experimentally adjusted for best performance.
3.2.4 Pitch Stabilization
Similarly, the pitch controller is always activated in low speed mode, and can be manually activated in high speed mode. The basic controller logic and associated gains are shown in the figure below.

Like the roll controller, direct pitch control of the airship is not available. The Pitch Controller acts as the Pitch Hold Control.

3.2.5 Position Hold Sub-system
The primary task of this sub-system is to hold the position of the airship during hover cargo operations. This sub-system receives the difference in commanded position and actual position, also known as position error. This position error is already converted into airship body reference system. For the airship to hold its position, all airship engines need to be pointed in the appropriate direction that would bring the airship back to its commanded hold position. At the same time, the main engines throttles need to be appropriately adjusted so that the airship doesn’t overshoot the target hold location.

The position hold command is activated by a button on the joystick. The signal from this button alternated between 0 (not activated) and 1 (activated). The following block shows the logic for controlling the engine throttle. Depending on the joystick command, the ‘IF Block’ alternates between activating and deactivating position hold.
When the position hold command is active, the position error is first converted into a range value. A PID controller is then used to regulate the throttle output based on the distance of the current airship position from the target position. A dead zone of 2 ft is also implemented which avoids confusion when the target location is acquired. When the position hold is deactivated, there is no effect on the engine throttle.

At the same time, the appropriate thrust vector for each main engine is also calculated as shown in figure below. Based on the status of the position hold command, the subsystem either outputs direct pilot commands or the calculated position correction vector.
3.2.6 Heading Hold Sub-system

The onboard magnetometer facilitates the need to hold a particular magnetic heading. The airship yaw is only controlled by the bow and tail engines. Only the bow and tail engines are used as they provide the maximum moment because of their further distance from the center of gravity. The heading hold subsystem first calculates the heading error and then creates an appropriate feedback control to capture the desired heading. The top level heading block is shown below:

![Heading Hold Block](image)

The airship heading is calculated by the AHRS sub-system. The target heading is adjusted by the user using the joystick. The target heading is adjusted in five degree increments using the ‘+’ and ‘-’ symbols.
‘-’ keys on the joystick. This is achieved by a counter that is connected to the joystick input. The heading error is simply the difference between the actual and target heading. There is a ten degree hysteresis designed into the system to reduce heading confusion. When heading error is within the hysteresis range, the heading error computations are removed and replaced by the yaw signal from the joystick. This implementation is shown in the figure below:

![Figure 21: Heading Hold Sub-System](image)

The above system also calculates the shorted travel to the target heading. Based on this calculation, the motors either create a positive or a negative yaw moment. A PID controller is then used to regulate the throttle of the bow and tail motors. The PID controller is adjusted to create a critically damped system.

### 3.2.7 Ballonet System

This airship is also designed to use dynamic lift and thrust to control altitude of the airship. The buoyancy of these airships is controlled by controlling the ballonet volumes within the airship. Ballonets also help maintain the shape of the envelope by automatically adjusting themselves with changing altitude. The internal pressure within the airship envelop is maintained at a slightly higher pressure than the corresponding outside atmospheric pressure. This helps to maintain tension in the airship envelop and maintain its hull shape. As the altitude of the airship
increases, the temperature of the atmosphere drops and the volume of the helium increases. Alongside, the outside atmospheric pressure also decreases. Hence, the volume of the ballonets is adjusted to account for the change in outside pressure. Ballonets are automatically controlled by the flight control system to maintain a constant pressure differential by changing the ballonet volumes. This requires the pressure and altitude feedback into the control system.

A higher internal pressure will be maintained in severe weather conditions (rain, ice, thunderstorm) to increase tension of the envelop fabric and maintain hull shape. Also, as the airspeed of the airship increases, the internal pressure will be slightly increased to avoid the nose of the airship from denting inwards.

The ballonets are also used for static pitch and roll trim. The ballonet trim controllers are designed for both manual and automatic control. In the automatic mode, the ballonet trim chase the control surface deflection eventually releasing all the pressure of the control stick. To avoid the controller chase, the ballonet trims can be controlled manually using the trim wheels. The response times for the ballonets are generally slower than the fin response and therefore they are mainly used for sustained attitude requirements.

The sub-scale model does not have ballonets installed so this part of the control system is not activated.
3.3 Graphical User Interface (GUI)

The graphical user interface has two main displays. Figure 23 shows the position, orientation, and the thrust of the four main engines. Figure 24 shows the attitude (roll and pitch) of the airship. These two displays are created in Simulink animation blockset.
The third component of the display sub-system is the instrument cluster, as shown below. The instrument cluster contains objects such as digital roll, digital pitch, analog heading, bow, and tail motor thrusts.
3.4 Servo and Motor Command

The control vector is the main bus of the system. The control vector passes through all the control logic and carries the actuation commands for the servo and motors. The control vector components and description is shown in the following table:

**Table 6: Servo and Motor Command**

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fin_1</td>
<td>Angle for aerodynamic surface 1</td>
</tr>
<tr>
<td>Fin_2</td>
<td>Angle for aerodynamic surface 2</td>
</tr>
<tr>
<td>Fin_3</td>
<td>Angle for aerodynamic surface 3</td>
</tr>
<tr>
<td>Top_Port_Throttle</td>
<td>Thrust for front left engine vector</td>
</tr>
<tr>
<td>Top_Port_Vector</td>
<td>Three component angles that define the thrust line for the front left engine</td>
</tr>
<tr>
<td>Top_Starboard_Throttle</td>
<td>Thrust for front right engine vector</td>
</tr>
<tr>
<td>Top_Starboard_Vector</td>
<td>Three component angles that define the thrust line for the front right engine</td>
</tr>
<tr>
<td>Bottom_Port_Throttle</td>
<td>Thrust for aft left engine vector</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Bottom_Port_Vector</td>
<td>Three component angles that define the thrust line for the aft left engine</td>
</tr>
<tr>
<td>Bottom_Starboard_Throttle</td>
<td>Thrust for aft right vector</td>
</tr>
<tr>
<td>Bottom_Starboard_Vector</td>
<td>Three component angles that define the thrust line for the aft right engine</td>
</tr>
<tr>
<td>Bow_Throttle</td>
<td>Thrust for bow engine</td>
</tr>
<tr>
<td>Bow_Vector</td>
<td>Three component angles that define the thrust line for the bow engine</td>
</tr>
<tr>
<td>Tail_Throttle</td>
<td>Thrust for tail engine</td>
</tr>
<tr>
<td>Tail_Vector</td>
<td>Three component angles that define the thrust line for the tail engine</td>
</tr>
</tbody>
</table>

This information is then converted into hex format and grouped in packets. These packets are then transmitted wirelessly to the airship. The following figure shows a glimpse of this implementation.

![Diagram of Command Packets]

**Figure 27: Command Packets**

### 3.5 Joystick (User Input)

A Saitek Aviator joystick is used to provide user input into the system. The joystick is connected using a standard USB connection. Using the joystick block from the Aerosim Blockset library,
all signals are easily extracted to Simulink. These signals are then used generating control signals.

Figure 28: Joystick Interface

3.6 Navigation/Position Solution
The primary purpose of this sub-system is to calculate the 3D position of the airship inside the hangar. This sub-system also calculates the position error of the airship between the actual and the target position. The calculated position error then goes through a series of axis transformations to convert the data in terms of the airship body reference system.

The airship is flown in an indoor hangar environment, where a standard GPS device will have no range. To circumvent this problem, position through Stereo Vision is considered. For a stereo vision system, two cameras placed at a known location and orientations are used. These two cameras look at the same object in their individual camera reference frames. Triangulation in stereo vision is the task of computing the 3D position of points in the images, given the disparity map and the geometry of the stereo setting. To accurately compute the 3D position, the following process has been followed.
Grid Setup and Camera Calibration
Calculate Intrinsic and Extrinsic Parameters
Motion Detection
Stereo Triangulation
Blob Analysis
Color Analysis
Axis Transformations
Position Error Calculations

Figure 29: Position Solution Process
Each of these steps is discussed in the following sections.

3.6.1 Intrinsic and Extrinsic Parameters
Two Dynex™ 1.3MP Webcam are used as cameras connection to the ground station using high speed USB 2.0 connections as shown in figure below. Each webcam captures video at 640 X 480 resolutions.

Figure 30: Dynex™ 1.3MP Webcam
Each camera has a set of internal and external parameters that need to be calculated for accurate triangulation.
The internal parameters are:

1) **Focal length (fc):** The focal length in pixels.
2) **Principal point (cc):** The principal point coordinates.
3) **Skew coefficient (alpha_c):** The skew coefficient defining the angle between the x and y pixel axes.
4) **Distortions (kc):** The image distortion coefficients (radial and tangential distortions).

These internal parameters are defined below:

Let \( P \) be a point in space of coordinate vector \( \mathbf{X}_C = [X_C; Y_C; Z_C] \) in the camera reference frame. This point is now projected on the image reference frame. Let \( \mathbf{x}_n \) be the normalized (pinhole) image projection:

**Equation 1**

\[
\mathbf{X}_n = \begin{bmatrix} \frac{X_C}{Z_C} \\ \frac{Y_C}{Z_C} \end{bmatrix} = \begin{bmatrix} X \\ Y \end{bmatrix}
\]

Let \( r^2 = x^2 + y^2 \).

After including lens distortion, the new normalized point coordinate \( \mathbf{x}_d \) is defined as follows:

**Equation 2**

\[
\mathbf{X}_d = \begin{bmatrix} X_d(1) \\ X_d(2) \end{bmatrix} = (1 + Kc(1)r^2 + Kc(2)r^2 + Kc(5)r^6)\mathbf{X}_n + \mathbf{d}_x
\]

Where \( \mathbf{d}_x \) is the tangential distortion vector:

**Equation 3**

\[
\mathbf{d}_x = \begin{bmatrix} 2Kc(3)xy + Kc(4)(r^2 + 2x^2) \\ Kc(3)(r^2 + 2y^2) + 2Kc(4)xy \end{bmatrix}
\]

The vector \( \mathbf{kc} \) contains both radial and tangential distortion coefficients. Once distortion is applied, the final pixel coordinates \( \mathbf{x}_{\text{pixel}} = [x_p; y_p] \) of the projection of \( P \) on the image plane is:
Equation 4

\[ X_p = f c(1)(X_d(1) + \alpha c \cdot X_d(2)) + cc(1) \]

\[ Y_p = f c(2)X_d(2) + cc(2) \]

Therefore, the pixel coordinates vector \( x_{\text{pixel}} \) and the normalized coordinate vector \( x_d \) are related to each other through the linear equation:

Equation 5

\[
\begin{bmatrix}
X_p \\
Y_p \\
1
\end{bmatrix} = KK \begin{bmatrix}
X_d(1) \\
X_d(2) \\
1
\end{bmatrix}
\]

Where \( KK \) is known as the camera matrix, and defined as follows:

Equation 6

\[
KK = \begin{bmatrix}
fc(1) & \alpha c \cdot fc(1) & cc(1) \\
0 & fc(2) & cc(2) \\
0 & 0 & 1
\end{bmatrix}
\]

These parameters and their relative errors are calculated using a Camera Calibration Toolbox developed by Caltech.

The external parameters are:

1) Rotation Matrix
2) Translation Matrix

A 10 ft x 10 ft check board is laid on the floor which forms the basis of external parameter calibration. This check board is used as an intermediate reference frame between the camera reference frame and the body frame. The check board reference frame is shown in figure 31:
Figure 31: Check Board Reference Frame

The above figure shows the reference frame (O, X, Y, Z) attached to that calibration grid. Let P be a point space of coordinate vector \( \mathbf{XX} = [X; Y; Z] \) in the grid reference frame. Let \( \mathbf{XX}_c = [X_c; Y_c; Z_c] \) be the coordinate vector of P in the camera reference frame. Then \( \mathbf{XX} \) and \( \mathbf{XX}_c \) are related to each other through the following rigid motion equation:

\[
\mathbf{XX}_c = \mathbf{Rc}_l \ast \mathbf{XX} + \mathbf{Tc}_l
\]

In particular, the translation vector \( \mathbf{Tc}_l \) is the coordinate vector of the origin of the grid pattern (O) in the camera reference frame, and the third column of the matrix \( \mathbf{Rc}_l \) is the surface normal vector of the plane containing the planar grid in the camera reference frame. The same relation holds for the remaining extrinsic parameters. Once the coordinates of a point is expressed in the camera reference frame, it may be projected on the image plane using the intrinsic camera parameters.

Similarly to the intrinsic parameters, the uncertainties attached to the estimates of the extrinsic parameters are also computed by the toolbox.
3.6.2 Camera Calibration and Setup

Two cameras and a check board are used for stereo calibration. Both the left and right cameras have to be calibrated to calculate their internal and external parameters. The following process is similar for both cameras and only the process for the right camera is shown below. The first step in calibrating is to set the check board at a set location without moving it during the entire calibration process. Then multiple pictures of the check board from different orientations are taken. This stack of multiple pictures is shown below:

![Uncalibrated Images](image)

**Figure 32: Uncalibrated Images**

For each picture, the four corners have to be manually extracted as shown below:
The calibration toolbox extracts all the corners of the check board along with the X and Y axis in the check board reference frame. The origin in this reference frame is denoted by o. The same steps are followed for all the images in the stack.
The different orientations used for taking pictures of the grid are shown below along with the grid reference frame. This is known as the world-centered view. The same information is also shown in a camera-centered reference frame.

Figure 35: World Centered View

Figure 36: Camera-Centered View
The toolbox also calculates the error in extraction of all the corners. The point of the error analysis is to reduce the re-projection error in pixels. The initial error projection is shown in fig (a). Only one picture and set of corners shown by red plus signs has higher error in comparison. This picture was reprocessed to reduce the over projection error. The final result of this analysis is shown in right side of figure 37. The maximum projection error has reduced from 2 pixels to 0.5 pixels.

**Figure 37: Pixel Projection Error**

The next step is to select a proper distortion model for the camera. In order to make a decision on the appropriate distortion model to use, it is sometimes very useful to visualize the effect of distortions on the pixel image, and the importance of the radial component versus the tangential component of distortion. These distortion models are drawn using the calibration toolbox. These distortion models are shown below:
There is no tangential distortion visible in the center of the image. The tangential distortion increases towards the camera corner. The radial component of distortion is also negligible at the center and increases towards the corner.

In comparing the magnitude of distortion, the tangential distortion is small compared to the radial distortion of the image. When both the distortions are added together, the tangential distortion is hardly visible. By inspection, only the radial distortion causes a significant effect, and is thus used for distortion correction.
This distortion matrix is stored and used during stereo triangulation.

3.6.3 Solving the Correspondence Problem
One of the key problems with stereo triangulation is solving the “Correspondence Problem.” Finding paired of matched points such that each point in the pair is the projection of the same 3D point. Triangulation depends crucially on the solution of the correspondence problem. Ambiguous correspondence between points in the two images may lead to several different consistent interpretations of the scene. Hence, to reduce this problem, a target red light is installed on the airship. This target light can then be tracked by both the cameras and a set of vision filters can be used to isolate this target in both the camera frame. These vision filters (motion detection, color analysis) will be discussed in the following sections. This help solves the correspondence problem. To be able to see this target from all directions, a set of reference LEDs are used oriented in eight different directions. This target is shown in the figure below:
3.6.4 Vision Filters
Three filtering techniques are used to help solve the correspondence problem.

1) Motion Detection – Isolate only moving objects
2) Color Analysis – Isolate red color.
3) Blob Analysis – Estimate target coordinates (X1, Y1) and (X2, Y2) in individual camera reference frames.

3.6.4.1 Motion Detection
The purpose of this filter is to isolate all the moving objects in the cameras view. This allows us remove all the static noise in the background. This process gets rid of approximately 70-80% of the noise from the camera’s view. This is the first filter that is applied to the raw video data. This raw video data is dissected into its primary color channels (Red, Green, and Blue). Each of these signals is processed individually. The raw video capture block is shown below:

Each color signal then goes through a background estimator. The purpose of this block is to estimate the background in the camera view frame. Once the background is estimated, the
current video frame is then subtracted from the background. This mathematical operation subtracts the static background, and leaves the output with any object that is moving.

**Figure 44: Background Estimation Filter**

Three different background estimation methods are considered which have different benefits in different initial conditions. All three background estimators work on the same basic logic. Every video frame for each color signal is a 640 X 480 matrix. The estimator compares the value of each pixel to its previous value. Based on this difference, the logic for every estimation method is different. The temporal Median estimator method estimates the median of every pixel value over a fixed time. If this median value is within a predetermined range, the estimator than classifies that particular as either background object or moving object. If it is classified as a background object, the pixel value is set to zero (black). Objects that are identified as moving objects are set to the original pixel value. The output of all the estimation methods is a 3x640x480 matrix. The temporal median method doesn’t have a predetermined range, and is calculated as an average value over the last 30 frames. Unlike the temporal median estimator method, where the background image once estimated remains the same for the duration of the flight, the temporal median method updates the background image periodically. The motion based background estimator method is a reversed estimated method. It tends to estimate already moving objects in the background during the estimation process and eliminates them. For example, if the background has a fluttering flag or a flickering light reflection, this method identifies such movement and identifies it as a static object. The implementation of these three methods is shown below:
3.6.4.2 Color Analysis

The three color signal outputs from background analysis are used as an input for color analysis. The objective of this analysis is to isolate any red objects and reject all other colors. To achieve this, a 640x480 green matrix is subtracted from the 640x480 red matrix. The blue 640x480 matrix is then subtracted from this result. This process removes all the traces of blue and green in the image. A surrounding factor was later added to correct for environment redness. This factor changes depending upon the sun, as the hangar where the airship was flown had open sky roofs.

This output then goes through a Median Filter and data conversion. The data conversion converts the red and black matrix into a black (0) and white (1) binary matrix.

Figure 45: Background Estimators

Figure 46: Color Analysis
3.6.4.3 Blob Analysis
The objective of the blob analysis is to calculate the centroid of the target. After applying motion
detection and color analysis, the remaining objects in the video frame should only be the LED
target light. The blob analysis then calculates the centroid of this target in terms of the pixel
reference frame as shown below:

![Figure 47: Pixel Reference System](image)

Figure 48: Blob Analysis

The centroid information is then used for stereo triangulation. To visualize this output, a
bounding box is put around the target and superimposed on the raw video image. This
information is calculated for both the cameras using the same process.
3.6.5 Stereo Triangulation
We now have all the information we need to triangulate the airship position. The stereo triangulation algorithm is coded using an embedded MATLAB function and is included in the appendix. The 3D position output of stereo triangulation is then sent to the ground control for position error calculation.

![Figure 49: Stereo Triangulation](image)

3.6.6 Axis Transformations
Many axis transformations take place during the entire position solution process which is shown below.
The sensor reference frame (also known as a pixel reference frame) is first converted into Camera reference frame. The camera reference frame is the coordinate system adjusted from the top right corner to the center. Along with the intrinsic and extrinsic parameters, the object in the camera reference frame is converted into a 2D position in the check board reference frame (grid reference frame). Based on the 2D position from the left and right camera, the 3D position of the target is calculated in the check board reference frame. This information is then used to calculate the position error and converted into airship body reference frame. This process is discussed in the next section.

3.6.7 Position Error Calculations
The position error calculation is initiated using a user input joystick command. When position hold is initiated, the current position of the airship is stored. This information is used to calculate the position error for all the subsequent frames. The calculated position is in the check board coordinate system.
reference frame; hence, the position error calculated is also in the check board reference frame. The control system logic is designed assuming input is in the airship body reference frame. Hence, the position error in the check board reference frame is then converted into the body reference frame as shown below.

**Figure 51: Position Error Coordinate Transformations**

The final position error in the body reference system is then used as the feedback for the position hold control block.
3.7 Attitude Heading Reference System (AHRS) Solution
The AHRS subsystem block outputs the best reference solution for the airship. This data uses raw data from the Inertial Measuring Unit (IMU) and magnetometer. A Kalman filter is then implemented to reduce the error in signals. A very brief description of this system is given below.

3.7.1 Inertial Measuring Unit (IMU) and Magnetometer.
The IMU provides the following raw information:
1) Acceleration local X Axis
2) Acceleration local Y Axis
3) Acceleration local Z Axis
4) Angular rate local X Axis
5) Angular rate local Y Axis
6) Angular rate local Z Axis

The magnetometer provides the raw compass heading. The following picture shows the IMU used for this project.

![Spark Fun Atomic Magnetometer](image)

3.7.2 Kalman Filter Implementation
The process used to generate a good reference solution is as follows:
1) Calculate Roll, Pitch, and Yaw angles using angular rates and kinematic equations.
2) Calculate Roll and Pitch using accelerations and gravity vector as reference.
3) Magnetic heading is used as a second source for yaw angle.
4) Apply a Kalman filter to these two sources of data to get the best possible result. This implementation is shown in figure 53. Data from the IMU is captured and imported into Simulink using the S-function serrea_sfun2 (included in Appendix). Similarly, data from the magnetometer is captured using S-function read_sfunhead (included in Appendix). The outputs of this implementation are Roll, Pitch, and Heading.

![Figure 53: Kalman Filter](image)

3.8 Communication and Actuation

Communicating control signals from the ground station to the airship is a very integral and complicated process, involving many different components. At the same time, airship attitude information is also communicated back to the ground station for feedback. The general data flow between the various components of the system is shown in the figure below:
There are three main data flows for this system:

1) 3D Position data from laptop to the ground station (RS-232)
2) Accelerations and heading from AHRS system to the ground station (Wireless)
3) Actuator commands from ground station to the on-board controller (wireless)

To transmit any data, data is converted into appropriate packets. For wireless communication XBEEs are used which interface at 9600 bps. The technical information and communication protocol for Rs232 and wireless communication is beyond the scope of this thesis.
4. RESULTS AND ANALYSIS
This thesis provides proof of concept for the control design logic used to control a very large cargo airship. Various tests were conducted to test and analyze various systems of the airship and the different control laws implemented. These tests were performed and demonstrated in front of the thesis committee and the workings of the airship were video recorded. A brief description of the tests performed and the corresponding analysis is provided below:

4.1 Attitude Heading Reference System (AHRS) Results
To check the accuracy of the data calculated by the AHRS system, the IMU and the magnetometer were mounted on high precision digital inclinometer and measurements were taken every 5 degrees. An average of three sets of such readings was taken. Readings were taken separately along the roll and pitch axis. The following table provides the measured angles by the inclinometer and the AHRS system.

<table>
<thead>
<tr>
<th>Inclinometer (deg)</th>
<th>Average Roll (deg)</th>
<th>Average Pitch (Deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-60.0</td>
<td>-54.3</td>
<td>-49.8</td>
</tr>
<tr>
<td>-55.0</td>
<td>-49.9</td>
<td>-45.4</td>
</tr>
<tr>
<td>-50.0</td>
<td>-47.6</td>
<td>-43.1</td>
</tr>
<tr>
<td>-45.0</td>
<td>-43.2</td>
<td>-38.7</td>
</tr>
<tr>
<td>-40.0</td>
<td>-41.5</td>
<td>-37.0</td>
</tr>
<tr>
<td>-35.0</td>
<td>-36.3</td>
<td>-31.8</td>
</tr>
<tr>
<td>-30.0</td>
<td>-31.3</td>
<td>-26.8</td>
</tr>
<tr>
<td>-25.0</td>
<td>-24.5</td>
<td>-20.0</td>
</tr>
<tr>
<td>-20.0</td>
<td>-20.9</td>
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</tr>
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</tr>
<tr>
<td>-10.0</td>
<td>-10.7</td>
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</tr>
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<td>-5.0</td>
<td>-4.8</td>
<td>-0.3</td>
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<td>0.5</td>
<td>5.0</td>
</tr>
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<td>5.0</td>
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<td>9.3</td>
</tr>
<tr>
<td>10.0</td>
<td>10.2</td>
<td>14.7</td>
</tr>
</tbody>
</table>
The above graph shows the error in calculation of the roll and pitch angle using the AHRS system. For roll angle, the error in calculation is less than 2 degrees for angles up to 45 degrees. The error in calculation increases as the bank angle increases. There is an approximately 4.5 degrees of bias in the calculation of the pitch angle. This error is a result of...
improper mounting of the IMU on the inclinometer. The IMU has various pins on the bottom, which restrict us from mounting it flat against the inclinometer surface. Thus, on the airship a bias parameter is included to level the static roll and pitch values. This bias value changes every flight based on the relative mounting of the IMU on the gondola.

Another important parameter under consideration is the update rate of the AHRS system. Proper tools were not available to test and measure this parameter, although general observations were made. The roll and pitch values update at a very slow rate. Although this was not considered an issue for our purpose, as the overall airship dynamic response is of very low frequency, and the slow update rate has never caused any lag induced control problems.

4.2 Vision Position System Results

The vision position system was tested for accuracy of 3D position solution compared to the actual measured position. Multiple points were randomly selected throughout the hangar and were measured from the origin of the grid reference frame system. The results of this are documented in the table below:

**Table 8: Vision Position System Error**

<table>
<thead>
<tr>
<th>Xmeasured (ft)</th>
<th>Ymeasured (ft)</th>
<th>Xvision (ft)</th>
<th>Yvision (ft)</th>
<th>Xerror (ft)</th>
<th>Yerror (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10.000</td>
<td>-10.000</td>
<td>-10.331</td>
<td>-10.298</td>
<td>-0.331</td>
<td>-0.298</td>
</tr>
<tr>
<td>-5.000</td>
<td>-5.000</td>
<td>-4.987</td>
<td>-5.122</td>
<td>0.013</td>
<td>-0.122</td>
</tr>
<tr>
<td>0.000</td>
<td>0.000</td>
<td>0.013</td>
<td>0.022</td>
<td>0.013</td>
<td>0.022</td>
</tr>
<tr>
<td>5.000</td>
<td>5.000</td>
<td>5.214</td>
<td>5.102</td>
<td>0.214</td>
<td>0.102</td>
</tr>
<tr>
<td>10.000</td>
<td>10.000</td>
<td>10.320</td>
<td>10.420</td>
<td>0.320</td>
<td>0.420</td>
</tr>
<tr>
<td>15.000</td>
<td>15.000</td>
<td>15.750</td>
<td>15.970</td>
<td>0.750</td>
<td>0.970</td>
</tr>
<tr>
<td>20.000</td>
<td>15.000</td>
<td>21.200</td>
<td>15.460</td>
<td>1.200</td>
<td>0.460</td>
</tr>
<tr>
<td>25.000</td>
<td>15.000</td>
<td>28.478</td>
<td>15.840</td>
<td>3.478</td>
<td>0.840</td>
</tr>
<tr>
<td>30.000</td>
<td>15.000</td>
<td>33.456</td>
<td>15.760</td>
<td>3.456</td>
<td>0.760</td>
</tr>
</tbody>
</table>
From the graph it is clear that the error in position solution increases with distance from the cameras. The error is less than 1 ft, up to a distance of 18.5 ft from the camera position. The vision system was unable to track the LED lights placed 30 ft away from the camera. Many reasons contribute to this error as discussed below:

1) Environmental Interference: Many filters are applied to the raw video signal to reduce atmospheric interference. Although as the distance between the camera and the LED source increases, the relative size and the intensity of the LED source reduces. Thus the environmental interference has a bigger influence as distance increases.
2) Correspondence Problem: On rare occasions, the left and right camera may track different objects at a given instance, hence resulting in an incorrect calculation of 3D position.

4.3 Control System Results

The various control logic implemented were tested in a series of flight tests. Although, due to the nature of these tests, there are no numerical results calculated. Roll hold and Pitch hold work very effectively. The airship has a natural tendency to level, which assists the dynamic stability system. The Low Speed Mode and High Speed Mode of the airship are effective in their individual operational envelop. In low speed mode, the control logic allowed the airship to successfully translate in all four directions. The high speed mode was effective in maneuvering the airship around the hangar. The heading hold system maintained the airships heading within 10 degrees, when activated.

One of the main research topics of this thesis was to study the effectiveness of the control system under crosswind conditions. To test this, the airship was commanded to hold a given position and heading. Manual fans were used to blow the airship away from its center. It was observed that the airship had a tendency to maintain its position in low winds condition. When the airship was displayed from its targeted hold position, the airship tends to return back to its original position. Although in most instances the airship overshot the target position. Gains were further adjusted to resolve this issue, which minimized this effect.
One major reason for the poor performance of the position hold system is the accuracy of the thrust vectoring and power output. The control assumes the engines can be rotated exactly without any actuator errors and the thrust rating is accurate. So when the control system may command a particular servo to turn 45 degrees, the actual rotation of the servo can vary between +-3 degrees. Similarly, due to the low fidelity of the speed controllers, a thrust of the engines is accurate to within +- 15%. The control system also assumes that there is no warping of the structure. Also the servos and engines are all mounted along the established thrust line. In reality, the particular aspect ratio of the airship and the structural design, leads to warping of the sub-scale model. As a result the thrust line for engines is different resulting in unbalanced thrust vectoring.

A few pictures from the test flights of the sub-scale model are shown below:

Figure 57: Airship in Flight # 1
Figure 58: Airship in Flight # 2
5. CONCLUSION AND RECOMMENDATIONS

The airship was successfully flown in the hangar and the implemented control laws were tested. The roll and pitch stabilization controller are very effective, as they are assisted by the static tendency of the airship to stabilize itself. The stereo-vision system serves the purpose of providing a position solution in the absence of a GPS signal. The position hold system tends to bring the airship towards the target position, although the gains need to be improved to reduce overshoot. The airship control laws maintain airships position and direction in low wind conditions.

5.1 Future Work

A vast amount of research was done on this airship. Many different methods were used to achieve the target and successfully fly the airship. Many improvements can be made to the system, as listed below:

1. Use of three cameras and stereo triangulation methods to estimate position and attitude of the airship. A three LED target system can be used to achieve this.
2. Add aerodynamic control surfaces to directly test these effects in low and high wind conditions.
3. Add ballonets to the airship to test the ballonet control system.
4. Improve position hold gains to get better control solution.
5. Altitude hold can be implemented which will further assist cargo operations.
6. REFERENCES


7 Arduino. 2010. <www.arduino.cc>


7. APPENDIX A: Printed Circuit Board (PCB) Design

To reduce the complexity of wiring between components, a PCB was designed and manufactured. This PCB was used to mount the XBEE, ARDUINO and other hardware connections directly onto it, thus reducing wiring weight and complexity. The PCB design is shown in the figure below:

Figure 59: PCB Design