**DOKUZ EYLÜL UNIVERSITY**
**GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES**

# LOW ALTITUDE SURVEILLANCE BLIMP WITH AUTOMATIC PILOT CONTROL

**by**
**Fatih Mehmet DAĞ**

**March, 2018**
**İZMİR**

# LOW ALTITUDE SURVEILLANCE BLIMP WITH AUTOMATIC PILOT CONTROL

**A Thesis Submitted to the**
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**in Electrical and Electronics Engineering**

**by**
**Fatih Mehmet DAĞ**

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## M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"LOW ALTITUDE SURVEILLANCE BLIMP WITH AUTOMATIC PILOT CONTROL"** completed by **FATİH MEHMET DAĞ** under supervision of **ASSIST. PROF. DR. ÖZGÜR TAMER** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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# LOW ALTITUDE SURVEILLANCE BLIMP WITH AUTOMATIC PILOT CONTROL

## ABSTRACT

Despite the fact that history of unmanned air vehicles (UAV's) are as old as history of conventional aircrafts, their recognition has been growing in recent years, especially after their civilian use became widespread. With evolution in all fields of technology, very advanced UAVs are in use now. However, limited flight time and payload capacities are still problem due to limited energy storage capacity. There is continuous force exerted on air vehicles, towards the earth because of gravity during the flight. Therefore, the air vehicles consumes most of its energy resources against to gravity in order to stay in air. Lighter-than-air (LTA) gases provide excellent solution to neutralize this force. LTA gases have lower density than the air therefore air applies buoyant force on LTA gases. Naturally, LTA gases have lifting capacity in the air. Hybrid airships are powered aircraft which obtains its lifts by using both lifting force from lighter-than-air (LTA) gases and aerodynamic lifting force generated by electro-mechanical components. Therefore they called as hybrid. A hybrid airship consist of mainly two parts. A blimp which carries the LTA gas and a propulsion system which generates thrust to allow airship to cruise and to make maneuvers. In this thesis, various methods are investigated to increase payload capacity and flight time of an UAV. As a solution, unmanned hybrid airship is developed by getting benefit from lifting force of LTA gases. As an LTA gas, Helium is used due to high lifting capacity and safety reason. In addition to blimp and propulsion system, a complete unmanned air system (UAS) is developed includes flight controller module, communication module and ground control module, in the scope of this thesis. It is observed that, developed unmanned airship has longer flight time and higher payload capacity with respect to comparable UAS's.

**Keywords:** Unmanned Air System (UAS), Lighter-Than-Air (LTA), hybrid

**OTOMATİK PİLOT KONTROLLÜ ALÇAK İRTİFA BALONLU KEŞİF VE GÖZETLEME ARACI**

## ÖZ

İnsansız hava araçları (İHA) tarihi, geleneksel hava araçları tarihi kadar eski olsa da, İHA'ların bilinirlikleri son yıllarda; özelliklede sivil kullanımlarının yaygınlaşmaya başlamasından sonra artmıştır. Teknolojinin bütün alanlarında yaşanan dönüşüm ile birlikte, oldukça gelişmiş İHA'lar hali hazırda kullanılmaktadır. Fakat kısıtlı enerji depolama kapasiteleri sebebiyle sınırlı uçuş süresi ve taşıma kapasitesi, İHA'lar için hala sorun teşkil etmektedir. Hava araçlarına uçuş sırasında yer çekiminden dolayı yere doğru sürekli bir güç uygulanır. Bu yüzden, hava araçları, enerji kaynaklarının büyük bir kısmını havada kalmak ve bu güce karşı koymak için harcamaktadır. Havadan hafif gazlar bu güce dengelemek için mükemmel bir çözüm sunmaktadır. Havadan hafif gazların yoğunluğu havanın yoğunluğundan düşüktür ve bu yüzden hava bu gazlar üzerine kaldırma kuvveti uygular. Doğal olarak, havadan hafif gazlar, hava içerisinde taşıma kapasitesine sahip olmaktaırlar. Hibrid zeplinler kaldırma güçlerini havadan hafif gazların sağladığı kaldırma kuvvetinden ve aynı zamanda elektro-mekanik sistemler tarafından üretilen aerodinamik kaldırma kuvvetinden sağlayan harici güç kaynağına sahip hava araçlarıdır. Bu yüzden hibrid olarak adlandırılırlar. Temel olarak iki kısımdan oluşur. Havadan hafif gazın taşındığı bir balon ve itme gücü üreterek aracın seyir etmesini ve manvera yapmasını sağlayan tahrik sistemi. Bu tezde, bir İHA'nın taşıma kapasitesini ve uçuş süresini arttırmak amacıyla çeşitli yöntemler araştırılmıştır. Çözüm olarak, havadan hafif gazların sağladığı kaldırma kuvvetininden fayda sağlayan insansız hibrid zeplin geliştirilmiştir. Havadan hafif gaz olarak, taşıma kapasitesi ve güvenlik gerekçeleri göz önünde bulundurularak helyum gazı tercih edilmiştir. Balon ve tahrik sistemine ek olarak, uçuş control modülü, iletişim modülü ve yer istasyonu modülü ile birlikte bütün bir insansız hava sistemi bu tez kapsamında geliştirilmiştir. Karşılaştırılabilir İHA'lara kıyasla, daha uzun uçuş süresine ve daha yüksek taşıma kapasitesine sahip olduğu görülmüştür.

**Anahtar Kelimeler:** İnsansız Hava Sistemleri (İHS), Havadan Hafif (HH), hibrid

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# CHAPTER ONE
# INTRODUCTION

Unmanned Air Vehicles (UAV) have been used since the beginning of the aircraft history (Barnhart, Hottman, Marshall and Shappee, 2012). Rapid advance of the technology in all fields allows engineers to develop the most advanced UAV like conventional aircrafts. Initially, UAVs operation range was limited by the line of sight of the operators. Nowadays, with the development of navigation and satellite systems, operator can give orders to UAV from thousands of kilometers away (Barnhart et al., 2012). Even the most advanced type of UAVs has the ability of autonomous flight. Like the other technology fields, the very first examples of the UAVs were developed for the military purposes. Still military applications are pioneer of development of the UAV technologies. In the last decades, these vehicles become one of popular product of civilian consumers (Meola, 2017). Respectively they have small and limited capacity, but all necessary materials are available in the market to produce more advanced types.

Whether it is used for military or civilian purposes, they have some critical limitations especially range, endurance, and payload capacity (Barnhart et al., 2012). The UAVs with fuel powered engine have longer range than the UAVs with an electric motor but it still is limited. In addition, production, operation, and maintenance costs are quite high. Also, they need more maintenance time after flight (Robertson). Only disadvantage of an electrically powered UAV is the power storage capacity of the batteries (Espasandín, Leo and Arévalo, 2014).

Lighter than air (LTA) gases provide an excellent opportunity to increase endurance and range of the unmanned vehicles. LTA gases has lifting capacity in the air. For example, 1-liter Helium gas is able to carry around 1.114-gram load at sea level (Helium, 2018). A blimp or a balloon with enough size and capacity is able to neutralize total weight of the aircraft. In this way, aircraft don't have to consume its energy against the gravity. Therefore, energy resources could be used at maximum efficiency. Combination of motor force and lifting capacity of the LTA gases, hybrid aircraft are gain ability of almost unlimited flight time.

In this work, design of the Low Altitude Surveillance Blimp as an Unmanned Air Vehicle System (UAVS), is described. This work is in context of final project of the Master of Science program of the Dokuz Eylül University, Electrical and Electronics Engineering.

## 1.1 Background

Wright brothers not only invented the first modern aircraft but also discovered and taught how to fly and started history of modern aerial vehicles. Just after 15 years from the flying of first modern aircraft, in 1918, U.S. Navy successfully tested first modern unmanned aircraft developed by the inventor of the first ground control system, Elmer Sperry (Barnhart et al., 2012). This aircraft was called as aerial torpedo. It was designed to carry explosive material and denote warhead to target nearly 1 km away from the ground control. Due to effective use of aircrafts in the World War I, armies were forced to develop advanced anti-aircraft weapons (Barnhart et al., 2012). Therefore, focus turned to develop target drones instead of developing weapon platforms until World War II. During World War II, Germany and USA developed advanced assault unmanned weapon platform with basic autonomous functions (Barnhart et al., 2012). In the late 1930's, primitive examples of surveillance aircrafts were developed. Early versions had low resolution cameras but after 1940s, they were equipped with better cameras (Barnhart et al., 2012). After 1950s, with the development of satellite systems, long range, and high altitude UAVS were developed and actively used during the Cold War. In the late 1970s, development of small size, light digital computer system and Global Positioning System Carried UAVS to next Level, fully autonomous flight (Barnhart et al., 2012). Now, many countries and many companies producing advanced UAVS. Some of the countries equipped the UAVS with advanced missiles to carry air to surface attacks. Beyond from all these developments, USA announced the JSF-35 will be the last manned fighter aircraft (Trsek, 2017).

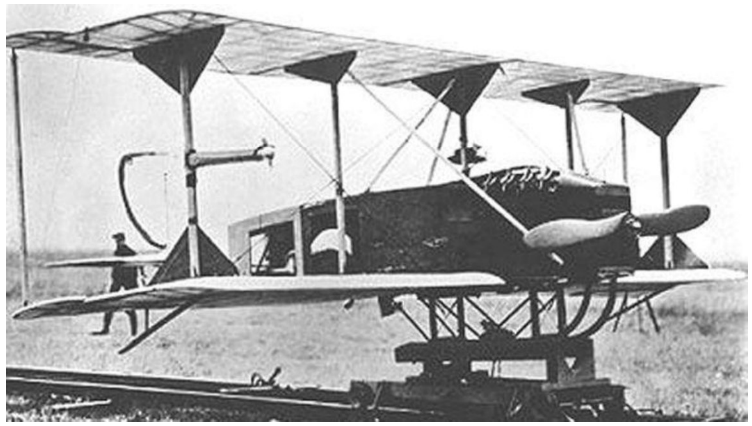


Figure 1.1 The first unmanned air vehicle, Aerial Torpedo (Barnhart et al., 2012)

The simplest description of the UAV is an aircraft operated by a computer system or radio link without any crew occupied the aircraft. UAVS is a combination of aircraft and sub systems like control system, communication system etc. Almost all subsystems have their equivalent with conventional aircraft except aircraft crew. When describing to UAV, it should be avoided to confuse with radio-controlled (RC) model aircrafts and drones. RC aircrafts are mostly used for hobby and they have limited abilities. They must stay at sight of the operators. Drones should have ability to fly out of sight but also, they have limited ability and no autonomy or intelligence. On the other side, UAV have different degree of intelligence and autonomy. They are able to communicate the controller and able to send collected data and flight data like orientation, altitude, position etc. Also, they are able to give decisions based on conditions and pre-defined tasks. Even if connection is lost with the ground control, they still are able to be complete the task or return home based on their design (Austin, 2010).

To say a system is an UAVS, at least following subsystem should be satisfied (Austin, 2010):

- Air Vehicle: Air vehicle is the main part and center of the whole system. It carries some other subsystem and payloads to perform specified tasks.

- Payload: Payload is the specific component of the UAVS design purpose. For example, it might be a video camera for surveillance purpose or a weapon system, it might also be the combination of different systems.
- Communication Datalink: Communication Data Link consists of uplink and downlink between the air vehicle to the ground control system and/or other communication end points. Air vehicles receive commands from uplink and sends collected data and flight data via the downlink.
- Command and Control System: Command and Control System includes both ground control and auto-pilot. Ground control is the master of the system and manages the operation of the air vehicle and payloads. During the execution of pre-defined tasks and changing environmental conditions, autopilot controls the air vehicle under supervision of the ground control.
- Launch and Recovery System: Launch and Recovery System is the platform or environment for taking off and landing of the air vehicles includes supporting system like fuel tanks, battery charge station or transportation systems.
- Human Element: Human element is still the most important part of the unmanned systems like manned aircraft. Mainly responsible to operate, control and maintenance of the unmanned systems.

The very first known example of Lighter Than Air (LTA) unmanned aerial vehicle used by famous Chinese General Zhuge Lhuge (180 234). He used paper balloons with an oil-burning lambs then flew them over the enemies at night. He tried to make enemy think there were something supernatural power over them (Barnhart et al., 2012). With the development of unmanned aerial systems, engineers get benefit also from LTA gases to design long-endurance and low-power consuming systems. Modern LTA-UAS are mainly classified as tethered and hybrid air vehicles (USA Secretary of Defense, 2012). Tethered air vehicles use only lifting power of the LTA gases and they are tied to ground station with a rope and communication cables. They are used to observe around specific areas like borders, critical buildings, check points etc. with on-board radar and surveillance system.

Figure 1.2 Tethered Lighter than Air Aircraft (Raytheon, 2018)

Unlike tethered systems, hybrid LTA UAS use motors as thrust sources to get ability of flying in addition to lifting power of the LTA gases. LTA-UAS's have several advantages against conventional UAS. LTA gases provide lifting power without consuming any energy resource. Therefore, LTA-UAS's have better energy efficiency performance. This energy performance also allows longer operation time and further operation range. By adding additional energy generator systems, these systems gain unlimited flight range and time. Other important specification is the payload. By adding bigger envelope, payload capacity can be increased without changing any mechanical parts. When considering all these advantages, LTA-UAS's production, maintenance and modification costs are lower than conventional UAS. LTA-UAS have mainly two disadvantages. Their envelope size is bigger and because of the envelope size, their speed is lower than conventional UAS (Lynch, 2011).

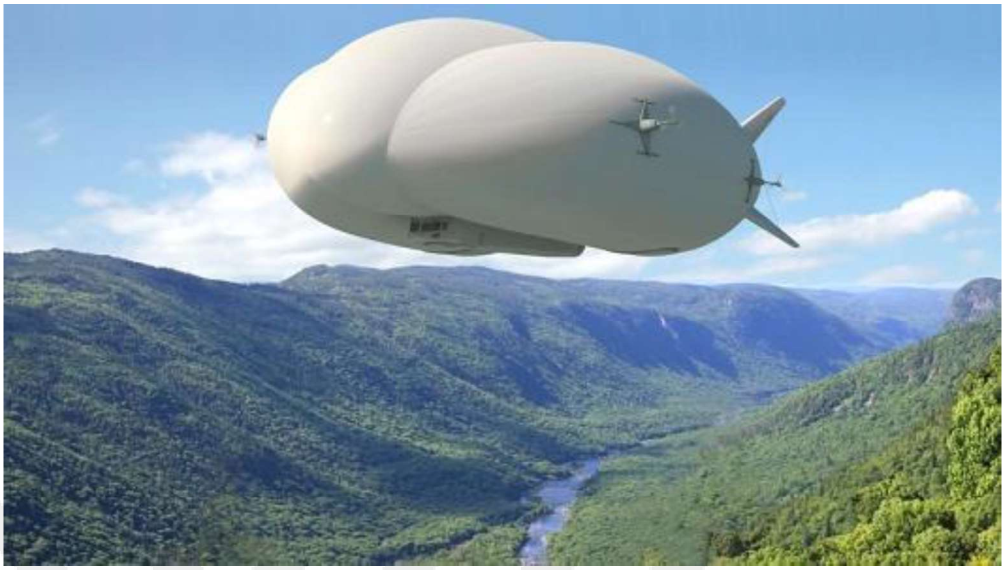


Figure 1.3 Hybrid lighter than air aircraft (Lockheedmartin, 2018)

## 1.2 Objectives

Aim of this thesis is to design and implement a Hybrid Lighter Than Air Unmanned Air System (LTA-UAS) in order to present energy efficiency and useful payload capacity of the LTA-UAS systems against to conventional UAS. Within scope of this thesis, following sub-systems are aimed to design and develop:

- Envelope: Envelope of the aerial vehicle to be used to carry LTA gas in order to provide lifting power. For this purpose, size and shape of envelope will be designed by considering payload capacity and aerodynamics design principles.
- Flight Controller: Flight controller is the central part of any aerial vehicle. It is used to orchestrate communication system, stability system, propulsion system and flight data generation systems.
- Ground Control: Ground control is used to control vehicle remotely and used to monitor vehicle during flight.

In this work, a hybrid aircraft is designed to prove how LTA gases increase endurance of the unmanned aircraft. A tilt-rotor mechanism which has independent flight ability, is combined a helium filled blimp. Design and verification steps are described in detail in the following chapters.

### 1.3 Thesis Organization

This thesis consist of four chapters:

- **Chapter One, Introduction:** In the first chapter, the motivation behind this thesis is discussed and thesis objectives are defined. Also brief information is given about background and example of previous works are briefly mentioned.

- **Chapter Two, Methodology and Design:** In the second chapter, way of working and methodology is defined. Based on specified solution, design and implementation are detailed.

- **Chapter Three, Conclusion:** In the third chapter, results are evaluated and compared with similar designs. Also possible future enhancement are discussed.

- **Chapter Four, References:** In the last chapter, all applied resources includes books, journals, digital files etc. are cited.

## CHAPTER TWO
## METHODOLOGY AND DESIGN

Design of Low Altitude Hybrid Surveillance blimp can be divided into 5 sections:

- Envelope Design
- Propulsion System Design
- Flight Controller Design
- Ground Control Module Design
- Auto-Pilot Module Design

Envelope is a LTA gases carrier and it will be filled with an LTA gas, preferably helium because of the non-flammable specification of the helium. Envelope size to be defined to satisfy payload capacity of the vehicle. Under normal conditions, 1-liter helium can carry 1.114 gr. load. Therefore, the higher volume of envelope, the more payload capacity it means. Material selection also effects the payload capacity. To increase payload capacity, lighter material should be used. In addition to the envelope size, envelope shape is also important as a design criterion. Aerodynamic structure of the envelope is important against air resistance. It directly effects power consumptions and air speed of the vehicle. Envelope to be designed based on all these considerations. Envelope design will be detailed in following sections.

As it is specified in the Introduction section, LTA-UAS's are mainly classified as tethered and non-tethered LTA-UAS. Non-tethered are also called as hybrid airship. Hybrid airships use motors to get ability to fly. Also, motors provide additional payload capacity to the vehicle. Motors and motor control units form propulsion system. Conventional air crafts and hybrid airships use wings, flaps, and tails to orient the vehicle. In this work, servo motors will be used to direct the vehicle by creating a tilt-rotor mechanism. Propulsion system will be integrated to envelope and design will be detailed in the following sections.

Flight-controller is the central part of all aerial vehicles. It is an interface between propulsion system, ground control, auto-pilot module and sensors. It receives orientation, position and altitude information from the sensors and generates flight data based on the flight algorithm. Commands received from the ground control during the manual flight are evaluated by the flight controller. Combination of all these data and commands will define the status of the propulsion system then proper commands to be sent to the propulsion system in order to define the speed and position of the motors. Also, flight controller sends flight data to the ground control continuously to the feed monitoring system. Flight controller design will be detailed later.

Ground control unit will be used to control flight and monitor the vehicle during flight. Command unit sends directives via a wireless transmitter. Also, during autonomous flight, ground control unit will send update commands to the vehicle. On the other hand, ground control system includes monitoring system and will receive flight data from the vehicle continuously. Ground control system design will be detailed in following sections.

Autonomous flight is an ability of flying a vehicle by itself without receiving directives. Basically, auto-pilot systems can define route, position and direction of the vehicle based on the predefined target and limits. Based on the decisions that are made by auto-pilot systems, directives to be sent to flight controller then flight controller will manage propulsion system to control the vehicle. Auto-pilot module design will be detailed in following sections.

### 2.1 System Specifications

Before designing a flaying system, defining specification of the vehicle is critical and important step of the development. Specifications define what vehicle will do and how it will work. Also, define the constraints of the research and design process. Based on the vehicle specification, hardware and software systems are developed accordingly. In this work, a Low Altitude Hybrid Surveillance Blimp is to be designed and implemented. Due to the thesis goals, design will be limited to build a prototype in order to highlight project objectives. High-level vehicle specifications are summarized below:

- Payload: 1000 gr.
- Maximum Altitude: 200 m.
- Operation Radius: 500 m.
- Communication Datalink: 2.4 GHz 2-Channel Radio Link
- Propulsion System: 2-Brushless DC Motor, 2-Servo Motor
- Energy Resource: 3S, 11.3V Li-Po battery

## 2.2 Envelope Design

Airship envelope design one of the most complex step in the airship design. Material selection, envelope shape and envelope volume are the key parameters of the envelope design. Weight of the envelope should be small due to save payload capacity of the airship. Weight/area ratio is the main selection criteria of the envelope material. Also, material's physical characteristics are important parameters to design more robust airship against to environmental conditions.

### *2.2.1 Lifting Capacity of Helium*

Static Lift of the lighter than air (LTA) gases can be explained with Archimedes' Principle. There is an upward force, called as buoyancy, is exerted on an object which is sunk in a Fluid. This force is equal to weight of the fluid displaced because of the object that is sunk in the fluid. The submerged volume ratio of the object depends on the density of the fluid and density of the object. If density of the object is not greater than fluid, object does not totally submerge (Buoyancy, 2018).

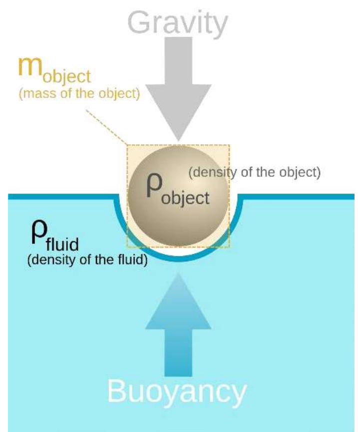



Figure 2.1 Buoyancy (Buoyancy, 2018)

LTA gases have lover intensity than the air. Therefore, an upward force is exerted to the LTA gases. This force can be balanced with the payload. By this principle, LTA gases have lifting capacity in the air and they are also called as Lifting Gases. Hot air, Hydrogen, Helium, Ammonia, Methane, Coal Gas, Neon, Nitrogen are well-known example of LTA gases (Lifting Gas, 2018).

Hydrogen has the highest gases with respect to lifting capacity and it is very easy to obtain it. But it is a flammable gas. In many countries usage of the hydrogen in airship application is restricted by law. Although it is an expensive and not easily obtained, most used LTA gases in the hybrid airship applications is helium because of the safety reasons. Lifting capacity of helium is calculated under the standard conditions (1 atm pressure, $0^0$ C temperature) as below:

$\rho_{air}$ : air density

$\rho_{he}$ : Helium density

$M$ : amount of mass that helium lift

$$\rho_{air} = 1.292\ gr/cm^3$$
$$\rho_{he} = 0.179\ gr/cm^3$$

$1\ cm^3$ helium lift capacity is:

$$M = (\rho_{air} - \rho_{He})x\ 1\ cm^3 = (1.292 - 0.179)\ x\ 1 = 1.114\ g \qquad (2.1)$$

As it seen above, $1\ cm^3$ helium can carry 1.114 g load under the standard condition.

### *2.1.2 Envelope Design*

There are 3 different types of envelopes that are used in design of airships and aerostat as Rigid, Semi-Rigid, and Non-Rigid. Rigid airships include a frame inside the envelope. This method is applied for large airships in order support to keep shape of the airship against the envelope material weight, load and dynamic loads during operation. Similar with rigid airships, Semi-Rigid airships have frame to support main envelope and their length and width. Comparatively, medium-size airships are constructed as semi-rigid airship. Unlike rigid and semi-rigid airships, non-rigid airships do not contain any frame. They keep their shape only by pressure of the gases inside (Airship, 2018). In this work, due to the vehicle specifications, non-rigid envelope to be designed.

Material of the envelope is also important point. First in case, material weight should be considered. Because, to allocate more payload capacity to the vehicle, envelope weight should be as light as possible. On the other hand, material strength should have good pressure resistance. Other critical point is leakage resistance. Helium molecules are very small when comparing the other molecules. Therefore, envelope material should prevent the leakage as much as it can. Even some materials have almost no leakage. Apart from these specifications, most of the commercially available materials present UV protection, working under wide temperature range etc. (Zhai and Eular, 2005).

There are many proved materials in the market like Tedlar, Kevlar, Polyethylene etc. for airship envelope. In this project, due to cost restrictions, cheapest available material option to be selected. Due to aerodynamic reasons, airship envelopes are designed as a hull shape. During volume and surface area calculation, ellipsoid formulas is considered in order to get approximate values for volume and surface area.

Envelope design includes lots of criteria and steps. Also, verification of all these criteria's need long and costly work. Therefore, designing a complete airship should be part of an individual work. Therefore, in this work, other design works are taken as reference instead of inventing the wheel again.

Total weight of the vehicle except envelope is around 500gr. In this work an envelope which can lift around 1 kg is highly enough to satisfy thesis objectives. Due to design an envelope with good aerodynamic structure, diameter/length ratio should be kept between 0.2 and 0.3.

Example design of an airship envelope which is 4-meter long and has 1.2 m diameter, is given below:

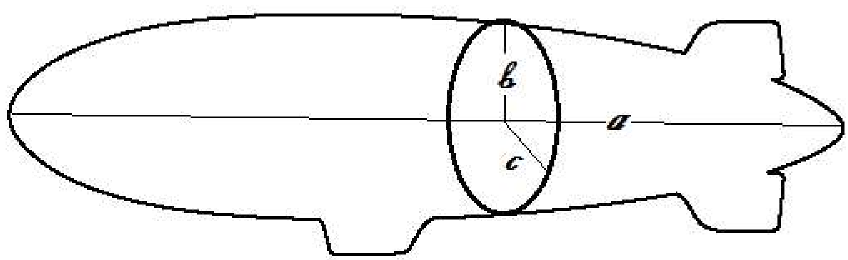



Figure 2.2 Envelope Outline

$V$: $Volume\ of\ the\ blimp,\ S$: $Surface\ area\ of\ the\ blimp$

$$V = \frac{4}{3}abc \tag{2.2}$$

$$S = 4\pi \sqrt[p]{\frac{a^p a^p + a^p b^p\ b^p c^p}{3}}\ (p \cong 1{,}6) \tag{2.3}$$

$$a = 4m, b = c = 0.6m$$

$$v = 3{,}016\ m^3$$

$$S = 12{,}27\ m^2$$

Materials which are used in airship design approximately have a density around 50 gr/$m^2$. Due to unavailability of those materials, PVC film is used as an envelope material which density is 181.7 gr/$m^2$. Weight of envelope is:

$$M_{env} = 12{,}27\ x\ 181.74 = 2230\ gr.$$

According to equation (1), $3{,}016\ m^3$ helium can carry nearly 3356 gr. load. When envelope weight is discarded, net payload capacity is expected around 1126 gr.

After design is completed, envelope is constructed by using PVC film. As it is stated before, because of aerodynamic properties, envelope shape is decided to be in hull shape. Cascading 2-dimensional ellipsoid surfaces form Hull shape. Using higher number of ellipsoid surface provides better shape. The envelope is constructed by using four ellipsoids. Length of ellipsoid is same with length of the envelope, 4-meters. Width of ellipsoid is calculated by dividing circumference length to number of ellipsoid. The envelope radius is 0.6 meter; therefore, circumference length is $\cong 2.512$ meters. So, width of ellipsoid is should be 0.942 meter.

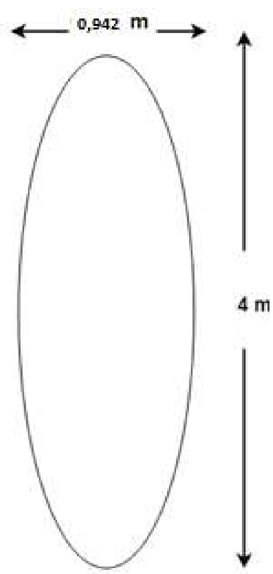



Figure 2.3 Ellipsoid Pattern

An ellipsoid pattern is drawn on a paper then four 0.942 x 4 m. polyethylene rectangles are stuck by using iron. Edges of rectangle polyethylene parts are melted with iron by following ellipsoid iron. After all parts successfully merged, the excesses were cut off and envelope is inflated to check in case of any leakage.

Figure 2.4 Envelope Construction (Personal archive, 2018)

## 2.3 Propulsion System Design

Propulsion system is used to generate required thrust for the vehicle to move in any direction in the sky. 2 DC brushless motor will produce thrust by converting electrical power to be received from battery to mechanical energy. Each motor is controlled by an Electronic Speed Controller (ESC) unit. ESC adjusts electric current of the motor according to the control signal which is produced by a flight controller. Brushless motors are mounted over the servo motors and servo motors will control direction of thrust. Each servo motor will be able to move independent of each other. Therefore, apart from vertical and horizontal move of the vehicle, it will able to turn right or left by controlling thrust direction of each motor via servo motors.

### *2.3.1 Propulsion System Elements*

In the vehicle, 2- Emax MT2213 935KV DC Brushless motors will be used with 10.45-inch length propeller. It has three inputs and they will be connected to ESC. Each motor can generate propulsion of 850 g. maximum. Specification of the motors as given below:

- Brand Name: Emax
- Item Name: Emax MT2213 935KV brushless motor
- KV: 935
- Weight: 55g
- Diameter: 27.9mm
- Length: 39.7mm
- Max Thrust: 850G

Figure 2.5 MT2213 DC Brushless Motor (Personal archive, 2018)

Brushless motors will be controlled via Electronic Speed Controller (ESC) devices. In the vehicle, 2 Hobbywing Skywalker 20A ESC to be used. ESC has 8 pins to connect motors, battery and flight controller. Two power cables are used to connect the battery. 3 connections cable is used to connect brushless motors. One of the three cables is used to receive PWM signal from the flight controller. During calibration of the ESC, maximum and minimum PWM width can be defined. Flight controller produces PWM signals between defined ranges then ESC adjusts current of the motor based on received PWM signals width. Other 2 cables are output of the Battery Eliminating Circuit (BEC). BEC converts battery voltage to 5V and able to be provide up to 2A current. This voltage source is used to feed servo motors, flight controller and sensors. Therefore, no add additional power supply or voltage divider is needed in the circuit.

Electrical and physical specifications of the ESC are below:

- Continuous Current: 20A
- Burst Current: 25A
- BEC Mode: Linear
- BEC Output: 5V/2A
- Battery Cell: 2-3S Li-po, 5-9 Cells NiMH
- Weight: 19g
- Size: 42x25x8 mm


Figure 2.6 Hobbywing Skywalker 20A Electronic speed controller (Personal archive, 2018)

As an electrical power supply, 11.1 V, 1500mah, 35C 3S Lipo-Battery is used. 3S means 3-cells. Each cell acts as a 4.7 V power supply. Combination of the cells generate a higher voltage supply and storage capacity. Li-Po batteries are commonly used because of their high storage capacity and comparatively light weight. But their storage capacity decreasing in time and increasing number of re-charge causes faster loose on storage capacity. To make longer life time, cell voltages should not fall below 80% of full capacity. ESC includes battery controller circuit and cut the power when battery reaches critical voltage. Also, flight controller will have battery controller circuit to measure battery voltage instantly and will help to give decision vehicle to return before battery run out of.


Figure 2.7 3S, 11,1V, 1500mah Li-Po Battery (Personal archive, 2018)

Specifications of the battery are listed below:

- Continuous Discharge Rate: 35C (52.5A)
- Max Burst Rate: 60C (90A)
- Min Discharge Volts: 9V
- Max Volts: 12.6V
- Number of Cells: 3

Propulsion system includes 2-servo motors. Servo motors are capable of carrying heavy load and providing high torque to the rotate loads. In the propulsion system, each brushless motor will be mounted on each servo motor via an interconnection part.

By this connection, brushless motors will be able to be make rotational movements up to 180 degrees.

Figure 2.8 TowerPro MG996R Servo Motor (Personal archive, 2018)

Specifications of servo motors are listed below:

- Brand: Tower Pro
- Model: MG996R
- Weight: 55g
- Dimension: 40.7×19.7×42.9mm
- Torque-Power: 9.4kg/cm (4.8v); 11kg/cm (6v)
- Processing Speed: 0.17sec/60degree(4.8v);0.14sec/60degree(6.0v)
- Working Voltage: 4.8-7.2v
- Temperature Range: 0- 55 Celsius Degree
- Plug: JR (Fits JR Futaba)
- Gear Type: Metal
- Cable Length: 32cm

### *2.3.2 Propulsion System Elements Integration*

Propulsion system elements are used to generate thrust and direct thrust to different axis. Therefore, the vehicle can move in the sky and can make all flying actions; roll, pitch, and yaw.

DC Brushless motors are mounted on servo motors with an interconnection part. This part is designed by using 3D sketching tool and printed by a 3D printer. It makes servo motor gear perpendicular to the brushless motor. Therefore, while servo motor rotates on horizontal axis, brushless motor can generate thrust on vertical axis.

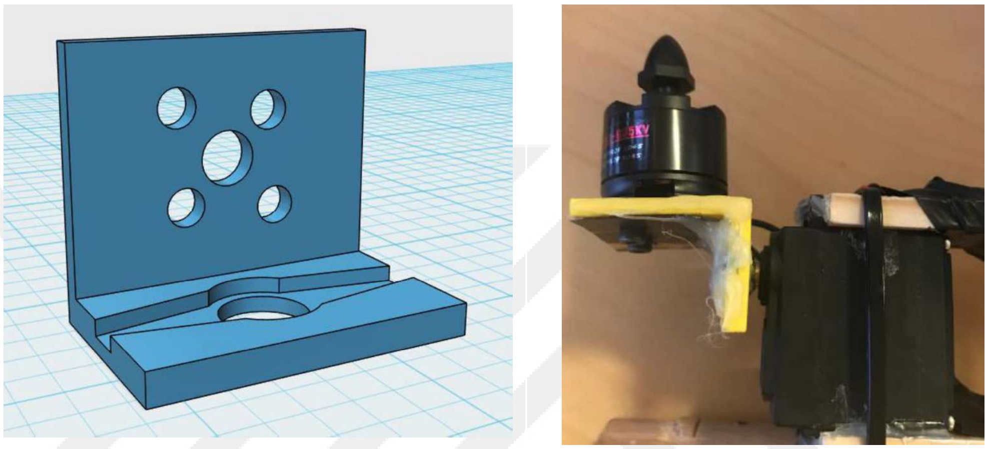


Figure 2.9 Interconnection Part for motors and servos (Personal archive, 2018)

Each servo motor and brushless motor couples are mounted at the end points of a single axis frame. ESC's are also mounted on the frame and connected to the brushless motors. As it is seen in the Figure 2.10, one of the ESC cables are connected to the brushless motor straight, other ESC cables are cross connected. This connection makes the motor turn around reverse rotational direction in order to suspend torque of each motor. If both motors turn in the same rotational direction, torque power make frame turn around itself which is an unwanted movement. Power input of the ESC's are connected to the battery with a common connection. BEC output of the ESC's act as 5V power supply and they will feed to the servo motors, flight controller and sensors. BEC output is connected to the 5V power line. Arduino UNO (or Pro Mini) is used as the flight controller. Vin and Ground pins of Arduino to be connected to 5V power line. In addition to Arduino, servo motors and sensors will be fed from this power line.

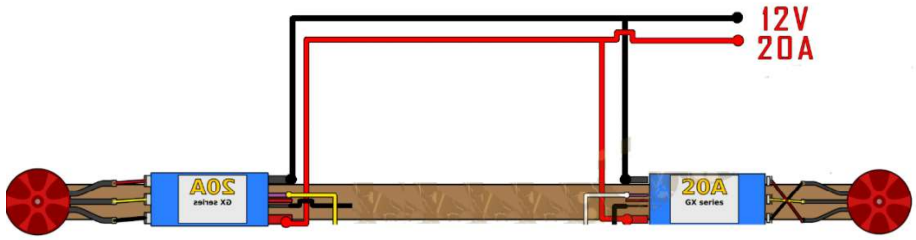



Figure 2.10 Frame of Propulsion System (Electronoobs, 2018)

Each brushless motor and servo motor have one input cable. Flight controller controls these motors by sending PWM signals to these inputs. Arduino UNO (or Pro Mini) has a 14 digital I/O and 4 of these I/O's to be allocated to control all 4 motors. All 4 I/O's generate PWM signal with width between 1000 and 2000µs. Servo motors input will be directly connected to I/O's and servo motors will be able rotate 0-180 degree. For brushless motors, firstly ESC's inputs are connected to the I/O pins then ESC's adjust the transferred current to the brushless motor according to the width of the PWM signal.

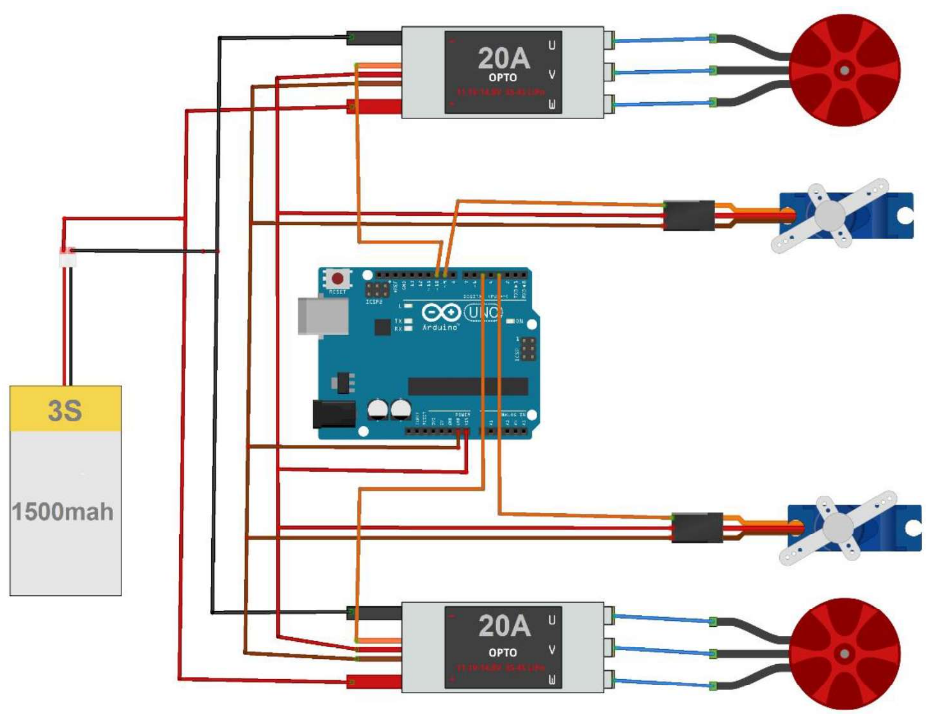



Figure 2.11 Propulsion System Integration Schematics

Propulsion system is constructed on a wooden frame as it is shown in Figure 2.12.

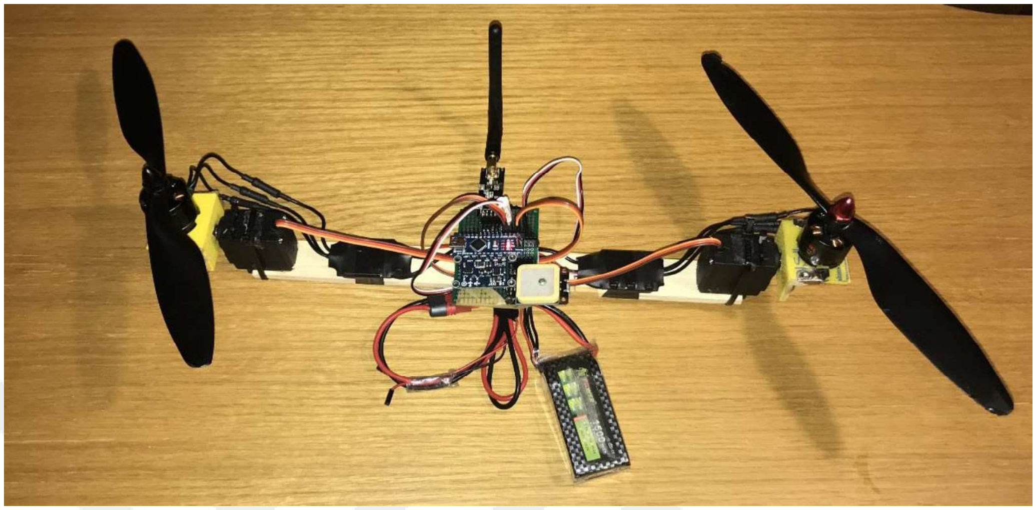


Figure 2.12 Propulsion System Implementation (Personal archive, 2018)

### *2.3.3 Direction of Movement*

Conventional aircrafts can rotate in three dimensions called as principle of axes; roll, pitch and yaw. In addition, to these rotational movements, some aircrafts have the ability to fly on vertical axis. Our vehicle will have also vertical take-off and landing (VTOL) functionality. All these movement is controlled with angle of servo motors and speed of brushless motors.

There are 4 forces on an aircraft as it seen in Figure 2.13. On vertical axis, gravity of the ground pull aircraft down. Lift forces pull aircraft to up. In fixed wing aircrafts, lift force is produced by wings by the function of speed, wing area, and wing shape. In hybrid airships, lift force is produced by LTA gases and motors thrust. On horizontal axis, thrust force which is produced by motors, pull aircraft forwards. Meanwhile, air resistance pulls aircraft back.

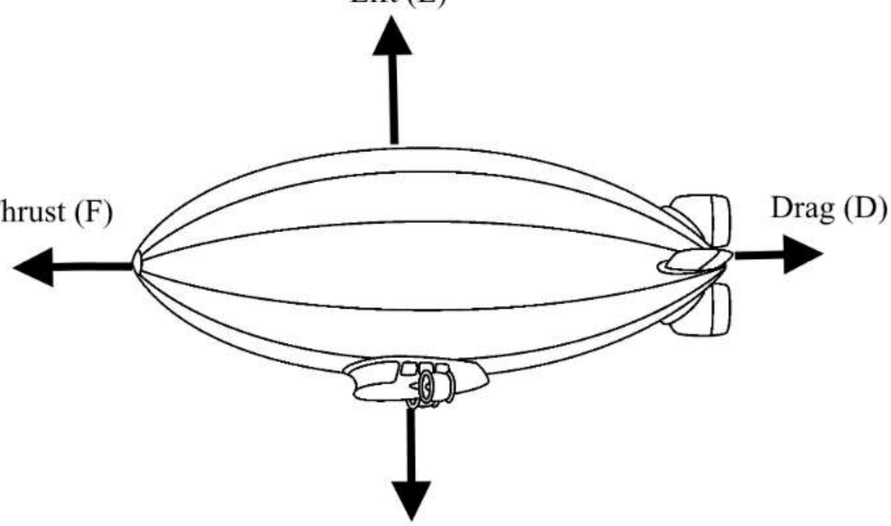



Figure 2.13 Forces on an aerial vehicle

Force on the vehicle could be examined with the variation of servo angles $\alpha_1$ (right) and $\alpha_2$ (left) motor speed $\omega_1$ and$\omega_2$.

**Case 1: $\boldsymbol{\alpha_1 = \alpha_2 = 90^0}$ and $\boldsymbol{\omega_1 = \omega_2 = \omega_2}$**

In this case, thrusts of motors are perpendicular to ground.

- If sum of lifting force of LTA gases and thrust force bigger than gravitational force, the vehicle can fly on vertical axis.
- If total force is zero, the vehicle saves its position on vertical axis.

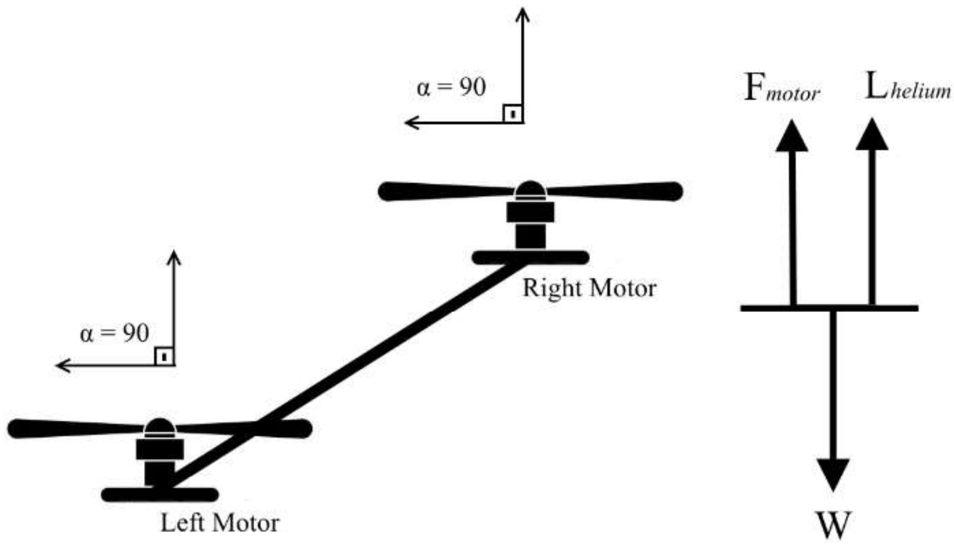



Figure 2.14 Vertical Movement

$$F_{vertical} = (F_{motor} + L_{helium}) - W \tag{2.4}$$

$$F_{horizontal} = 0 \tag{2.5}$$

**Case 2: $0^0 < \alpha_1 = \alpha_2 < 90^0$ and $\omega_1 = \omega_2 = \omega$**

In this case, motors can produce thrust on both horizontal and vertical axis.

- If Sum of vertical and horizontal forces are zero, the vehicle saves its position.
- If thrust of forces on horizontal axis greater than drag force, the vehicle can move forward.
- If vertical thrust is greater than gravitational force, the vehicle makes pitch action and nose of the vehicle turn to up.
- If vertical thrust is lower than gravitational force, the vehicle makes pitch action and nose of the vehicle turn to down.

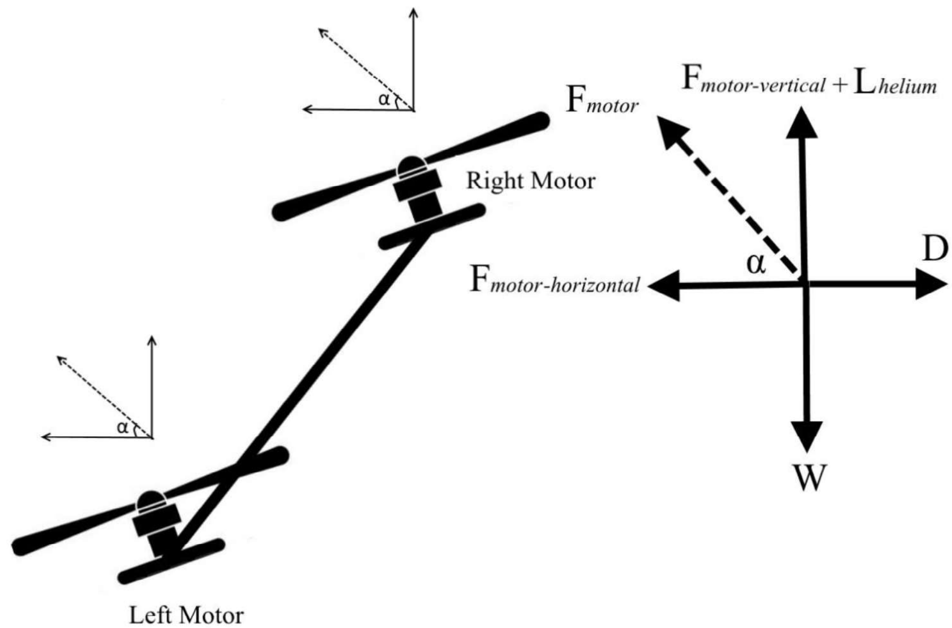



Figure 2.15 Pitch Movement

$$F_{vertical} = (F_{motor}\ x\ sin\alpha + L_{helium}) - W \tag{2.6}$$

$$F_{horizontal} = F_{motor}\ x\ cos\alpha - \mathrm{D} \tag{2.7}$$

**Case 3:** $\boldsymbol{\alpha_1} = \boldsymbol{\alpha},\ \boldsymbol{\alpha_2} = -\boldsymbol{\alpha}$ **and** $\boldsymbol{\omega_1} = \boldsymbol{\omega_2} = \boldsymbol{\omega}$

Similar with case-2, motors can produced thrust on both axis. But whatever the initial position of the motors, when rotating motors in reverse direction with a small and equal angle, the vehicle can rotate around vertical axis. Therefore, the vehicle can make the yaw movement. To minimize force change on vertical axis in order to save altitude, angle of $\alpha$ should be small.

- If horizontal thrust force of right motor is greater than left motor, the vehicle rotates to the right.

- If horizontal thrust force of right motor is less than left motor, the vehicle rotates to the right.

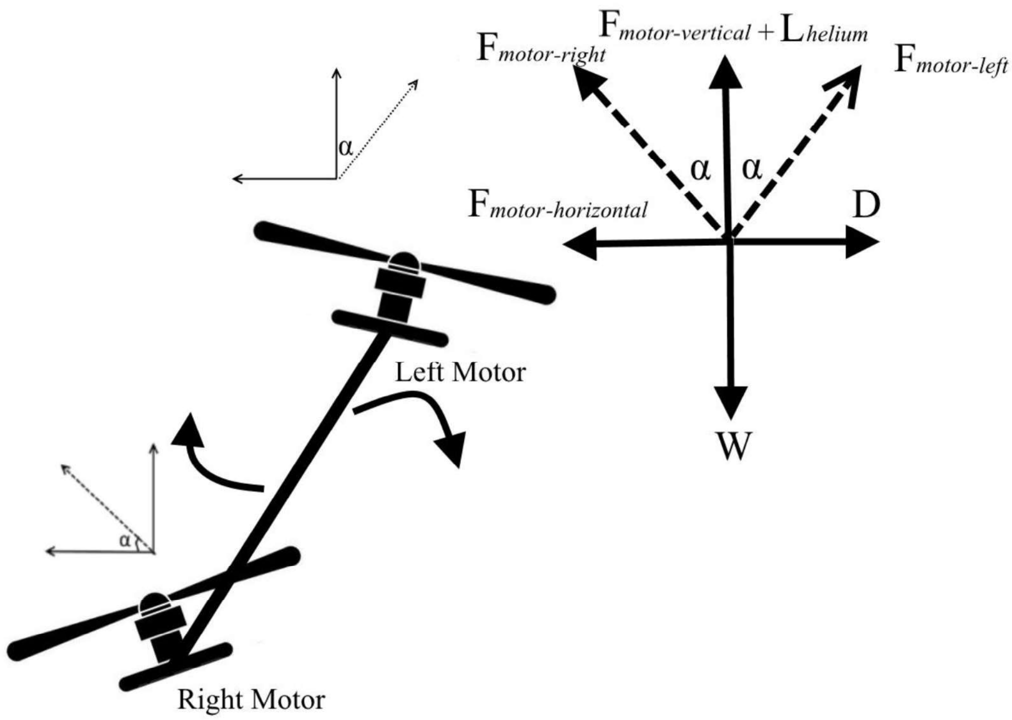



Figure 2.16 Yaw Movement

$$F_{vertical} = F_{motor-right}\ x\ cos\alpha + F_{motor-left}\ x\ \cos(-\alpha) + L_{helium} - W \qquad (2.8)$$

Assumed that, each brushless motor produces same power. Therefore, equation (2.8) turns into to equation (2.9).

$$F_{motor-right} = F_{motor-left} = F_{motor} \qquad (2.9)$$

$$F_{vertical} = 2\ x\ F_{motor}\ x\ cos\alpha + L_{helium} - W \qquad (2.10)$$

$$F_{horizontal} = F_{motor-right}\ x\ sin\alpha + F_{motor-left} xsin(-\alpha) - \mathrm{D} \qquad (2.11)$$

$$= F_{motor-right}\ x\ sin\alpha - F_{motor-left} xsin(\alpha) - \mathrm{D}$$

As stated in equation (2.9), each motor produces same power. Therefore, total horizontal motor power becomes 0. If vehicle moves forward during the time of yaw, only Drag force effects the vehicle in that time. If vehicle does not move on horizontal there is no horizontal force applied on the vehicle and net horizontal force is 0. In this case, vehicle makes rotational movement around center of gravity of the vehicle due to horizontal force which are produced by each motor. This movement called as yaw.

**Case 4: $\boldsymbol{\alpha_1 = \alpha}$ and $\boldsymbol{\omega_1 \neq \omega_2}$**

In this case, motor speeds are little bit different. Therefore, the vehicle can rotate around horizontal axis and make roll movement. But difference should be kept small in order to save position of the vehicle.

- If speed of right motor is greater than left motor, the vehicle rotates to left.
- If speed of right motor is less than left motor, the vehicle rotates to right.

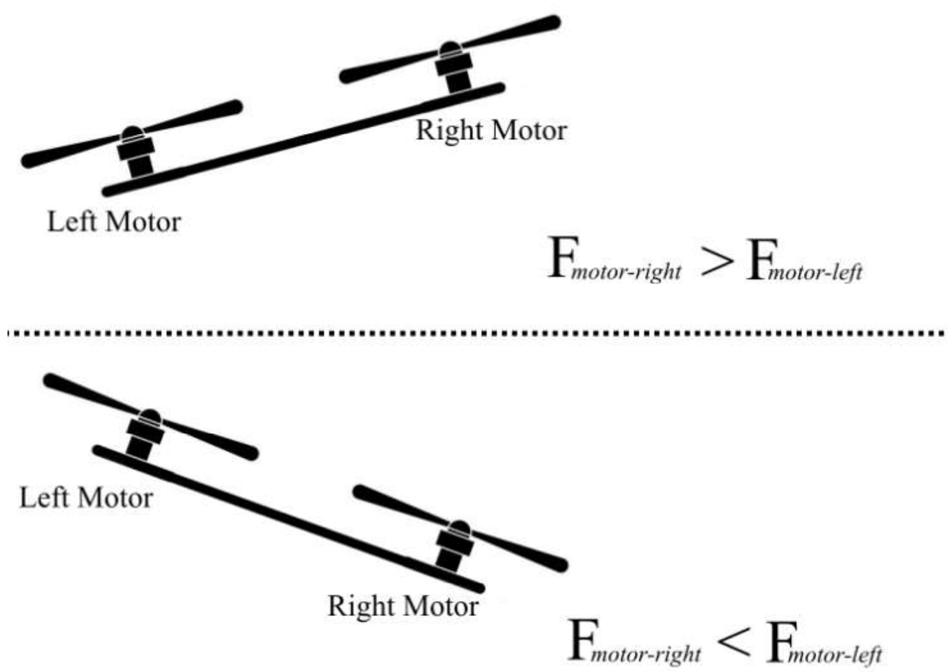



Figure 2.17 Roll

## 2.4 Flight Controller Design

Flight controller is main part of the vehicle. It computes flight data by using information received from the sensors and generates parameters which are used by other modules. Flight controller consist of a microcontroller and flight control algorithm. Arduino Nano is used as a microcontroller and algorithm is developed with C++ programming language. Flight controller interacts with several hardware.

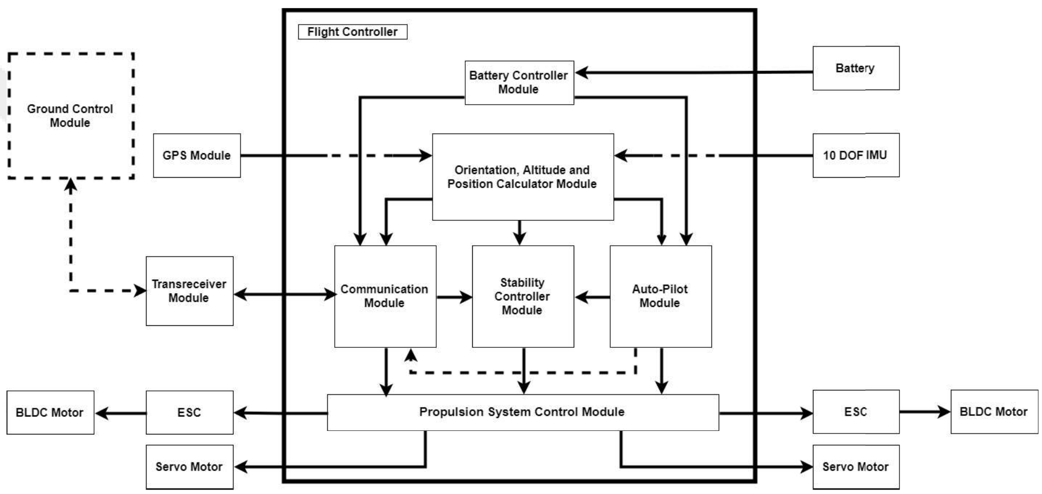



Figure 2.18 Flight Controller Block Diagram

Battery controller module instantly measures battery voltage. On the vehicle, an 11.1 V battery is used. But Arduino accepts maximum 5V as an input. Therefore, a voltage divider circuit is divide the voltage to 3. Then output of voltage divider circuit is connected one of analog input of Arduino. Battery controller module calculates real voltage level of battery then sends it to ground control and autopilot module via communication module.

10 DOF IMU includes accelerometer, gyroscope, magnetometer, and barometer sensors. It interacts with flight controller via I2C communication interface. Orientation, altitude and position calculator module receives raw data from the sensors then calculates orientation angles and altitude. Also, it interacts with GPS module via I2C bus and calculate position of the vehicle. All these data are important flight data

and it sends these data to ground control module via communication module, stability controller module and auto-pilot module.

Communication module works in two-directions. NRF24L01 wireless transreceiver is used to communicate with ground control module. It is connected to Arduino via SPI interface. It sends flight data to ground controller and receive control commands from ground controller then sends them to propulsion system controller module and auto-pilot module.

Stability controller module includes control algorithm for roll angle, yaw angle and altitude of the vehicle. It is used to keep the vehicle in pre-defined or desired position. Orientation, altitude, and position controller module sends orientation angles, altitude and position values and stability controller modules tries to keep position by using PID controller algorithm then sends commands to propulsion system.

Propulsion system control module adjust speed of brushless DC motors via ESC’s and position of the servo motors. ESC’s and servo motors are connected to Arduino with digital in-out (I/O) pins of the Arduino. Digital, I/O pins send PWM signals to ESC’s and servo motors. According to width of PWM signals, speed of DC motors and position of servo motors are controlled. Propulsion system control module adjust speed and positions based on the command received from ground control via communication module, stability controller module and auto-pilot module.

Auto-pilot module consist of auto-pilot algorithm and controls the vehicle during autonomous flight. Before or during the flight, it receives flight task and based on the task, it executes pre-defined use cases in order to complete flight task. During flight it is in communication with stability controller module, propulsion system and ground controller via communication module.

### *2.4.1 Orientation, Altitude, and Position Calculator Module*

Orientation, altitude, and position parameters are key parameters for flight and flight control. These parameters are calculated by flight controller by using measured data retrieved from sensors. Theory and implementation are detailed in following sections.

#### *2.4.1.1 Orientation Theory*

In mathematics, orientation describes how an object is placed in the three-dimensional space. Orientation or attitude is the angular position of an object with respect to a reference placement (Orientation, 2018). Therefore, orientation gives relative angular position of the object from the reference placement which is specified in a three-dimensional Cartesian coordinate system.

Flight Dynamics is a branch of science in aviation and defines orientation of an aerial vehicle with three critical parameters of flight dynamics pitch, roll and yaw. These parameters are angles of rotation with respect to vehicle's center of mass in three-dimensional space. They are also called as "Aircraft Principal Axes". In flight dynamics, axes convention is standardized way of defining the location and orientation of an aerial vehicle. Orientation of a flying vehicles is defined by taking references from an external fixed frame and other frames on the vehicles.

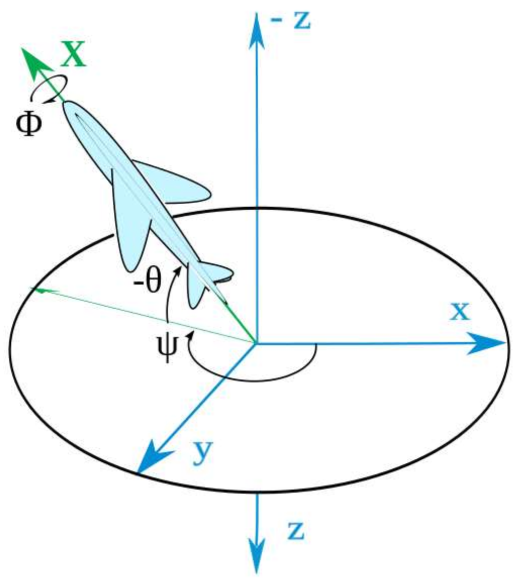



Figure 2.19 Orientation of an aircraft (Orientation, 2018)

Figure 2.19 describes principal of axes on a fixed-wing aircraft. Principle of axes refers to rotation around the axes. Starting point of the principal axes is steady flight position of the aircraft. During the steady flight, there is not any force applied on the aircraft and net acceleration of the aircraft is zero. In this state, wings of the aircraft parallel to ground and roll angle is assumed zero. As per the Figure 2.19, Roll angle ($\phi$) is rotation round the X axes also called as wing angle. Yaw is rotation around the Z axed and called as heading ($\psi$). Pitch is rotation around the Y axis and called as trim or angle of attack ($\theta$) (Aircraft principal axes, 2018).

Roll, pitch, and yaw angles are dynamics parameters and continuously measured during the flight. These parameters are main input parameters of aircraft control systems. They are measured by using several sensors. In this work accelerometer, gyroscope and magnetometer are used to define the angles of roll pitch and yaw.

Accelerometer measures rate of velocity change, acceleration. When and accelerometer device lays on the ground, it measures gravity of earth. Rotating the accelerometer around itself, changes the measured gravity value applied on each side of the accelerometer.

Gyroscope is a device that measures to angular velocity of an object. During the rotation around any axis of the object, angular velocity of the rotation could be measured. Magnetometer measures magnetic field of the earth. It consists three orthogonal sensors and therefore, it measures magnetic field in three dimensions.

For small scale aerial vehicles, there are lots of sensors available in the market at affordable prices. Usually, two or three of these sensors are integrated on a single board and called as Inertial Measurement Unit (IMU). IMU's are classified according to number of Degree of Freedom (DOF). DOF shows number of parameters that are measured. In the vehicle that is being designed, 10-DOF IMU is used. 10 DOF indicates measurement of 3-axis acceleration, 3-axis angular velocity, 3-axis magnetic field and the atmospheric pressure. Accelerometer, gyroscope, and magnetometer measurements are used to calculate roll, pitch, and yaw angles; atmospheric pressure is used to measure altitude of the vehicle.

Roll, pitch, and yaw angles are calculated by combining Accelerometer, gyroscope, and magnetometer measurement readouts. Accelerometer measures acceleration and therefore measures gravity. Accelerometer sensor includes three individual sensors for each of three dimensions. Ratio of amount of gravity measured by each sensor, used to calculate orientation with respect to the ground. With accelerometer, only roll and pitch angel can be calculated. Because z-axis is defined at the same direction with gravity and rotation around the z-axis does not change the measured value by accelerometer. To calculate yaw angle, magnetometer will be used. Roll and pitch angles can be calculated with accelerometer by using equation (2.12) and (2.13). ax, ay, and az refer acceleration measured for x, y and z-axis.

$$roll_{accel} = \arctan\left(\frac{ay}{\sqrt{ax^2 + ay^2}}\right) \text{ rad} \tag{2.12}$$

$$pitch_{accel} = \arctan\left(\frac{-ax}{\sqrt{ax^2 + ay^2}}\right) \text{ rad} \tag{2.13}$$

Roll and pitch angle can be calculated with gyroscope by using equation 2.14 and 2.15. gx and gy refers to angular velocity of rotation around x and y-axis respectively.

$$roll_{gyro} = roll_{gyro} + \text{gx.dt rad} \tag{2.14}$$

$$pitch_{gyro} = roll_{gyro} + \text{gy.dt rad} \tag{2.15}$$

Accelerometer can measure roll and pitch angle alone, but it is very noisy. It is also possible to calculate these angle with gyroscope, but it tends to drift over time. The best result can be achieved by combining accelerometer and gyroscope readout.

There are several methods to filter accelerometer noise and reduce gyroscope drift. Most known method is the Kalman Filter. Kalman filter calculates rotation angles with sensor measurement and system noise. It provides good and smooth outputs, but it is hard to determine the system noise and it requires high number of computations. Therefore, it uses high resource from the controller. Similar with the Kalman Filter, Mahony and Madgwick filters also provide good outputs but use very high resources from the microcontroller. Another method is the Complementary Filter. Despite its ease to implement and use of very low resource from the microcontroller, it provides accurate outputs (Treffers and Wietmarschen, 2016). It compensates gyroscope drift by using accelerometer readout. Equation 2.16 and 2.17 gives the roll and pitch angle calculation by using complementary filter; $\alpha$ is the filter coefficient and must be between 0 and 1. It determines the weight of the accelerometer and gyroscope measurement in the output.

$$roll = \alpha\left(roll_{gyro}\right) + (1 - \alpha)\, roll_{accel} \text{ rad} \tag{2.16}$$

$$pitch = \alpha\left(pitch_{gyro}\right) + (1 - \alpha)\, pitch_{accel} \text{ rad} \tag{2.17}$$

Yaw angle cannot be measured with only an accelerometer. Because for orientation calculation, Earth is selected as the reference frame and z-axis determined towards to direction of gravity. So, rotation of around z-axis does not change the measurement result and readout is always equal to gravity. Magnetometer can measure the magnetic field of earth which is perpendicular to gravity. So, it is sensitive to rotation around z-axis. Magnetometer sensor includes three individual magnetometers for each axis and these magnetometers are align with axis of the sensor. Therefore, readout should be corrected with pitch and roll angles to get yaw angles. Yaw angle can be calculated by using Equation 2.20. mx, my and mz are normalized values of magnetometer sensors. Roll and pitch angle are measured angles by accelerometer and gyroscope which are shown in equation 2.16 and 2.17.

$$magx = mz * \sin(roll) - my * \cos(roll) \tag{2.18}$$

$$magy = mx * \cos(pitch) + my * \sin(pitch) * \sin(roll) + mz * \sin(pitch) * \cos(roll) \tag{2.19}$$

$$yaw = \arctan(magx/magy) \text{ rad} \tag{2.20}$$

*2.4.1.2 Altitude Theory*

Altitude indicates the height of an on object with respect to a reference point. In aviation, altitude can be used either from mean sea level (MSL) or above ground level (AGL) (Lish, 2017). In this thesis, altitude indicates vertical distance of the vehicle from the sea level. Altitude will be measured by using a pressure sensor which measures atmospheric pressure. Altitude is calculated by using atmospheric pressure and temperature readouts from the sensor with using equation 2.21.

$$P_0: sea - level\ pressure\ in\ hPa$$

$$P: pressure\ measured\ by\ sensor\ in\ hPa$$

$$T: Temperature\ in\ celcius\ degree$$

$$altitude = \frac{\left(\left(\frac{P_0}{P}\right)^{\frac{1}{5.2571}} - 1\right) * (T + 273.15)}{0.0065}\ meter \tag{2.21}$$

*2.4.1.3 Position Theory*

Geographic Coordinate System identifies every location on the earth with a set of numbers called as latitude and longitude. These numbers show the location of the objects with respect to equator and prime meridian. Latitude is an angle and specifies north-south position of a location. Equator is defined as $0^0$ and poles are defined as $90^0$. Longitude is an angle and specifies east-west position of a location. Prime meridian is defined as $0^0$. It ranges from prime meridian to $+180^0$ eastward and $-180^0$ to westward. There are three formats used to indicate the position of a location or an object with latitude and longitude angles (Geographic Coordinate System, 2018).

*degrees minutes seconds: 40° 26′ 46″ N 79° 58′ 56″ W*
*degrees decimal minutes: 40° 26.767′ N 79° 58.933′ W*
*decimal degrees: 40.446° N 79.982° W*

With the development of technology, satellites are used to define exact position of an object and it is the fastest and more accurate way of defining the position. Global Positioning System (GPS) is the first space-based radio navigation system which is developed by USA. It consists of 33 geo-stationary satellites in the orbit. During defining the location, it sends signal to GPS receiver from at least 4 satellites and defines the position with accuracy of around a few meters. Without requiring any license, it can be used freely if having a GPS receiver. Apart from USA, Russia developed GLONASS, Chine developed COMPASS and European Union is developing GALILEO space-based positioning systems. Also, Japan and India have regional space-based positioning systems (Jin, 2012).

In this thesis, GY-NEO6MV2 GPS receiver is used to define the position of the vehicle.

*2.4.1.3 Orientation Calculation*

To calculate roll, pitch, yaw angles and altitude, Adafruit 10 DOF IMU sensor is used. It includes LSM303DLHC accelerometer and magnetometer sensors, L3G4200D gyroscope sensor and BMP180 pressure sensor. All these sensors are integrated on a single board and supports I2C and SPI interfaces. During measurement, I2C interface is used. SDA pin is connected to A4; SCL pin is connected to A5 pin of Arduino board.

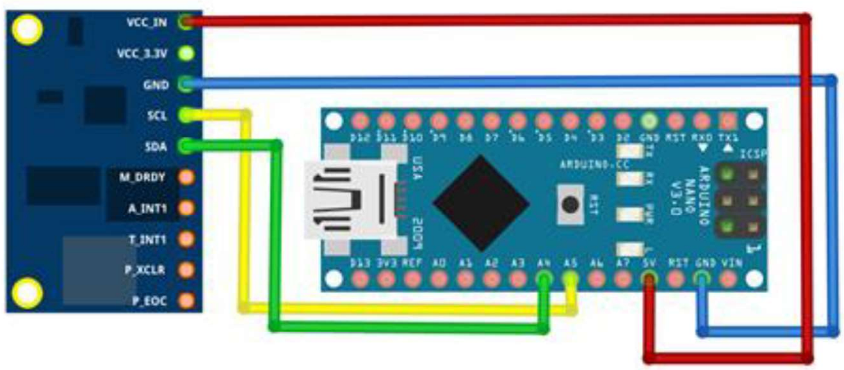



Figure 2.20 Arduino and 10 DOF IMU Integration

There is a master-slave relation between the sensors and the flight controller. Once the flight controller activates the sensors, they generate outputs as long as they are active. Each sensor produces outputs as a number between pre-defined range. These numbers should be converted to a meaningful format with a unit. Conversion methods and formulas are provided by the manufacturer in datasheet of sensors. Despite sensors are calibrated during fabrication, still they may produce some offset. To get accurate readouts, sensors should be calibrated first. All three sensors have very high sensitivity. Therefore, they are open to produce noise. Even a small vibration may cause high amount of noise. To get rid of noise, sensor readouts should be filtered. After sensor outputs are filtered, roll and pitch angle are calculated then results are combined with complementary. Once roll and pitch angle are calculated, yaw angle will be calculated by using roll and pitch angles and normalized magnetometer readouts. Same process will be applied also to define altitude. To determine position, no need to apply any filter or compensate the outputs.

*2.4.1.3.1 Accelerometer Measurement.* Adafruit provides out-of-box library to get accelerometer readouts from the sensors. For accelerometer readings, Adafruit_LSM303.h library is used. It provides accelerometer outputs in $m/s^2$ and therefore no need to apply additional conversion. To calibrate accelerometer, it should be considered that there is always gravitational force applied on the accelerometer. While 10 DOF IMU board lay on a flat surface, gravitational acceleration pulls board towards the ground and it can be measured by the accelerometer on z-axis. It should be around 9.80 $m/s^2$. For calibration, it is measured for 1000 times and average values is accepted as mean gravity ($g_{mean}$). For +z-axis, offset is assumed zero and it will be used as a reference value for calibration of other axis. After that, same gravitational force is applied on all axis and average acceleration is measured for all axis. Difference between $g_{mean}$ and average measurement for each axis to be added or subtracted from readouts for each time and calibrated values will be obtained with function defined in equation 24.

$$g_{mean} = \frac{\sum_{k=0}^{1000}(az)}{1000} \tag{2.22}$$

$$a_{z-cal} = g_{mean} \tag{2.23}$$

$$a_{i-cal} = a_i - [\sum_{n=0}^{1000}(a_i) - g_{mean}],\ (i = x, -x, y, -y\ - z) \tag{2.24}$$

Raw data and calibrated accelerometer readings are shown in Figure 2.21 and Figure 2.22 respectively.

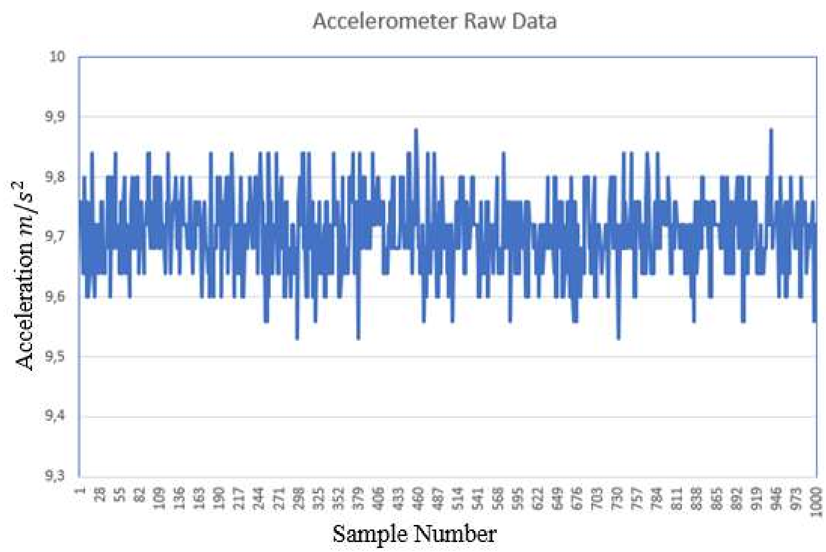



Figure 2.21 Accelerometer Raw Data

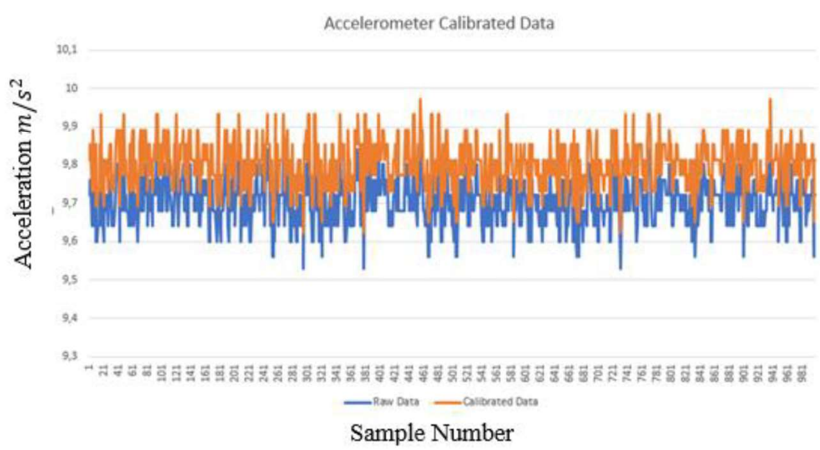



Figure 2.22 Accelerometer Calibrated Data

After accelerometer readouts are calibrated, noise parameters are filtered by using Exponential Moving Average (EMA) filter. EMA filter take average of last few readouts compress noise elements. Average value is multiplied with a coefficient. This coefficient is calculated with equation 2.25 by using difference of last readout and previous output of the filter then multiply it a filter multiplier which is between 0 and 1 and defined after some trial. Filter algorithm is below:

$$f(x) = 1 - (1/(1 + \mathrm{x})) \tag{2.25}$$

```
NoiseFilter(RawData, Multiplier)
{
Delta = abs(RawData FilterOut);
FilterCoeff = 1.0 (1.0/((((DeltaX))*(Multiplier) + 1.0)));
FilterOut = (FilterOut + (RawData FilterOut)*FilterCoeff);
}
```

Filtered accelerometer readouts are given in Figure 2.23.

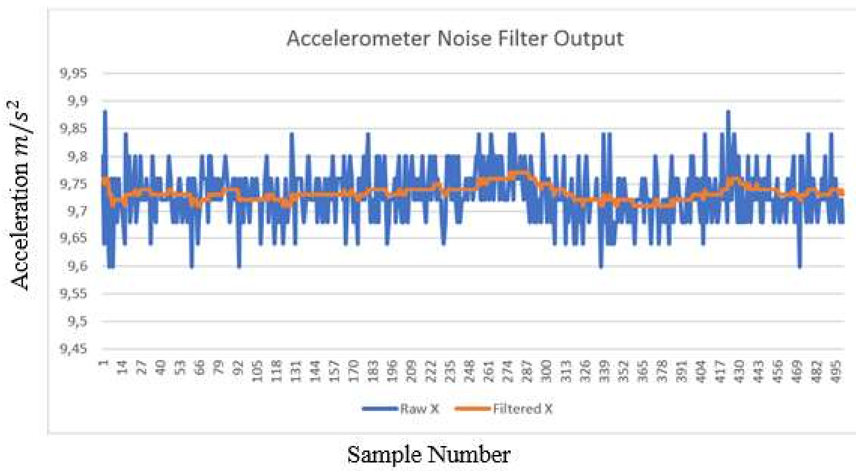



Figure 2.23 Filtered Accelerometer Data

*2.4.1.3.2 Gyroscope Measurement.* Like the accelerometer, Adafruit provides out-of-box library to get gyroscope readouts from the sensors. For gyroscope readings, Adafruit_L3G200D.h library is used. It provides gyroscope outputs in $degrees/s$ and therefore no need to apply additional conversion. Gyroscope readouts include offset and noise. To compensate offset, gyroscope should be calibrated first. Gyroscope measures speed of rotation. Therefore, when sensors lay on a surface and it does not move, readouts of all three axis are expected to be zero. According the Figure 2.24, for all three axes, readouts are not zero. To correct offset values of all axis, firstly, average offset value is defined for each axis then average offset will be subtracted from each axis for all measuring.

$$g(i)_{offset} = \frac{\sum_{k=0}^{1000} g(i)}{1000}, \quad (i = x, y, z) \tag{2.26}$$

$$g(i)_{calibrated=}g(i) - g(i)_{offset}, (i = x, y, z) \tag{2.27}$$

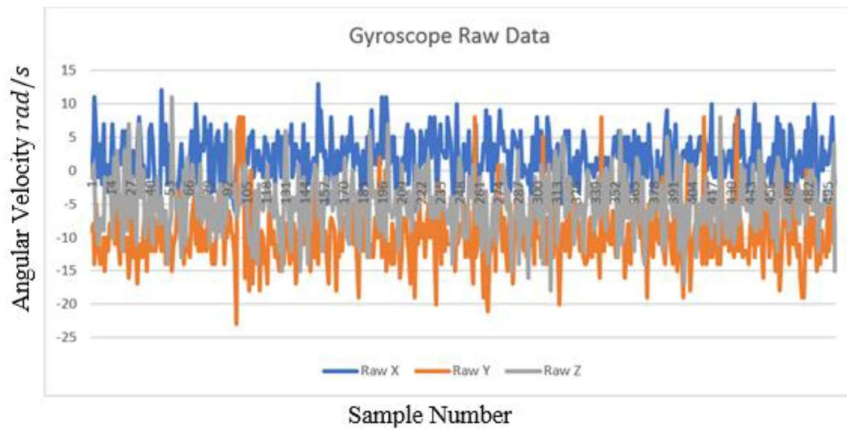



Figure 1.24 Gyroscope Raw Data

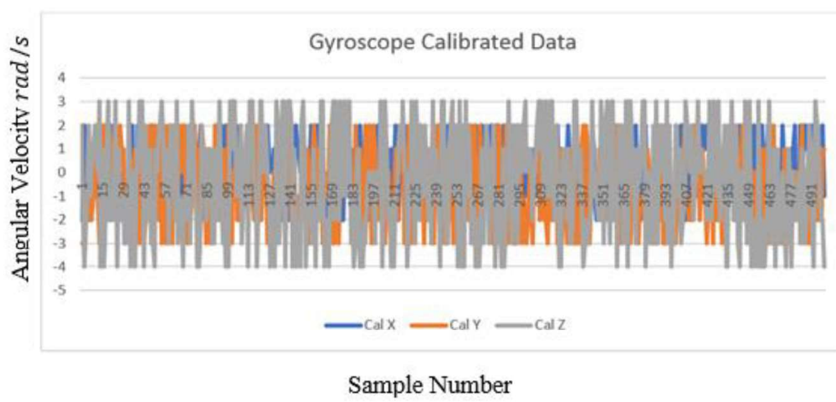



Figure 2.25 Gyroscope Calibrated Data

After gyroscope readouts are calibrated, noise parameters are filtered by using same Exponential Moving Average (EMA) filter that was used for accelerometer readouts. Filtered gyroscope read outs are given in Figure 2.26.

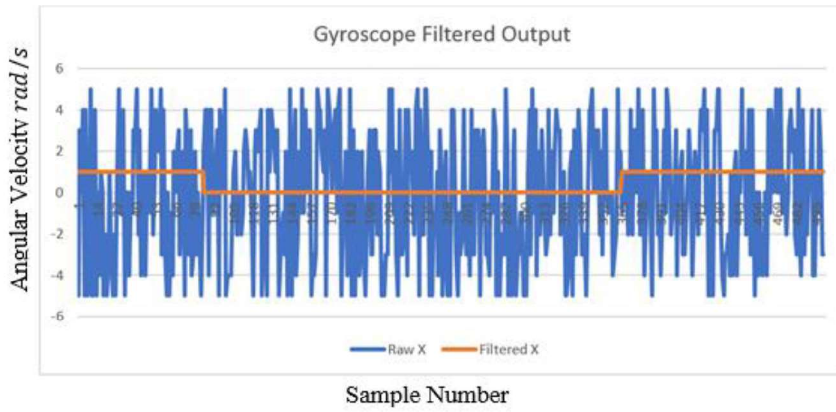



Figure 2.26 Gyroscope Filtered Data

*2.4.1.3.3 Roll and Pitch Angle Calculation.* Once sensors are calibrated and readouts are filtered, roll and pitch angle are calculated individually by using accelerometer and gyroscope sensor outputs then they will be combined with complementary filter. To convert roll and pitch angles in degree, result is multiplied by $\frac{180}{\pi}$.

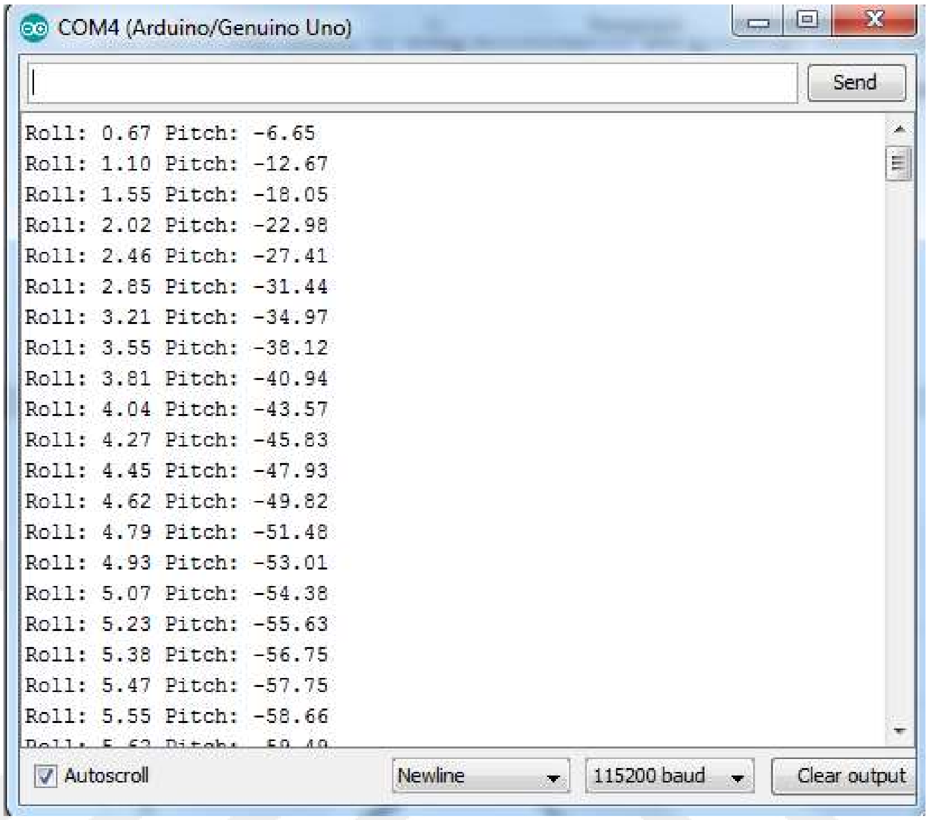



Figure 2.27 Roll and pitch angles measurements

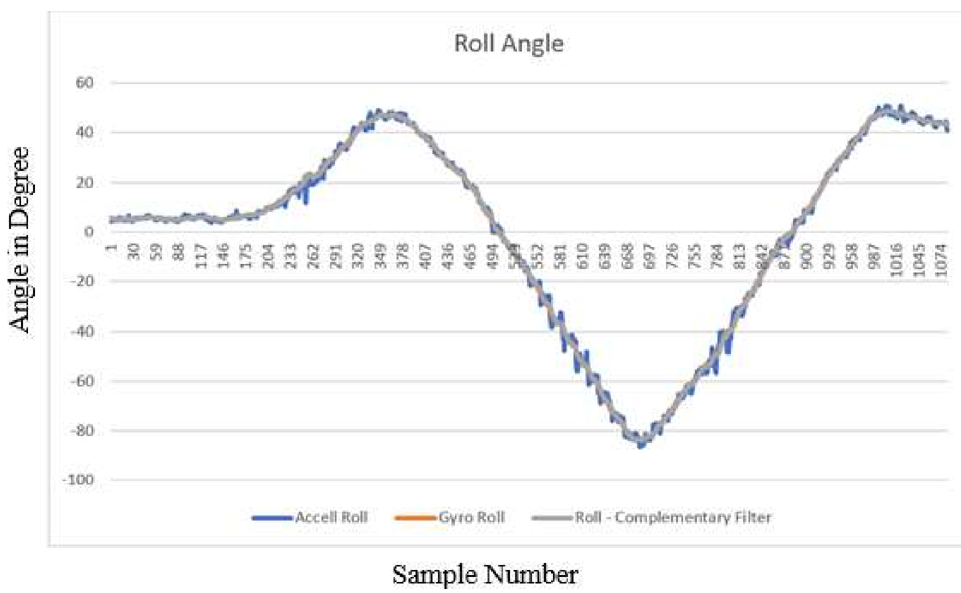



Figure 2.28 Roll Angle

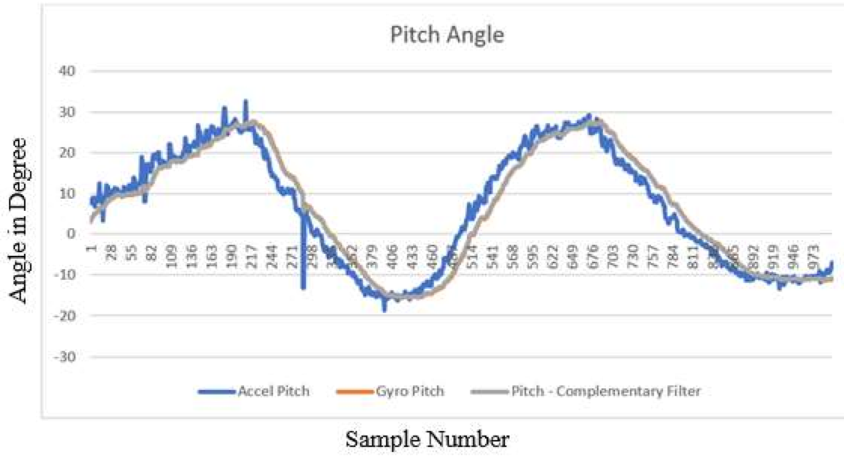



Figure 2.29 Pitch Angle

*2.4.1.3.4 Magnetometer Measurement.* Like the accelerometer and gyroscope, Adafruit provides out-of-box library to get magnetometer readouts from sensors. For magnetometer readings, Adafruit_LSM303.h library is used. It provides gyroscope outputs in $\mu T$ and therefore no need to apply an additional conversion. Magnetometer sensor used to measure the strength of earth's magnetic field. Most electrical components produce magnetic field and these magnetic fields may affect the sensor measurement. Source of interference are analyzed under two group called as Hard Iron Losses and Soft Iron Losses. Hard Iron Losses are due to the magnetized components of electronics device of the sensor and Soft Iron Losses are due to the induced current because of earth's magnetic fields (Treffers and Wietmarschen, 2016). To calculate Hard and Soft Iron Losses, "Motion Sensor Calibration Tool" is used. This tool defines Hard and Soft Iron Losses In equation 2.28 [C] matrix represents soft iron losses and the tool measures its value as "Magnetic Mappings". [B] Matrix represents hard iron losses and the tool measures its value as "Magnetic Offset".

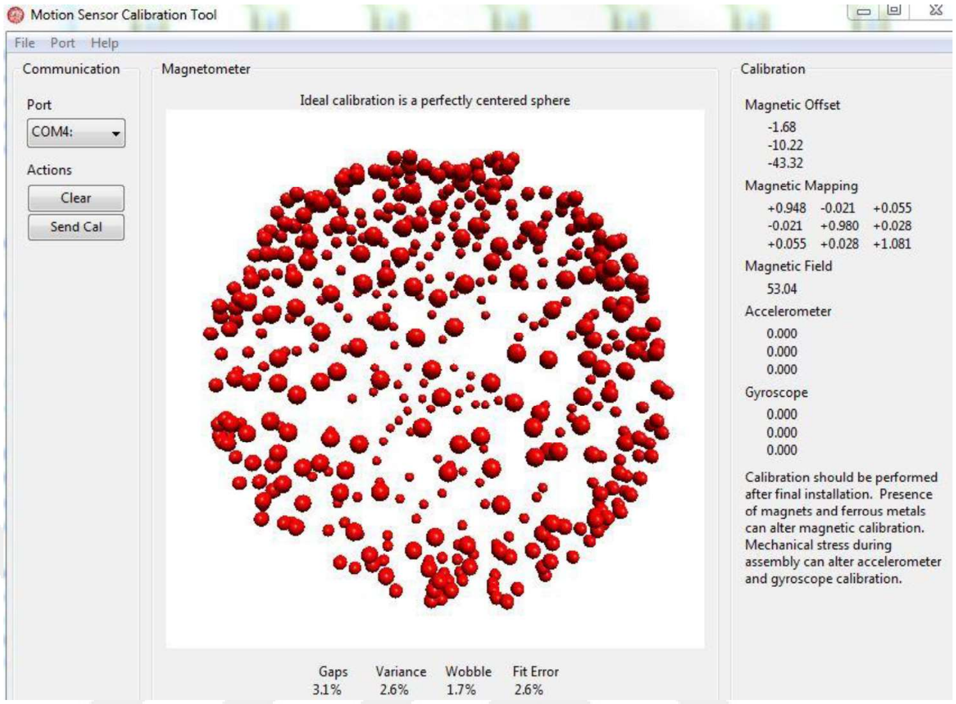


Figure 2.30 Magnetometer Calibration

$$\begin{pmatrix} mx_{cal} \\ my_{cal} \\ mz_{cal} \end{pmatrix} = \begin{pmatrix} C_1 & C_2 & C_3 \\ C_4 & C_5 & C_6 \\ C_7 & C_8 & C_9 \end{pmatrix} \begin{pmatrix} mx - B_x \\ my - B_y \\ mz - B_z \end{pmatrix} \tag{2.28}$$

After magnetometer readouts are calibrated, noise parameters are filtered by using same Exponential Moving Average (EMA) filter that was used for accelerometer and gyroscope readouts.

*2.4.1.3.5 Yaw Angle Calculation.* Once magnetometer is calibrated and readouts are filtered, yaw angle is calculated by using equation 2.20. Equation 2.20 gives yaw angle in radian. To convert yaw angle into the degree, it is multiplied with $\frac{180}{\pi}$.

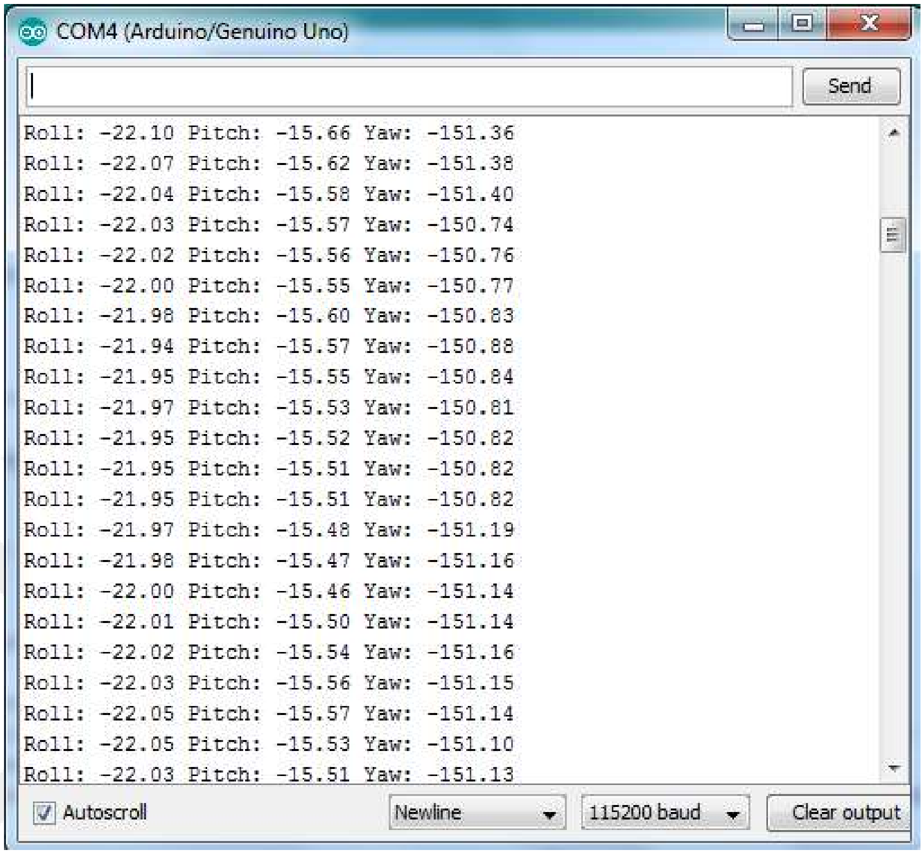



Figure 2.31 Roll, pitch, and yaw angles measurements

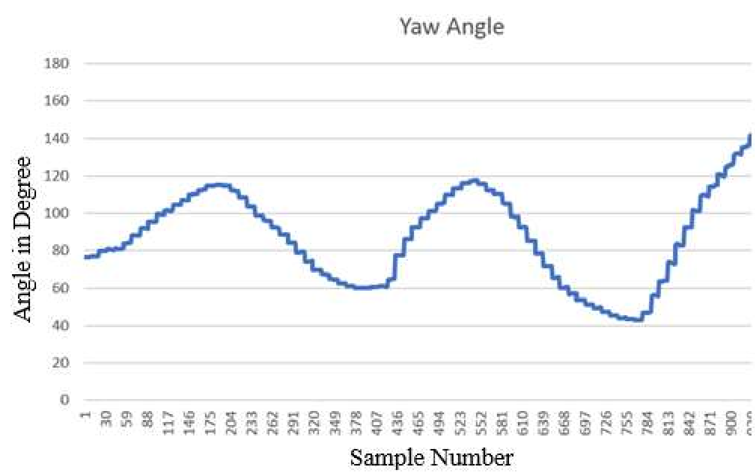



Figure 2.32 Yaw Angle

*2.4.1.4 Barometer Measurement and Altitude Calculation*

Like the accelerometer, gyroscope, and magnetometer, Adafruit provides out-of-box library to get barometer readouts from sensors. For barometer readings, Adafruit_BMP180.h library is used. It provides gyroscope outputs in $hPa$ and therefore no need to apply additional conversion. Pressure information alone does not carry any altitude information. It just gives the atmospheric pressure at this level. According the equation 2.21, sea-level pressure and Temperature must be known to calculate altitude. Sea level pressure is not a constant every time. Before the flight, it should be set by using meteorology bulletin information. For Turkey, this information can be obtained from Turkish State Meteorological Service official web site, daily report.  Other variable temperature can be measured by using temperature sensors. BMP180 sensor includes also a temperature sensor and it measures temperature continually during the flight.


Figure 2.33 Turkish State Meteorological Service, daily meteorology bulletin (Turkish State Meteorological Service, 2018)

After sea-level pressure value is set, equation 2.21 is ready to provide altitude information. Similar with other sensors, firstly it is calibrated. For calibration, measurement should be taken in sea-level or in equation 2.21, $P_0$ should be set the value of current pressure level.

$$h_{offset} = \frac{\sum_{k=0}^{1000}(h)}{1000} \tag{2.29}$$

$$h_{cal} = h - h_{offset} \tag{2.30}$$

During time of calibration, atmospheric pressure is measured as 995.09 hPa at the location of measurement. Then average offset is calculated as 0.38 meter. It is subtracted from each altitude measurement.

After sensor is calibrated, readouts to be filtered by using same EMA filter which is used for accelerometer, gyroscope, and magnetometer. During altitude calculation, see level pressure is set as 1003 hPa which is provided sea level pressure for Izmir by Turkish State Meteorological Service on February 27, 2018.

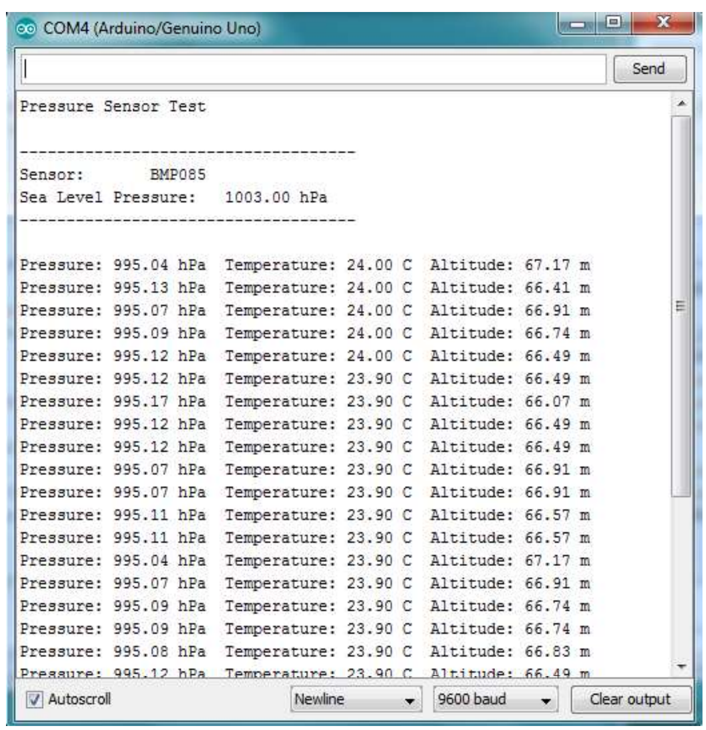


Figure 2.34 Pressure and altitude measurement

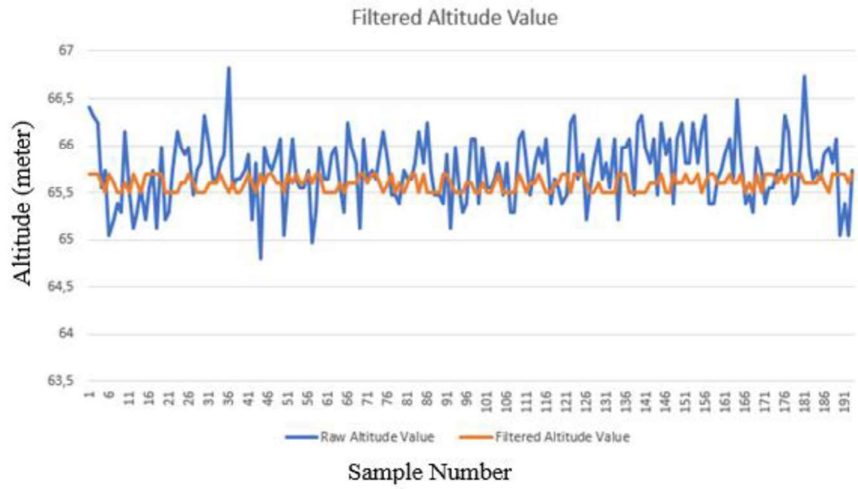



Figure 2.35 Filtered altitude measurement

*2.4.1.5 GPS Module Measurement and Position Calculation*

GY-NEO6MV2 GPS receiver is used to calculate position of the vehicle. It communicates with the flight controller via serial communication ports of the Arduino. It produces longitude and latitude information in decimal degree format. It can be then converted into the decimal degree minutes and decimal degree seconds by using conversion formulas.

Results is verified by using online coordinate checker tools and according to Figure 2.37, GPS receiver shows correct position with a perfect accuracy.

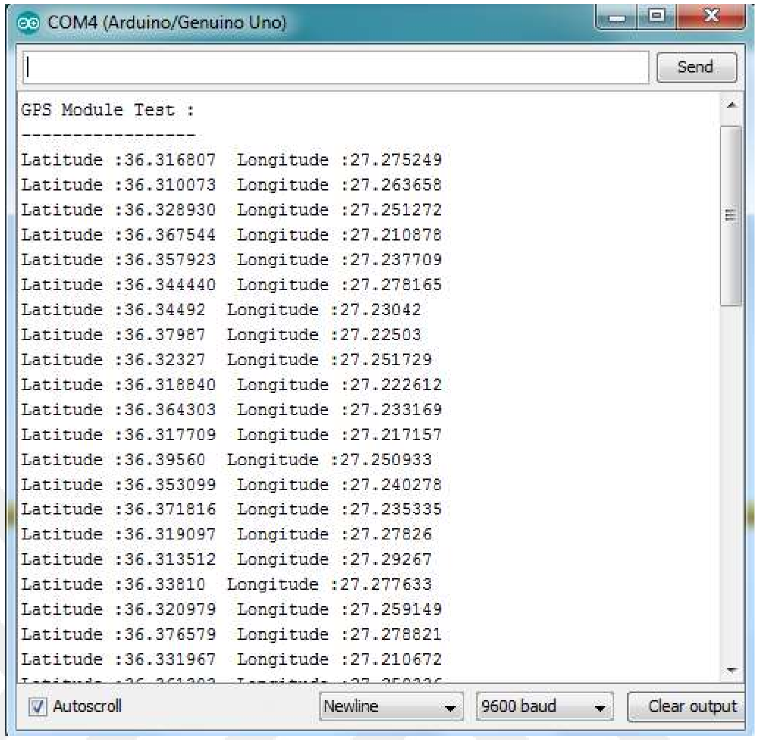


Figure 2.36 Position measurement

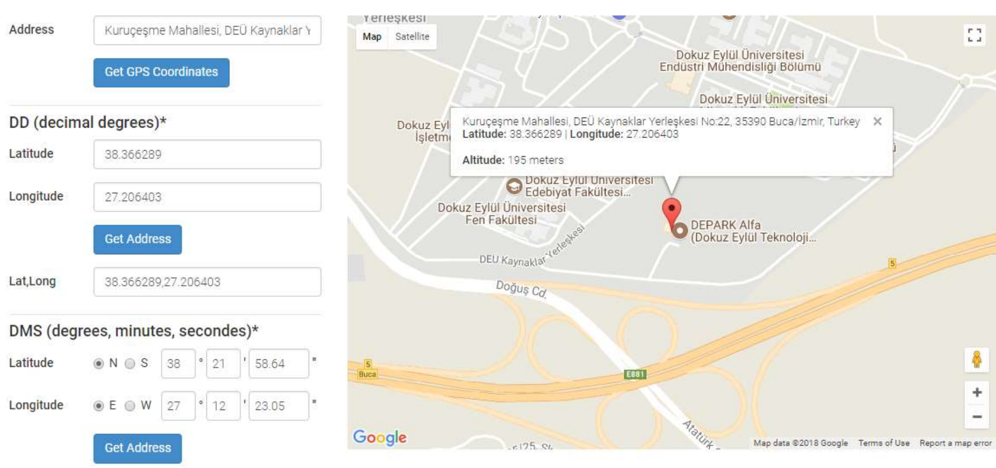


Figure 2.37 Position verification

### *2.4.2 Controller Design*

An aircraft should save its position against internal and external effects. Ideally, an aircraft is expected to fly in equilibrium state, unless pilot or operator does not attempt to change the position of the aircraft. During steady state, all motors on the vehicle should work in same speed. Also, all elements of the vehicle should work simultaneously. Therefore, while ignoring external effects, an aircraft should work stable without any stability control system. But in real world, those elements do not work at the same speed or simultaneously and it may make aircraft unstable due to internal effects. Apart from the internal effects, air conditions, wind, temperature can be counted as the external effects which may make aircraft unstable. To make aircraft stable against to those internal and external destructive effects, control systems are indispensable part of the flight controller systems (Azevado, 2014).

Controller system tries to keep aircraft in adjusted position unless these set point is changed. Adjusted position might be value of roll, pitch, yaw angles, altitude or position. In the vehicle that is designed, three controller systems are used to maintain balance of the vehicle. First is used to save the vehicle in steady state position which means roll angle must be always zero. Second is the heading controller which means yaw angle must be kept in adjusted value. Heading parameter indicates direction of flying. In order to reach target location, heading parameter must be kept as it was adjusted during flight plan or unless it is changed by pilot or operator. The last controller is for the altitude. Flight altitude should be kept as what was adjusted during flight plan unless the operator changes it.

#### *2.4.2.1 PID Controller*

Proportional-Integral-Derivative (PID) control is a loop feedback mechanism used widely in control engineering. It is an industrial control standard and mainly used in industrial system as well as used in a lot of applications. Basically, in a control system, sensors read output of the system and output of the system is read by control system via a feedback loop. Control system measures error by calculating the difference between the output and the reference value. Then control system generates response by using transfer function of the control system. Finally control system output is added to the system output. It will continue until the system reaches the steady-state condition. Then control system tries to keep the system output in its steady-state value (Åström, 2002).

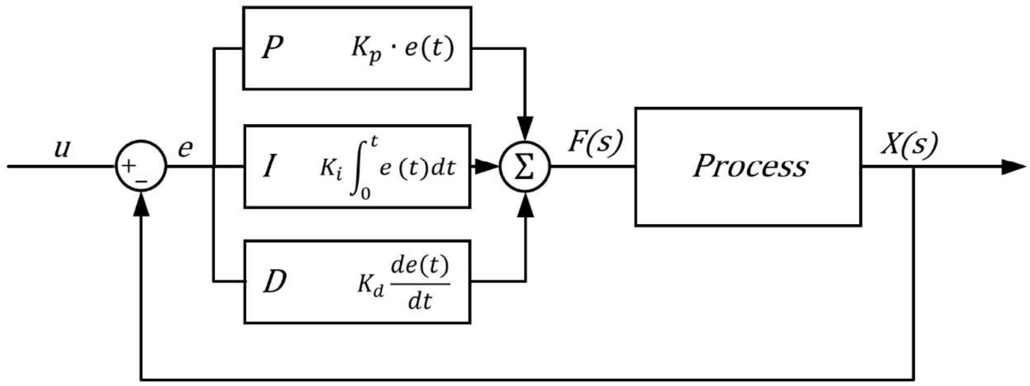


Figure 2.38 PID Controller (Åström, 2002)

PID controller has three elements called as proportional, integral, and derivative. Proportional component depends on only difference between set point and process output. It is called as error. Proportional gain $K_p$ is the ratio of the output response to the error. Higher $K_p$ value increases the speed of the control system response. However, larger $K_p$ value may oscillate process variable and makes system unstable, even causes oscillation out of the control (Åström, 2002).

Integral element sums the error over time. Each processing loop, integral part sums current error with previously summed errors. Therefore, integral response of the control system continuously increases over time unless error is zero. Integral component is sensitive also for small errors and it causes that integral component increases slowly in time. Therefore, steady state error can be reduced with integral element. Integral component tends to increase over time. Therefore, integral gain $K_i$ should be small. In most of the applications, integral component is limited to be active in small range of the error (Åström, 2002).

Derivative component generates rapid response to any error change in order to stabiles process output. Response of derivative component depends on rate of change of error over time and based on rate of change, it estimates future characteristics of error. Derivative gain and loop time should be low as much as possible. Because derivative element is very sensitive to noises Therefore, even a small noise can make system unstable. General PID control function is given in equation 30 (Åström, 2002).

$$u(t) = K_p * e(t) + K_i * \int e(t)dt + K_d \frac{de(t)}{dt} \tag{2.31}$$

PID algorithm is easy to implement with almost all programming language. In embedded systems, set point is defined as hardcoded in program. Sensors are continuously read process variable. Embedded systems are continuous systems and program calculates processing time for every loop which is used to calculate integral and derivative component of the controller. PID algorithm is given below.

*error = reference processVariable*

*pre*

*dT: loop time*

*PID: Controller Output*

*P: Proportional Component*

*I: Integral Component*

*D: Derivative Component*

*Kp = Proportional Gain*

*Ki = Integral Gain*

*Kd = Derivative Gain*

*P = Kp*error*

*I = I + (ki*error*dT)*

*D = kd*(error-previous_error)/dT*

*PID = P + I + D*

The hardest part of designing a PID control system is defining gains and it is called as PID tuning. The most used method is trial and error. Firstly, $K_p$ gain is defined and it is increased until system oscillates. Also, response time should be noted. System should provide fast response, but the engineer should ensure that the system should not be unstable. Then integral gain should be set. Optimum Integral gain should stop or reduce to oscillation. Integral component is expected to reduce steady-state error, but it is normal to increase overshot. Finally, derivative gain is adjusted to reach system to set point quickly. After three gains are set, if requires, all three gains should be adjusted to get better response.

### 2.4.2.2 Equilibrium (Roll) Controller

The vehicle has two motors, each motor is mounted on the end of a single-axis frame. The single-axis frame lays on y-axis and the frame can rotate around x-axis. To keep frame in balance, rotation angle (roll angle) around x-axis should be zero during the flight. Roll angle is continuously measured by using accelerometer and gyroscope sensors. PID algorithm calculates the error and generates a PID response. PID response increases or decreases width of PWM signals which are sent to ESC's to adjust speed of motors according to PWM width. ESC's are calibrated to receive PWM signals which have width between 1000 µs and 2000 µs. PWM signal is a kind of rectangular periodic signal an its total length is 20 ms. Positive part of the signal called as PWM width. In this work, PWM width adjusted to vary between 1000 µs and 2000 µs. Flight controller generates four PWM signals to control BLDC Motors and servo motors independently.

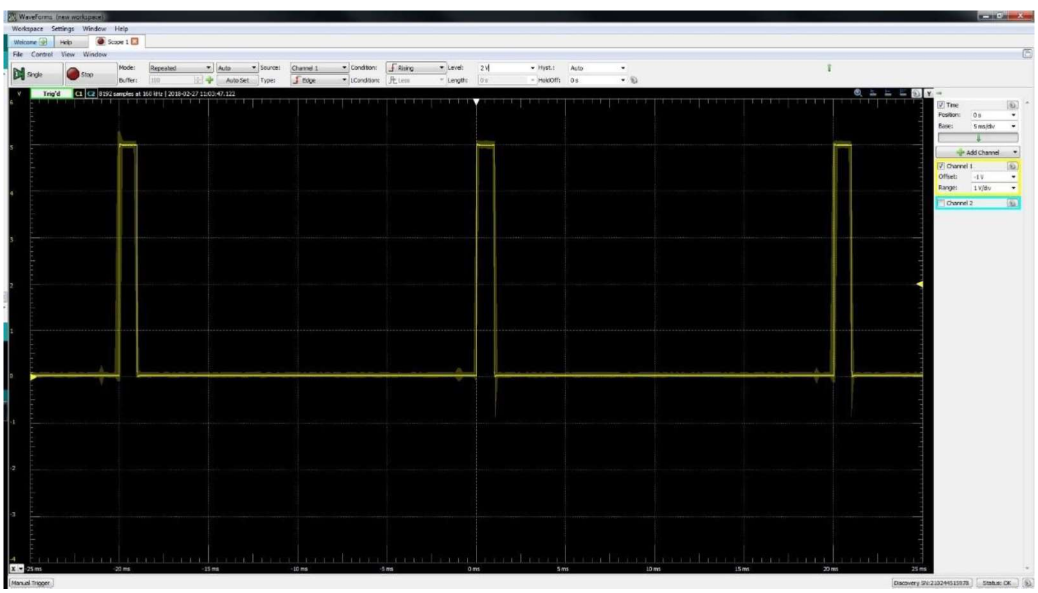


Figure 2.39 PWM Signal

There three conditions for roll controller;

- If roll angle is around zero-degree, right motor and left motor should have same speed and PID output should be zero. Therefore, there is not any effect expected by PID controller.

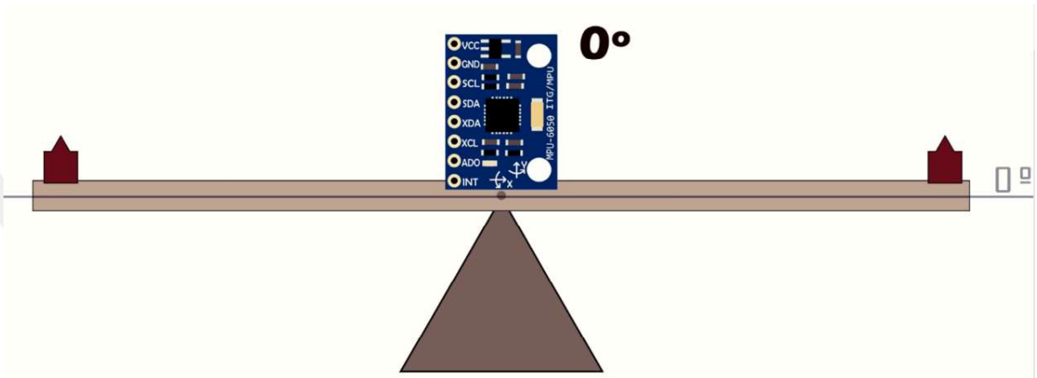



Figure 2.40 Steady-state of the frame (Electronoobs, 2018)

In this case, error is also 0 degree then flight controller generates same PWM signals for each motor as it is seen in figure below.

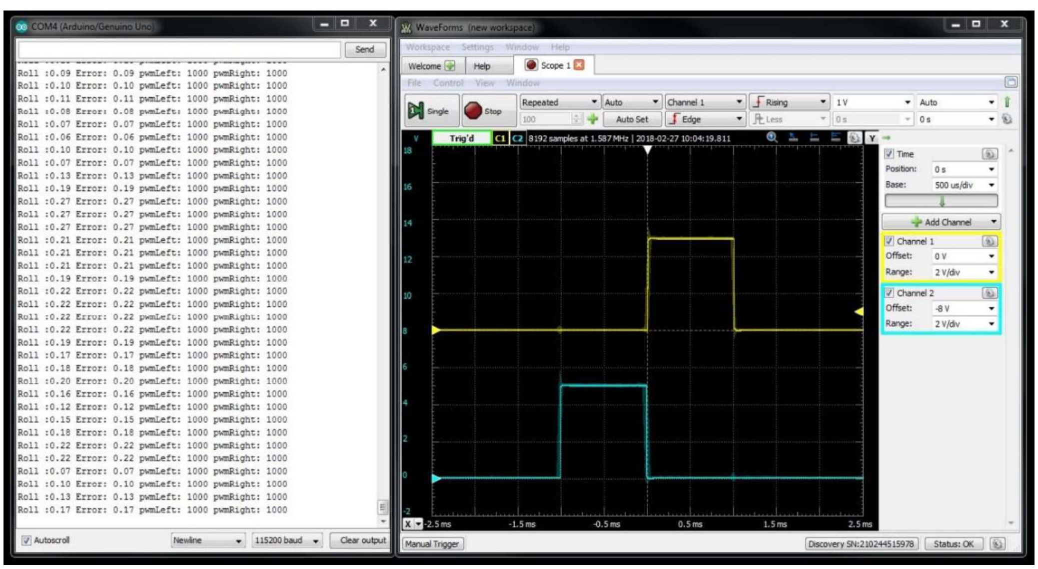


Figure 2.41 BLDC control PWM signals during state-state of the frame

- If roll angle is positive, it means frame falls towards to right, then speed of the right motor decreases; the left motor speed increases by amount of the PID response.

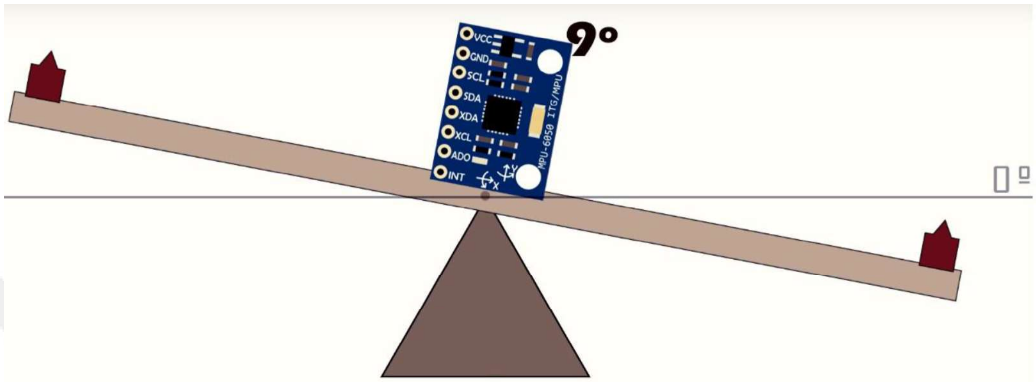



Figure 2.42 Frame lies to the right (Electronoobs, 2018)

In this case, to make frame balanced, flight controller should increase speed of the right motor. As it is seen in figure below, width of PWM signal for right motor is increased.

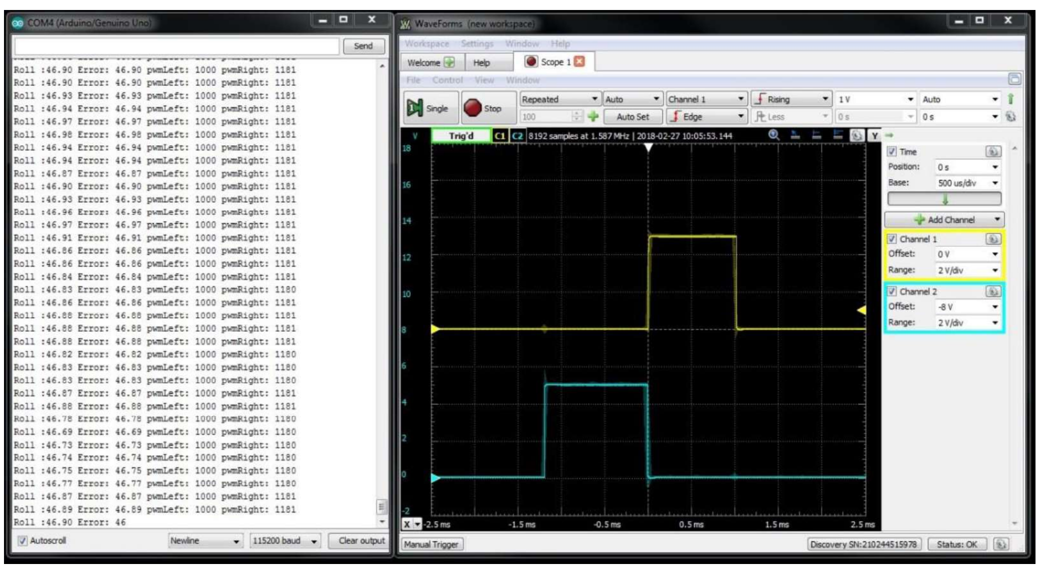


Figure 2.43 BLDC control PWM signals during frame lies to the right

- If roll angle is negative, it means frame falls towards to left, then speed of the left motor decreases; the right motor speed increases by amount of the PID response.

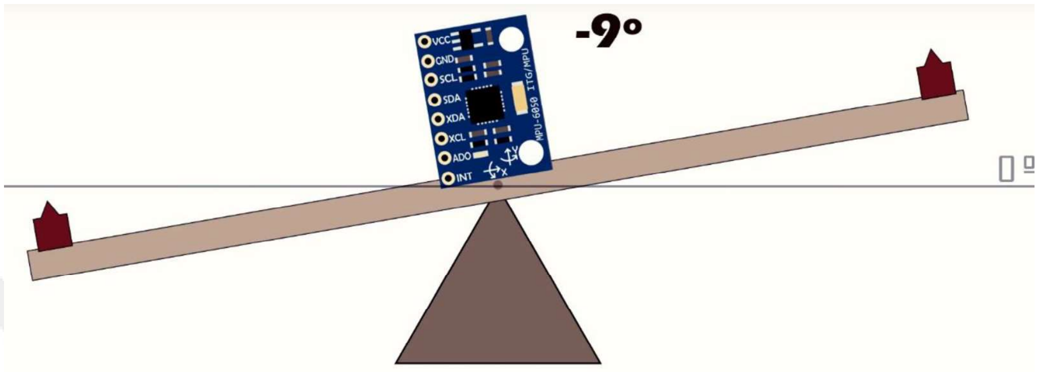



Figure 2.44 Frame lies to the left (Electronoobs, 2018)

In this case, to make frame balanced, flight controller should increase speed of the right motor. As it is seen in figure below, width of PWM signal for right motor is increased.

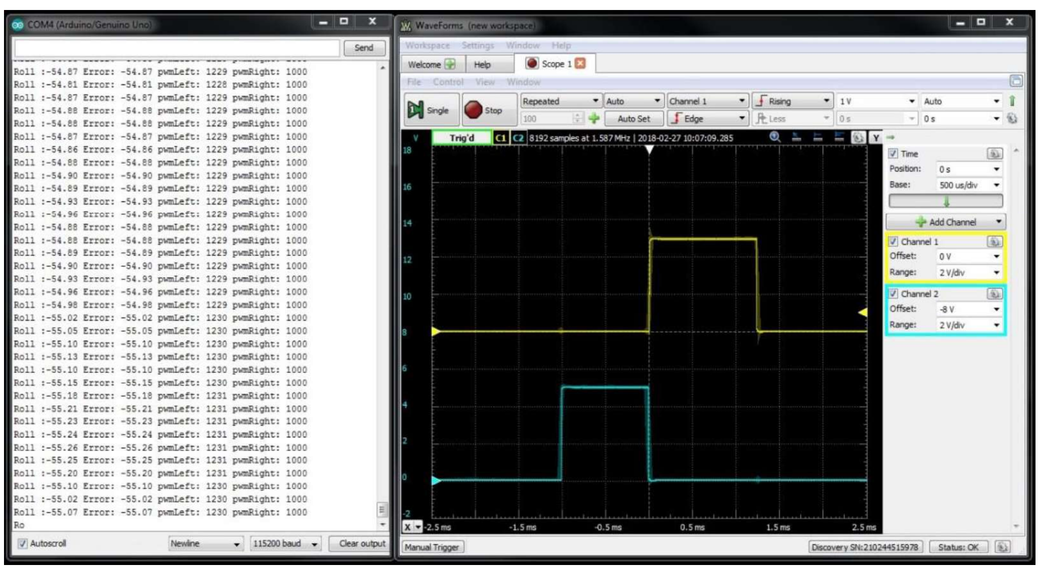



Figure 2.45 BLDC control PWM signals during frame lies to the left

### *2.4.2.3 Heading (Yaw) Controller*

Heading, in other word yaw angle, indicates where the vehicle is flying to. Therefore, heading angle should be stable to reach in fastest and shortest way to target. Heading of the vehicle is controlled by two servo motors. Servo motors change directions of horizontal thrust of the motors. By this way, heading of the vehicle is controlled.

During testing of Yaw controller, +120 degrees is set as reference for yaw angle. Controller tries to keep heading angle always around reference angle. In Figure 2.46, the vehicle heading angle is around 120 degrees, therefore relative position of each servo motor is same. So, the vehicle does not rotate any direction. In Figure 2.47, the vehicle lost its heading position and turned towards to right. In this case, flight controller changes position of the right servo motors and rotates the vehicle towards right, in the third case which is seen in Figure 2.48, opposite of second case occurs.

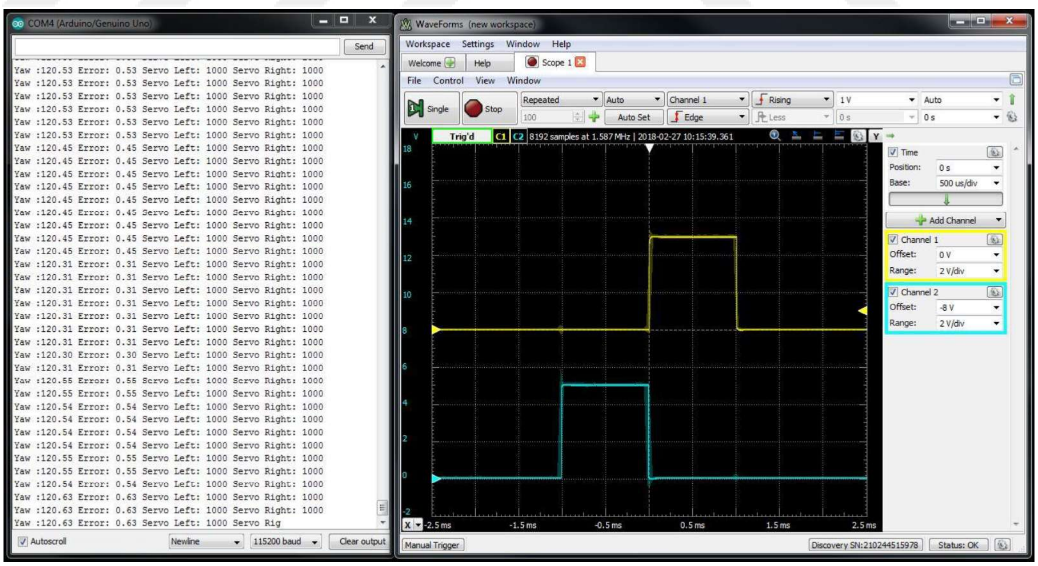



Figure 2.46 Servo motors control PWM signals during steady-state

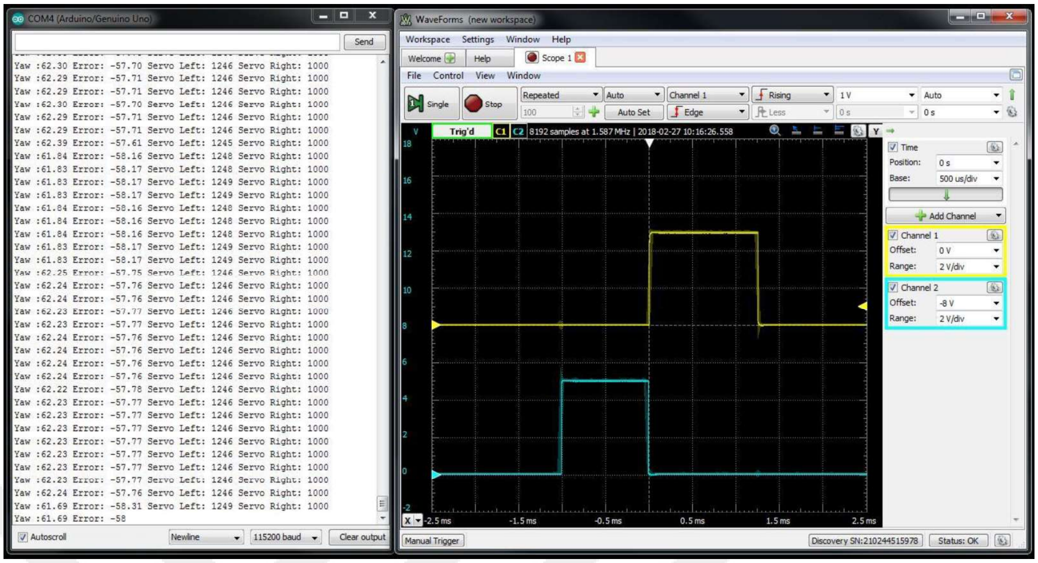



Figure 2.47 Servo PWM signals during the vehicle turned to the right

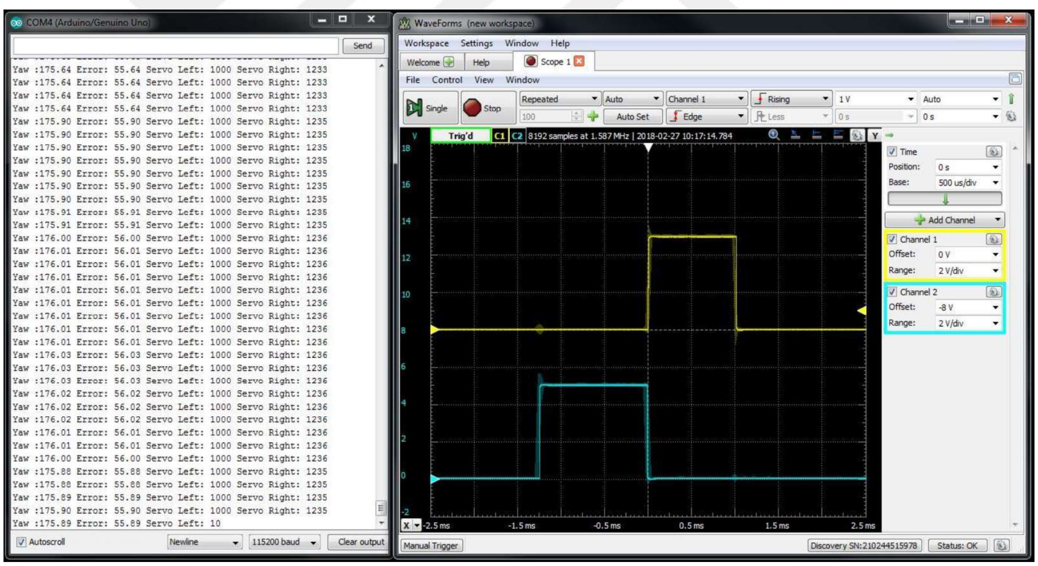



Figure 2.48 Servo PWM signals during the vehicle turned to the left

### *2.4.2.2 Altitude (Height) Controller*

Aircraft flying altitude is a key parameter during the flight. One of the reason is geographical condition on the route. Altitude should be higher than the highest point on the route. It is valid also for human made constructions. In addition, most of the countries have altitude restriction or allowed an altitude range for each flight based on flying types. Therefore, altitude controller is a kind of obligation that a flight controller must have.

The vehicle gains altitude with vertical thrust of motors. By using pressure sensor, flight controller calculates the altitude of the vehicle. Then PID controller measures altitude error. If altitude is higher than the set point, thrust of both two motors decrease by amount of PID response and vice-versa.

During testing of altitude controller, altitude of location where test is executed, is set as reference altitude, as 183 meters according to sea-level. When altitude of the vehicle is around the reference point, flight controller tries to keep vehicle in this position therefore width of the PWM signals do not change. When the vehicle is below its reference point, flight controller increase width of both PWM signals to increase speed of each motor. When the vehicle is above reference point, vice-versa.

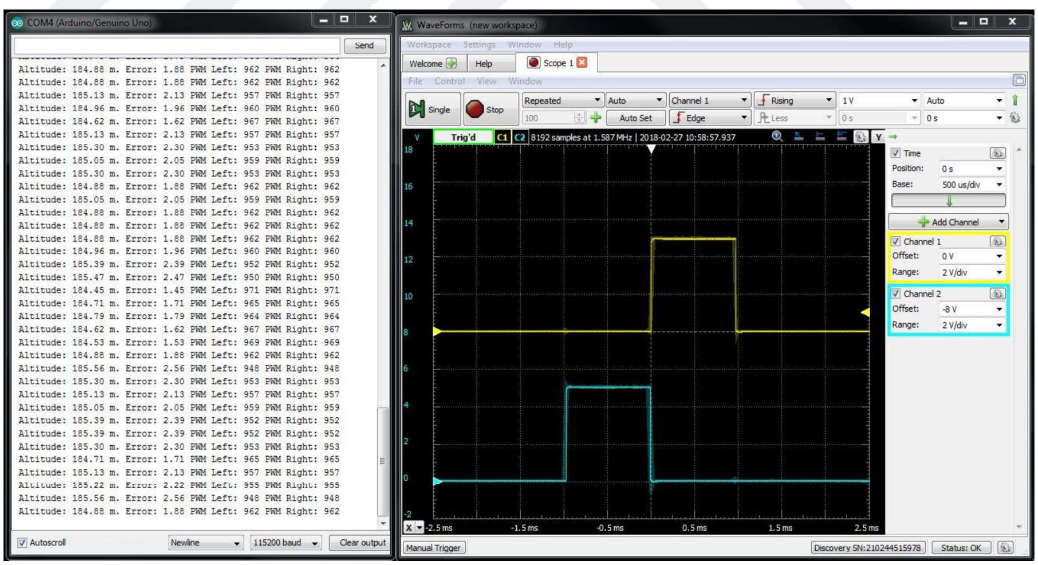



Figure 2.49 DC motors PWM signals during the vehicle in steady-state

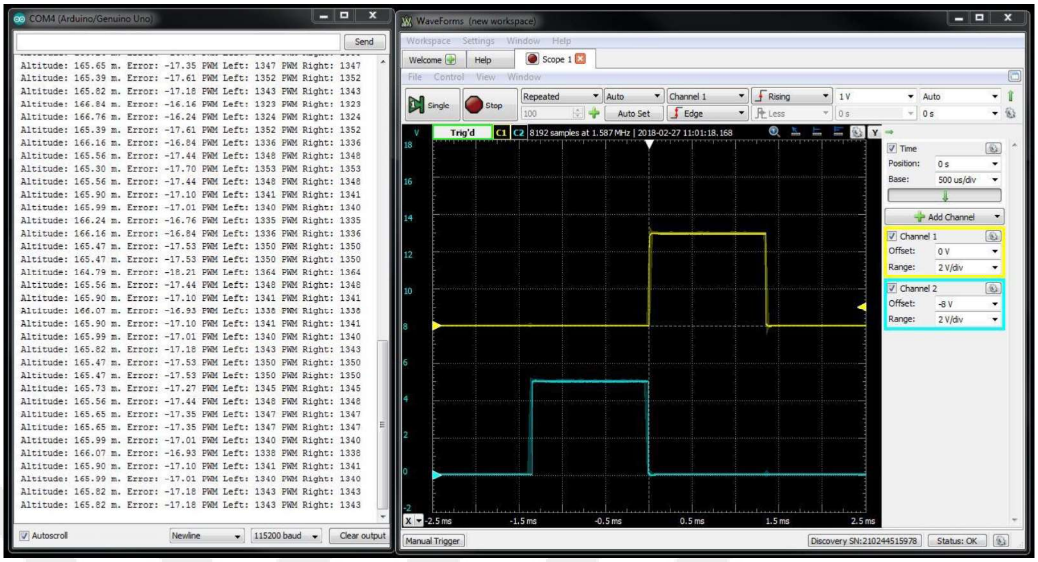


Figure 2.50 DC motors PWM signals during the vehicle below reference altitude

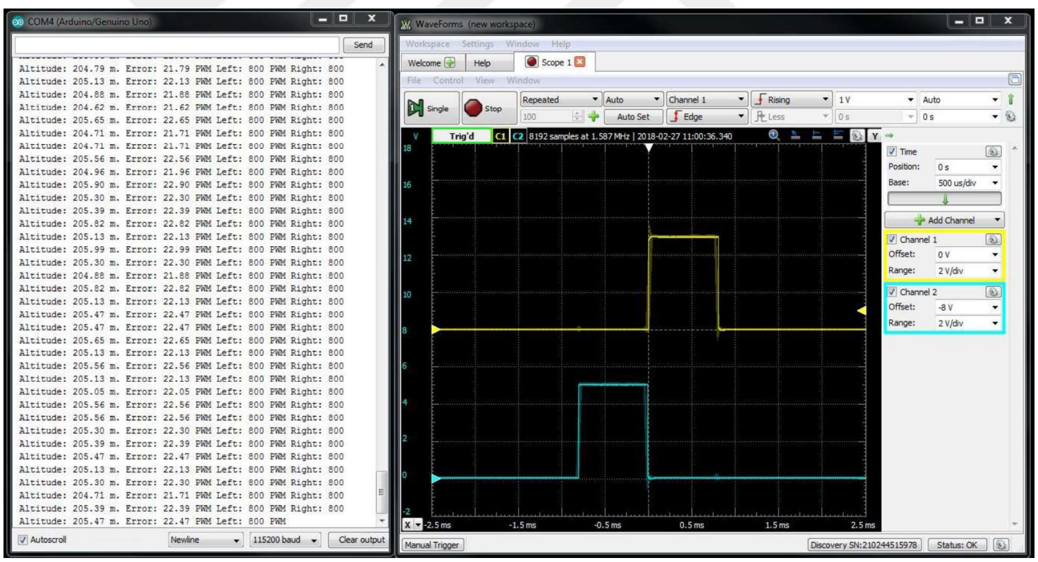


Figure 2.51 DC motors PWM signals during the vehicle above reference altitude

### *2.4.3 Communication Module Design*

The vehicle communication module supports two-way communication with ground control module. As a receiver, communication module receives control commands from the ground control module. As a transmitter, it sends flight data and system data like orientation, altitude, position, battery status etc.

Communication module consists of a wireless transceiver and a communication algorithm. As a transceiver, NRF24L01 wireless transceiver device is used. It is produced by Nordic Semi-Conductor Company. It supports 2-way communication. It works at 2.4 GHz ISM band and it provides 2 MBps data transmission speed rate. While using with Low Noise Amplifier (LNA) and Power Amplifier (PA), it can transmit data up to 1200 meter. NRF24L01 trans-receiver. NRF24L01 communicates with flight controller with SPI interfaces.

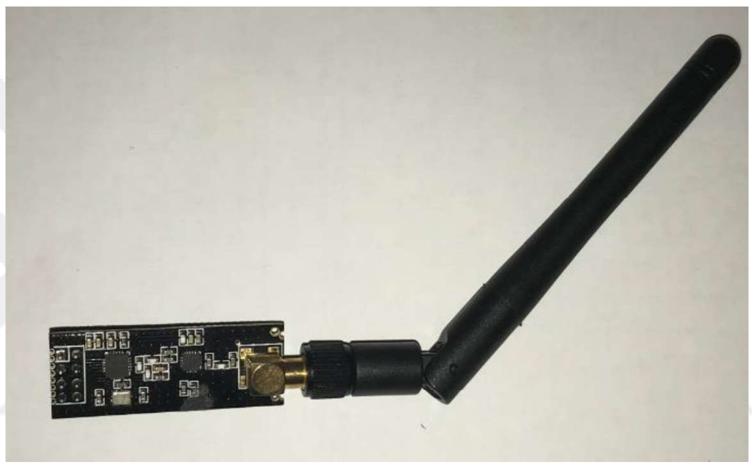


Figure 2.52 NRF24L01 with LNA and PA (Personal archive, 2018)

Communication algorithm defines how communication module behaves; transmitter or receiver and handle the data is sent or received. 2.4 GHz ISM band is also used for unlicensed wireless communications. Therefore, hundreds of signals might be interfering for this frequency band. NRF24L01 uses 6-byte addressing to match the transmitter and the receiver. Communication module uses different address for transmitter and receiver modes. In a single loop, communication module acts as both transmitter and receiver. At the beginning of the loop, module acts as a receiver and it waits commands from ground control module for a while. If no signal is received from ground control, communication module stops listening then flight controller executed flight algorithm. If communication module receives signal from the ground control, it parses data and set the command parameters in flight algorithm. At the end of loop, communication module switch to transmitter mode and sends flight and system status information to the ground controller.

### *2.4.4 Battery Control Module Design*

Battery status is measured continuously during the flight in order to prevent that vehicle run out of energy. 11.1 V, 1500mah Li-Po battery is used as a power supply. During the flight, battery supplies brushless motors, servo motors, sensors, communication devices and microcontroller via ESC's. Maximum battery voltage is 12.4 V and the battery voltage decreases over time. When it reaches the critical voltage level, ESC's cut power transmitted to brushless motors. Therefore, vehicle will lose ability of flying. To make the vehicle return to home safely, flight should be planned according to battery status.

Battery voltage can be measured by analog input of the Arduino. But Arduino allows maximum 5V as an input. Because of this restriction, battery voltage measured is measured via a voltage divider circuit. With voltage divider, battery voltage is divided to 3. Analog input of Arduino converts analog readings an integer value between 0 and 1023. By using mapping method, this reading is mapped to 0 to 5V. After mapping, result is multiplied with 3 then real battery voltages will be measured. This measurement is set battery voltage parameter in flight controller and flight controller executes flight algorithm accordingly.

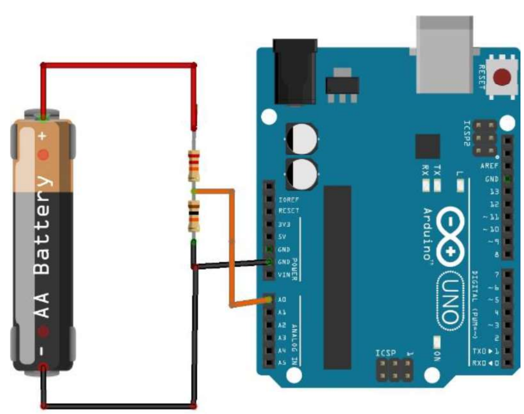



Figure 2.53 Battery Control Module schematics

## 2.5 Ground Control Module Design

Ground control module consist of a remote controller and a monitoring system. Remote control module sends flight commands to vehicle via communication module while communication module acts as transmitter. Monitoring system receives flight and system data from the vehicle during the flight.

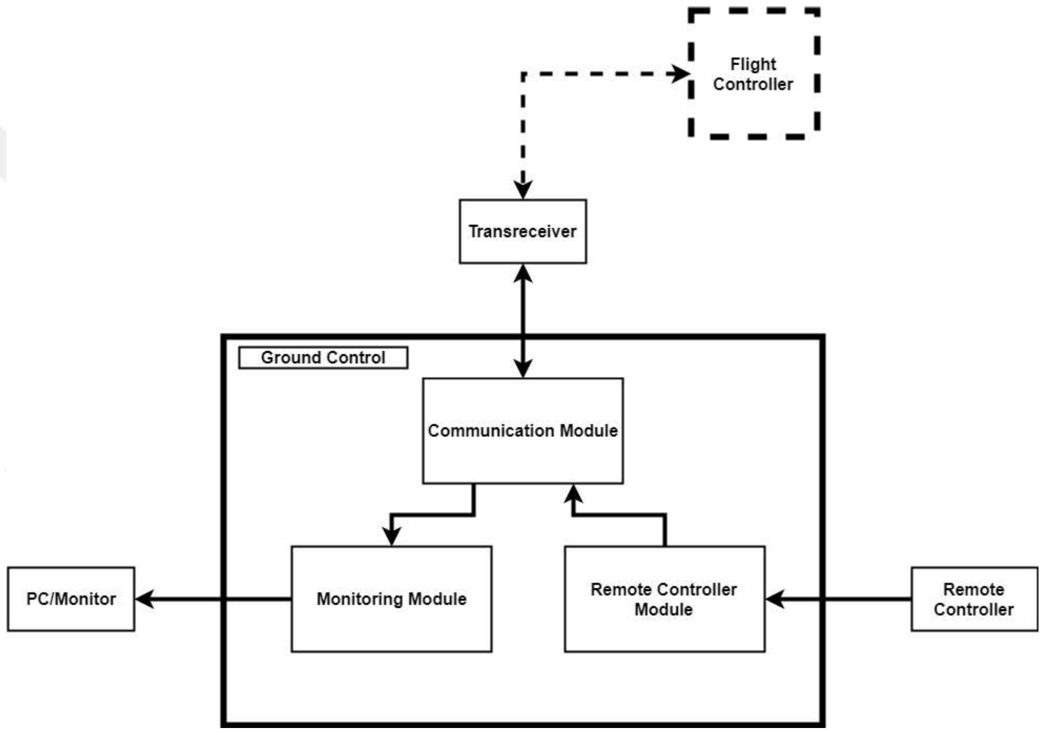



Figure 2.54 Ground Control Module block diagram

### *2.5.1 Communication Module Design*

Similar to the communication module on the vehicle, communication module on the ground control is developed by using NRF24L01 wireless trans-receiver and communication algorithm. When no command is sent to vehicle, ground control module is in listener mode and continuously receiving flight and system data from the vehicle. Once remote control is triggered, communication module stops listening and sends commands to the vehicle. After remote control returns its initial position, communication module acts as transmitter again until remote controller triggers it.

### *2.5.2 Remote Control Module Design*

Remote control is used to control the vehicle manually. It consists of two joysticks and a microcontroller. Arduino mini is used as a microcontroller. Each joystick has 2-input for power connection 2-output to send position information of the joysticks for x-axis and y-axis. Joysticks outputs generates voltage between 0 to 5V based on its position and they are connected to Analog inputs of Arduino. Arduino converts readouts to integer between 0 and 1024 and sends readouts to flight controller via communication module. Once flight controller receives the remote controller outputs, it sets throttle speed, servo motor positions or executes specific command based on the combination of joysticks outputs.

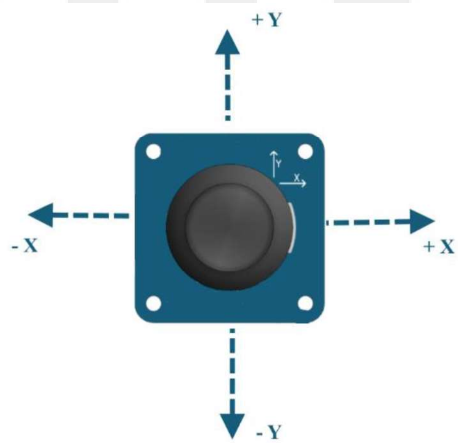



Figure 2.55 Joystick positions

Joystick can move in 4-directions on 2-axis. For right joysticks, movement on x-axis is defined in flight algorithm as $R_x$; and $R_y$ for y-axis. For left joystick, they are defined $L_x$ and $L_y$ for x and y-axis respectively. While moving joysticks to top and bottom positions, $R_x$, $R_y$, $L_x$ and $L_y$ values are read from microcontroller as they are stated in table 2.1.

Table 2.1 Joystick readouts based on the position

| **Joystick Position** | **$R_x$** | **$R_y$** | **$L_x$** | **$L_y$** |
|---|---|---|---|---|
| Initial Position | 512 | 512 | 512 | 512 |
| + X | 1023 | 512 | 1023 | 512 |
| - X | 0 | 512 | 0 | 512 |
| + Y | 512 | 1023 | 512 | 1023 |
| - Y | 512 | 0 | 512 | 0 |

During manual flight control, flight controller executes related algorithms to take necessary action based on the Joysticks readouts. List of use cases are designed based on the joystick positions are given in table 2.2.

Table 2.2 Joystick readouts based on the position

| Use Cases | Joystick Positions |
|---|---|
| Speed Up | Ry > 1000 |
| Speed Down | Ry < 20 |
| Vehicle Up | Ly > 1000 |
| Vehicle Down | Ly < 20 |
| Turn Right | Rx > 1000 |
| Turn Left | Rx < 20 |
| Emergency Stop | Rx < 20 and Lx > 1000 |

### *2.5.3 Monitoring System Design*

Monitoring system is used to monitor flight and system status during the flight. It becomes more important when vehicle is out of line of sight and during autonomous flight. Flight controller continuously sends flight data like orientation, position, altitude and system and environmental status like battery voltage, temperature etc. to ground control module. Ground control module sends these data to monitoring system. Monitoring system convert this data in meaningful format. Also, it visualizes this information to provide user-friendly and interactive monitoring system. Figure 2.56 shows example of a monitoring system.

Figure 2.56 Ground Control Module prototype (Personal archive, 2018)

### 2.6 Auto-Pilot Module Design

Autonomous flight is an ability to complete a pre-defined flight task by an auto-pilot system without requiring constant hands-on control by a pilot or an operator. It has supportive functions during manual controlled flight. It does not mean to replace human factor completely but to assist human element during the flight.

Auto-pilot system design requires high level skills in avionics, software and aviation. To implement a complete auto-pilot module requires a long time of work and it is a multidisciplinary work. Therefore, in this thesis, some basic functions are implemented for autonomous flight.  There are three uses cases are implemented as Take-off, landing, and constant flight. During a complete autonomous flight, the vehicle executes take-off use case firstly. When it reaches to flight altitude, it will execute at constant flight speed. Finally, it reaches to destination then it will execute landing use case.

To plan an autonomous flight, auto-pilot module needs four parameters.

- Departure Position: Position information of departure location is required to calculate heading angle of the vehicle with arrival point position information.
- Destination Position: Position information of destination location is required to calculate the heading angle of the vehicle with arrival point position information.
- Reference Heading Angle: The vehicle measures yaw angle relatively. Therefore, before flight starts, reference angle should be defined. Than auto-pilot module calculates heading angle by using departure and destination points with respect to reference heading angle. Angle between two coordinates called as bearing and calculated equation with 2.32, 2.33 and 2.34 in degree. Bearing indicates angle with respect to true north.

$L : Coordinates\ of\ a\ Location\ consist\ Lattitude\ and\ Longitude$

$LocationA : latA, longA$

$LocationB: latB, longB$

$$Bearing = \text{atan2}(X, Y) \tag{2.32}$$

$$X = cosLatB\ x\ sin\Delta L \tag{2.33}$$

$$Y = cosLatA\ x\ sinLatB - sinLatA\ x\ cosLatB\ x \cos \Delta L \tag{2.34}$$

- Flight Altitude: Flight altitude should be defined based on geographical conditions and height restriction by law. Altitude should indicate sea-level height of the vehicle.

Aircrafts turn nose towards to desired course direction. But actual route may change because of wind. Heading angle indicates direction of the air vehicle. Actual cruise direction may effect to wind and

# CHAPTER THREE
# CONCLUSION

In this thesis a hybrid unmanned LTA airship is designed and implemented in order to present energy efficiency and higher payload capacity of the UAS which uses an LTA gas against to conventional UAS.

The thesis started by asking a research question as how an unmanned air system can fly longer with a higher payload capacity. The first answer comes in mind increasing battery or fuel capacity or power of motors. However, increasing battery or fuel capacity means higher load and therefore it reduces payload capacity. On the other hand, increasing motor power requires more battery of fuel capacity. Therefore, to answer question in this way causes a vicious cycle.

There is a continuous force on a flying object which pull the object down called as force of gravity. To keep the object in the sky, most of the energy capacity is used against to gravity. Fortunately, nature provides free resource to get rid of negative effect of gravity by using lifting gases. After solution was addressed, air vehicle specifications were defined. Then system is designed to satisfy system specifications. First part of the system design is the envelope design. Envelope encloses the lifting gas and generates lifting power together with the propulsion system. In this part, critical design point is the envelope volume. The higher volume means the more capacity envelope least. Volume of the envelope was defined to neutralize at last the weight of the entire system with a payload capacity. Therefore, energy source could be used only for flying. After design is completed, it was implemented by using an envelope material. Envelope weight should be as low as much as possible to prevent decrease of the payload capacity. However, well-known, light materials like tedlar, are not easily reachable in Turkey. Importing these materials are very costly and rarely available for retail sale. Therefore, PVC blimp is used which is heavier than tedlar, Kevlar and similar materials. Despite helium gas is an expensive for retail, it is easy to find even high amount of it.

Mechanical part of the vehicle includes a propulsion system, a flight controller and sensors. All these electromechanical parts are working with coordination of flight controller. The mechanical part is a complete unmanned air system and able to fly individually. Design of mechanical part is highly complex than designing the envelope. Because it includes many subsystems and all subsystems have to work together.  On the other hand, due to nature of electronics, devices work little bit different than their ideal conditions. These differences are less but can't be ignored due to sensitive measurements and calculations are required to control air vehicle. Big amount of effort has been spent to implement stability, altitude and heading control modules with PID controller. PID algorithm is very easy to implement but it is very hard to define proportional, integral, and derivative gains. Also, even a small change on the system distort balance of the system and all these parameters should be set again.

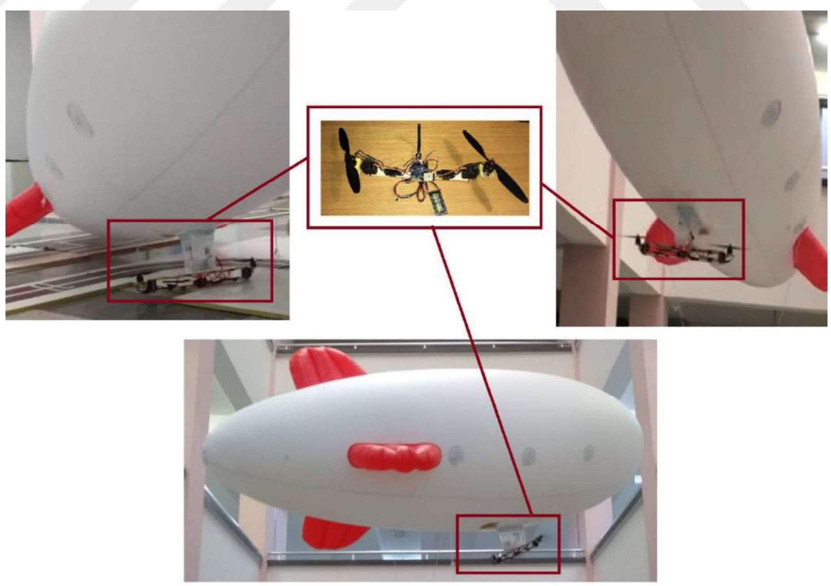


Figure 3.1 Envelope and Propulsion System Integration (Personal archive, 2018)

After all subsystem are integrated, thesis objectives are verified by testing the system specifications. The blimp that is used as an envelope has 3,016 $m^3$ volume. During the time of verification, temperature was 16 degree Celsius and sea level pressure was 1023 hPa. Test was executed at 189 meter above from sea-level.

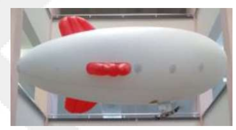
Theoretically, 1 $cm^3$ helium was expected to carry 1.04 gr. and fully filled blimp with helium was expected to lift 3136 gr. load. Envelope weight is 2230 gr. and net theoretical lifting capacity is 906 gr. However, lifting capacity was measure as 863 gr. There are possible two reasons that cause these difference. The first might be impurity of helium gas inside the blimp; the second might be that actual volume of blimp is different than calculated. Because equation 2.2 gives approximate result and these result might be vary according to shape of ellipsoid. However, error margin is around 5% and it is low as acceptable.

Electro-mechanical part which contains propulsion system, flight controller, communication module and sensors etc. has 986 gr. weight. After integration, net weight of entire vehicle was measured as 123 gr. It means, at least 123 gr. thrust is enough to make airship fly. Each BLDC motors on the airship generates maximum 850 gr. thrust, total thrust is generated by airship reaches to 1700 gr. Therefore net payload capacity of the airship became 1577 g.

Figure 3.2 Flight Test (Personal archive, 2018)

To measure maximum flight time of the airship, fully charged 1300 mah. battery is used and throttle engines were powered to generate minimum thrust to make airship fly. Until engines stopped, no manual control signal was sent total time was measured as 123 minutes. Table 3.1 contains comparison between hybrid airship and well-known commercial unmanned air vehicles according to flight time and payload capacity. While considering all specifications and functionality of the all vehicles, it is not a complete comparison but it can give a clue about the target of thesis.

Table 3.1 Comparison of Hybrid Airship and Other Unmanned Systems

| | DJI Phantom 4 | Parrot Disco | Hybrid Airship |
|---|---|---|---|
| |  |  |  |
| Weight | 1388 g | 750 g | 123g |
| Battery | 2700 mAh | 5870 mAh | 1300 mAh |
| Net Payload | 320 g | 120 g | 1573 g |
| Flight Time | ~ 30 min. | 45 min | 93 min |

Despite thesis objective is satisfied, results could have been more impressive if envelope and frame weight were lighter. Envelope is made by PVC and its density is 182 g per square-meter which is very high to use as a part of an LTA aircraft. For example if an envelope material which has weight around 50 g per square-meter were used, same size blimp could have been had around 1600 g more payload capacity. Or, same payload capacity could have been obtained with smaller envelope. Same assumption is valid also for the frame and other systems on the airship. In this thesis, a prototype is developed and with fabricated materials, net weight of the airship could be decreased and total payload capacity and flight time of the airship could be increased accordingly.

However, the vehicle has significant advantages against conventional UAS', it is not as fast as the other UAS's systems. Also, envelope size makes entire system significantly bigger with respect to other systems.

This system is very suitable for further enhancements. By saving basic design principles, larger envelope size and lighter envelope material allows to carry higher capacity. By adding flexible solar panel on the surface of envelope, required electrical power can be produced continuously. Also, by implementing advanced communication systems like satellite communication, it can be controlled and monitored independently from the location. Consequently, LTA-UAS' are a strong alternative for conventional UAS' for tasks which are not required high speed and small vehicle size.

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