DESIGN AND DEVELOP A VERTICAL TAKE-OFF AND LANDING FIXED-WING HYBRID UNMANNED AERIAL VEHICLE

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2019

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A report submitted
in partial fulfillment of the requirements for the degree of
Bachelor of Mechatronics Engineering with Honours

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2019

DECLARATION

I declare that this thesis entitled “DESIGN AND DEVELOP A VERTICAL TAKE-OFF AND LANDING FIXED-WING HYBRID UNMANNED AERIAL VEHICLE is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : ALBERT CHAN BAO DER

Date : 30th May 2019

APPROVAL

I hereby declare that I have checked this report entitled “DESIGN AND DEVELOP A VERTICAL TAKE-OFF AND LANDING FIXED-WING HYBRID UNMANNED AERIAL VEHICLE” and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Mechatronics Engineering with Honours

Signature :

Supervisor Name :

Date :

DEDICATIONS

To my beloved mother and father

ACKNOWLEDGEMENTS

First of all, I would like to express my appreciation to Dr. Hairol Nizam bin Mohd Shah on guiding me all along the project here in terms of technical support and documentation guidance. Moreover, I would like to show gratitude to Dr. Lee Shian who is proficient in Aerospace Engineering, to guide me all along during designation and aircraft building phase. I appreciated both Dr.Hairol and Dr. Lee who inspired me and keep me motivated in this project.

I would like to say thank you for all the supports either physically or mentally, from my beloved friends and family. They had lent me a hand without any second thought during this project, whenever I need it.

Building an aircraft is not easy, especially for me, whom not studying Aerospace Engineering as major of degree, but these people lead me in it, with the aid of my Mechatronics Engineering skills that trained in Universiti Teknikal Malaysia Melaka, these all made this project from impossible to possible.

ABSTRACT

Applications using Unmanned Aerial Vehicle (UAV) is growing since the past decade in both civilians and military industry. This robot has promising advantages in performing various tasks, especially without risking any single human life. Meanwhile, different requirement of various tasks leads to various types of UAV being designed to overcome with. This project focused on design and develop UAV with combination between the fixed-wing aircraft and the multirotor drone, named as fixed-wing hybrid type of UAV. Reviews on others work relevant to design and develop fixed-wing hybrid UAV has been done to come out with solid ideas to complete this project. There are plenty types of configurations available, thus they have been analyzed for selection of suitable ones to be involved according to design requirement established in early stage of this project. The results obtained in this project is a fixed-wing hybrid with a quadcopter UAV is designed and built to fly. All the calculations, fabrication steps, materials chosen and electronics components are included in this report. At the end of this project, flight evaluation is done on the flight test of UAV. There are a few suggested future work stated as well for further improvement for this project.

ABSTRAK

Aplikasi yang menggunakan Kenderaan Penerbangan Tanpa Manusia (UAV) berkembang sejak dekad yang lalu dalam kedua-dua sector awam dan industri ketenteraan. Robot ini mempunyai kelebihan menjanjikan dalam melaksanakan pelbagai tugas, terutama tanpa mengambil risiko terhadap sebarang kehidupan manusia. Sementara itu, pelbagai keperluan bagi berbagai tugas membawa kepada pelbagai jenis UAV yang direka untuk diatasi. Projek ini memberi tumpuan kepada reka bentuk dan membangunkan UAV dengan gabungan antara pesawat sayap tetap dan drone multirotor, yang dinamakan sebagai jenis hibrid tetap jenis sayap UAV. Ulasan mengenai orang lain yang berkaitan dengan reka bentuk dan membangunkan UAV hibrid tetap sayap telah dilakukan untuk menghasilkan idea-idea kukuh untuk menyelesaikan projek ini. Terdapat banyak jenis konfigurasi yang tersedia, oleh itu mereka telah dianalisis untuk pemilihan yang sesuai untuk terlibat mengikut keperluan reka bentuk ditetapkan pada peringkat awal projek ini. Keputusan yang diperolehi dalam projek ini adalah hibrid sayap tetap dengan UAV quadcopter direka dan dibina untuk terbang. Semua pengiraan, langkah fabrikasi, bahan terpilih dan komponen elektronik dimasukkan ke dalam laporan ini. Pada akhir projek ini, penilaian penerbangan dilakukan pada ujian penerbangan UAV. Terdapat beberapa kerja masa depan yang dicadangkan dan juga penambahbaikan untuk projek ini.

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INTRODUCTION

1.1 Introduction

The advance of technologies ease human to perform a lot of difficult, dangerous, time-consuming work with being there, we call them robots. A robot is a machine capable of carrying out a complex series of actions automatically, especially one programmable by a computer. One of the most commonly known flying robots nowadays is Unmanned Aerial Vehicles (UAVs), which also known as drones. According to Market And Market Research Private Limited's analysis, drones market is expected to grow from USD 13.81 Billion in 2016 to USD 48.88 Billion by 2023 [1].

Almost every drone has featured in taking photos and videos, therefore, drones are used in photography industries, they are mainly used in the defense industry worldwide. Border patrol and surveillance missions are always risky and full of unknowns, these made flying robots the best option to perform the task without risking any humans' life while protecting the other humans. In the coming 10 years' time, the Pentagon plans a USD 40 billion budget in purchasing more than 700 medium- and large-size drones, according to a Congressional Budget Office study [2]. Based on the report of CNET, the US Army is getting tiny personal surveillance drones as part of a $2.6 million contract with Flir, a thermal imaging, and technology company[3].

Generally, there are four types of UAV can be found, Multi-Rotor, Fixed-Wing, Single-Rotor, and Fixed-Wing Hybrid. Among those 4 types of UAVs stated, Multi-Rotor type is the most popular drone type, due to the financial barrier to entry in the multirotor market is low enough for the public, moreover it gives users to have much more control over positioning and framing the camera to get you that perfect aerial photo shot. Although there are plenty of pros in using multi-rotor type UAVs, there are cons too. It has small payload capacity and short flight time (normally around 20 mins flight). Hence, fixed-wing hybrid UAV is chosen to be developed in this project because this type of drone is capable to perform vertical take-off and landing (VTOL) which requires minimal spaces to take-off and land. In addition, it has significantly longer flight endurance and distance compared to multi-rotor drones.

Contributions from me will be designing the structure of UAV, in the sense of choosing configurations of aircraft, calculating the size of aircraft parts needed and thrust power required, then manufacture according to own design.

1.2 Problem Statement

Border patrolling has been troubling mankind for centuries as it needs huge manpower to be done, yet it is quite dangerous during patrolling when a job needs high efficiency while easing the process safely, robots are the best option to replace human power in it. There are a few requirements for a robot need to be achieved in order to do border patrolling.

1. Able to travel in long distance.
2. Long endurance in use.
3. Travel at high speed to reach a destination in a short time.
4. Do not have any constraint on the reachable place or travelable route.

With all the requirements stated above, fixed-wing hybrid UAV is the most suitable choice to be designed to solve this problem.

There a few problems need to be solved during designation and building a fixed-wing hybrid UAV as stated below.

1. Design and functional requirements for fixed-wing hybrid UAV.
2. Electronics parts needed to achieve functional requirements.
3. Structure and size of UAV to fulfill the design requirements and functional requirements.
4. Materials to fabricate UAV.

.

1.3 Objectives

1. To design a fixed-wing hybrid UAV then draw in SolidWorks.
2. To build a fixed-wing hybrid UAV based on own design and control by remote control.
3. To evaluate flight performance with flight test.

1.4 Scope

This project is focused on designing and developing a dual system fixed-wing hybrid UAV that is powered by lithium battery ion, controlled by a pilot using a remote control. The design will need to consider flight endurance, mission range, and maximum airspeed. After designation phase, it will be built and evaluated with flight test later. Meanwhile, all parameters related in designing a remote controlled aircraft is considered besides crew weight and fuel weight (due to lithium-ion battery will not decrease in weight while providing energy). The parameters are stated below.

1. Estimation of take-off weight.
2. Estimation of total drag coefficient, C_D, cruising lift coefficient, C_{Lc}
3. Wing reference area, S_{ref}
4. Electrical motor propulsion thrust/power
5. The weight of components and UAV's weight

However, during designation phase, manufacturability and cost are main concerns, hence, optimization needed between the efficiency of UAV structure and those two concerns.

1.5 Motivation

While choosing fixed-wing hybrid UAV as this final year project, including two general motives which are motives of choosing UAV and motives of choosing a fixed-wing hybrid type of UAV.

As mentioned in the Introduction part of this chapter, drones' market growth is so significant in past years, whereas it is going to grow even more in the coming ones. Goldman Sachs reported that the total expenses on UAV will exceed USD 100 billion by the year 2020. Among all the spenders on drones, the defense sector is the largest group, which is expected to spend around USD 70 billion between 2016 to 2020. The commercial business also trying to implement usage of drones in recent years, hence this sector shows the fastest growth opportunity, which projected to hit USD 13 billion of total spending between 2016 and 2020 [1]. This indicates that drones are a trend of technologies developed with its enormous market value. This type of UAV is currently in the developing phase, it is not available on the common market yet so it’s totally worth for us as a Malaysian undergraduate engineer to spend time on developing it. Meanwhile, the UAV system helps police, fire and other first responders save lives in the event of natural disasters, locate missing children and help fight wildfires too. It assists the coast guard in rescue missions and helps the border patrol [4].

Fixed-wing hybrid UAV is a type of drones that generate lift by forwarding airspeed, meanwhile capable of VTOL. This hybrid UAV enable it to carry higher payload because lifting by the aerodynamic lift of an airfoil is much power saving. This property also allows it to have longer flight endurance, meaning that it has a larger mission range. By comparing to multi-rotor drones, it has a higher airspeed, in other words, it reaches target location much faster. Although this hybrid UAV will not have better endurance, faster airspeed not power efficient compared to fixed-wing UAV, because of the vertical propulsion parts are causing a lot of drag, but this UAV comes out with another pro, it is capable of VTOL. VTOL allows users to launch this UAV without a spacious flat ground (a runway). This property makes UAV possible to launch in a small, uneven ground such as jungle. Other than launch, landing space is a concern as important as launching space. Fixed-wing hybrid UAV can do landing in almost any area as long as there are no obstacles in landing range (around 50 percent larger than the wingspan of UAV).

Chapter 2

LITERATURE REVIEW

2.1 Overview

This chapter presents theoretical backgrounds which are related to this project. Many journals and conference papers related to this research are studied and evaluated based on a few specific criteria. Then, the most suitable setup is chosen to be used in this project.

2.2 Unmanned Aerial Vehicle (UAV)

A UAV, also known as a drone, is an aircraft that outstands from a traditional aircraft, where a human pilot is unneeded. This type of vehicle is either operated by a pilot by using a telemetry control system or controlled autonomously by microprocessors in it [5]. Applications of UAV had already included in fields like scientific research, environmental observation, law enforcement, disaster support, and industrial support [6]. In [7], there are three main types of drones available, fixed-wing system, multirotor system, and other systems. A multirotor system is a type of drone equipped multiple rotors for stability purposes. Without any doubt, the multirotor drone is the most common one in the market, such as DJI Phantom, Parrot AR Drone, Hubsan x4 Drone, etc. It is due to its easy configuration to build and use, capable of VTOL and high stability. The other system drones are the type that does not use fixed-wing nor multirotor or using both, which make them cannot be classified into two previous types. Example of this type of drones is ornithopter, fixed-wing hybrid and unmanned balloon. shows the pros and cons in a few types of drone.

Table 2.1 Pros and Cons of different types of drone[8]

	Pros	Cons	Typical Uses
Multi-Rotor	• Accessibility • User control friendly • Capable of VTOL and hovering • Good stability for photographing • Usable in a confined area	• Short flight endurance • Small payload capacity	Aerial Photography and Video Aerial Inspection
Fixed-Wing	• Long flight endurance • Large area coverage • Fast in forward transitioning	• Runway needed to takeoff and landing • Unable to hover • More difficult in piloting • Expensive to fabricate	Aerial Mapping, Pipeline and Powerline inspection
Fixed-Wing Hybrid	• VTOL and long flight endurance	• Not perfect at either hovering or forward transitioning • Still in developing phase	Drone Delivery

2.3 Fixed-Wing Aircraft

In the aviation industry, fixed-wing is used to define an aircraft with fixed yet static wings that use forward airspeed to generate lift force [7]. The best example of this kind of aircraft is the civil aviation, such as Boeing and Airbus, the most known aircraft. In [9], designing a fixed-wing aircraft, there are some configurations as below needed to be chosen.

2.3.1 Wing types

The most common wing type on fixed-wing aircraft is a monoplane, also known as a one-wing plane. Conventional monoplane has advantages like greater manufacturability, more predictable aerodynamical performance and, higher stability, lower induced drag, better movement capacity, and faster speed. Figure 2.1 refers to a different kind of wing type configuration for monoplanes. While

Table 2.3 refers to the comparison of wing types by using merit system.

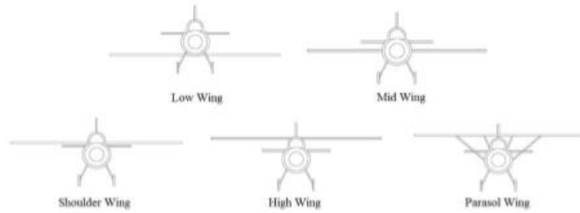


Figure 2.1 Wing types for Monoplanes

Table 2.2 Comparison of wing types[9]

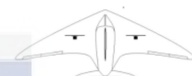
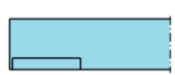
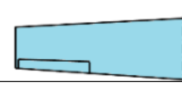
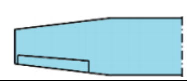
Figure of Merit	Score of Factor	Monoplane	Biplane	Flying Wing
				
Weight	40	2	1	2.5
Lift/Drag	30	2.5	3	2.5
Stability	10	3	3	1.5
Manufacturability	10	2.5	1.5	1.5
Aerodynamics Performance	10	3	2	2.5
Total	100	240	2.5	230

Table 2.3 Comparison of the straight wing [10]

Figure of Merit	Score of Factor	Rectangular	Tapered	Prismatic mid-Section
				
Manufacturability	60	5	3	4
Strength	20	4	5	5
Aerodynamic Performance	20	3	5	4
Total	100	440	380	420

Among these configurations, high wing type has the highest lifting capacity whereas rectangular wing is easy to manufacture while maintaining good strength and high aerodynamic performance. Therefore, a rectangular high wing type of monoplane configuration is chosen to develop fixed-wing hybrid UAV in this project.

2.3.2 Tail types

A tail of a plane, also known as a horizontal stabilizer, is a smaller wing that provides lift at the rear of a fixed-wing aircraft. The most common configuration for aircraft's tail is the conventional configuration based on Raymer and his team. It helps in adapting the changes in center of gravity caused by altering in speed and attitude, or when fuel is used during flight, or when a payload is released. Table 2.4 shows merits in term of weight, drag, and stability of three types of tails.

Table 2.4 Comparison of tail types [10]

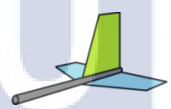
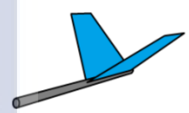
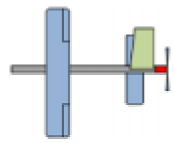
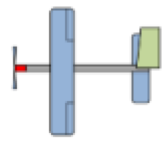
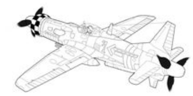
Figures of Merit	Score of Factor	Conventional	V-Tail	T-Tail
				
Weight	55	3	1	1
Drag	20	2	2	3
Stability	25	2	3	1
Total	100	255	170	140

Table 2.4 above clearly shows that the conventional tail type has the best performance among these three types compared. Hence, the conventional tail is chosen in designing UAV in this project.

2.3.3 Motor placement

Table 2.5 indicates that tractor type motor is the best in three types of motor configurations. In the tractor type motor, both propeller and motor are placed on the nose of the aircraft, it helps to maintain the stability and reduces the weight of the whole system. Thus, tractor type motor is the best fit for the design of UAV in this project.

Table 2.5 Comparison of motor types [9]

Figures of Merit	Score of Factor	Pusher	Tractor	Push-Pull
				
Weight	55	3	3	1
Efficiency	45	1	2	1
Total	100	210	255	100

2.3.4 Airfoil selection

Basic shapes of wings and tails in most aircraft are known as airfoils, or sometimes known as aerofoils, are structures with curved surfaces designed to give the best lift to drag ratio (C_l/C_d). While designing airfoil, the angle of attack (AOA) plays an important role as the greater the AOA, the better the aerodynamic characteristics, but it causes a stall at the same time, critical AOA is determined at 15°. Meanwhile, AOA is the angle between the reference line on a body and the incoming flow act on the body. Few types of selected airfoil configurations, as shown in Figure 2.2, is compared in merit form in Table 2.6.

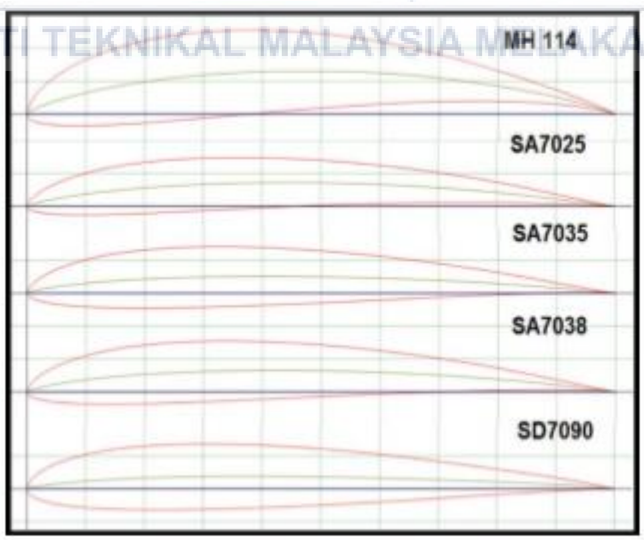


Figure 2.2 Selected airfoil configurations

Table 2.6 Comparison of selected airfoil configurations [9]

Figure of Merit	Score of Factor	MH 114	SA 7025	SA 7035	SA 7038	SD 7090
C_l/C_d-α	40	3	1.5	2	2.5	1
C_l-α	60	3	2	2	2.5	2.5
Total	100	300	180	200	250	190

Where α indicates the angle of attack.

Table 2.6 shows that MH 114 is the best type of airfoil among selected ones, hence, MH114 is chosen [9].

2.4 Multi-Rotor Aircraft

A multirotor is a rotorcraft but different from traditional helicopter configurations. This type of rotorcraft employs identical rotors to provide both lift and control, rather than using mechanically-complex main and tail rotors in helicopters. However, additional rotors introduced changes the aerodynamic performance of the system, adding extra mass and typically requiring greater supporting structure [11]. Due to any configurations use more than 4 motors are overweighed, they are not considered in this project and will not be included in explanation.

Bi-copter – It has two motors which are movable with servos. It is considered as the cheapest multi-rotor aircraft since it is enriched with two servo motors, but it is the least stable and is most difficult rotorcraft to tune. Furthermore, it is less likely to be robust and generating least lifting power because it has only two rotors. There are no failsafe in this rotorcraft, if one of the rotors fails, then copter definitely crashes which leads to its biggest limitation.

Tri-copter – This copter consists of three motors which is also one of the cheapest configurations in multi-rotor aircraft. Servo motors are required as well but since brushless motors are far more expensive, servos do not increase the cost significantly. The greatest advantage of the tri-copter is having the widest angle (120 degrees) between two front motors, causing it remains the propellers out of shot during photographing or video capturing. Even though, tri-copter is more stable compared to bi-copter, but it is still highly unstable compared to multi-rotor copters with more motors. The limitation of this copter is the same as bi-copter, where one motor fails, the whole copter fails[12].

2.4.1 Quad-copter

A quadcopter, as known as quadrotor helicopter, is a multi-rotor aircraft that generates lift with four vertical rotors. A quadcopter consists of 4 motors which are mounted on four symmetrical frame arms, each arm is 90° apart especially for X4 configuration. The propellers mounted on the motors are rotating in two pairs, the clockwise pair and the counter-clockwise pair, to create an opposite force to balance it [12].

The primary benefit of the quadrotor lies in its mechanical simplicity, its lifting force and controlling moments are supplied exclusively through manipulation of the four fixed-pitch rotors. The motion control principle is shown in Figure 2.3, that explains how quadrotor yaws, lifting and transitioning [11].

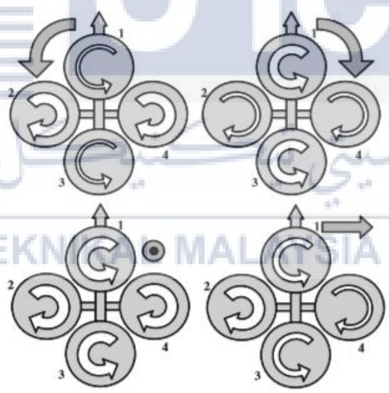


Figure 2.3 Quad rotor type motion principle. The width of the arrows is proportional to the propellers' angular speed [13]

This multi-rotor configuration is chosen for this project because of its mechanical simplicity, moreover in [14] stated that it is capable of high payload, yet gyroscopic effects are reduced.

2.5 Fixed-Wing Hybrid Mini UAV

Fixed wing hybrid UAVs are categorized into tail-sitter type or convertiplane type in this paper. There are four sub-types of convertiplane, which are tilt-rotors, tilt wings, rotor-wings and dual system [15]

2.5.1 Tail Sitter

Tail-sitter is capable to do VTOL on its tail, the whole aircraft tilts in pitch angle until it achieves horizontal forward transition.

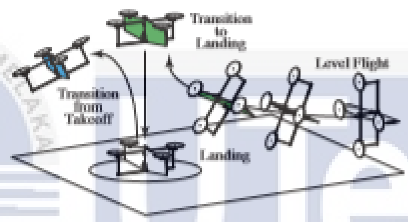


Figure 2.4 VTOL of a tailsitter

2.5.2 Convertiplane

Tilt-rotor is that multiple rotors mounted on rotating shafts that tilts from the upward direction to forward direction during the change of flight mode from VTOL to forward transition. As shown as Figure 2.5

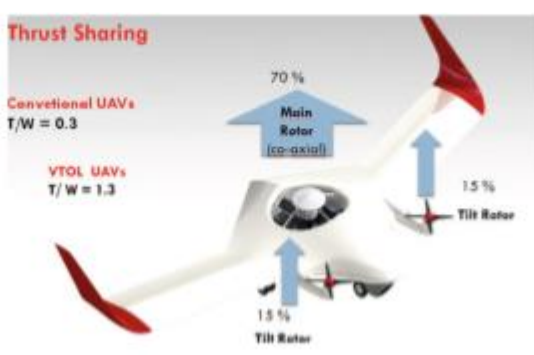


Figure 2.5 Tilt-rotor UAV named TURAC [11]

Tilt-wings as Figure 2.7 [16] is that multiple rotors mounted on rotating wings, which tilts as tilt-rotor does.

Figure 2.6 QUX-02 view

Rotor-wings is a convertiplane aircraft that rotatable wings spin to provide a lifting force to perform VTOL, consecutively stop and act as a fixed wing during the forward transition.

Figure 2.7 Boeing X-50A

According to this paper, the dual system is simple to apply in terms of design, controllability, stability, and modeling due to two flight modes can be analyzed separately. It is a UAV with multiple rotors fixed at the upward direction for VTOL, another separate tractor or pusher for a forward transition.

Figure 2.8 Arcturus JUMP 15 [17]

2.6 Mini UAV Materials

Selection of suitable and manufacturable materials is another part of the crucial task in developing UAV. Materials selected supposed to have enough strength to overcome tensile stress during flight, approachable fabrication method as no any specified yet expensive machines to process and light-weighted. In [18] hybrid tri-copter/flying wing VTOL UAV project, the aircraft frame is made of light plywood and carbon fiber tube support structures, Kevlar tow, and thin cyanoacrylate are used to lashed support tubes together then epoxied to the plywood baseplate. However, in [19], materials selected are Balsa wood to build fuselage frame whereas fiberglass reinforced plastic is chosen as fuselage skin. The comparison of materials shown in the journal is as below.

Table 2.7 Comparison of materials for Fuselage Frame

[Rated from 1 (the best) to 3(the worst)]

	Aluminum	Balsa Wood	Stainless steel	Carbon Rod	Iron
Manufacturability	3	1	5	5	5
Cost	4	1	5	5	3
Strength	2	5	1	3	1
Weight	2	1	5	5	5

Manufacturing Cost	4	1	5	5	5
Easily Available	2	1	5	5	4
Total	17	10	26	28	23

Table 2.8 Comparison of materials for Fuselage Skin

[Rated from 1 (the best) to 3(the worst)]

	Fiber Glass Reinforced Plastic	Carbon Fiber Reinforced Polymer	Spectra Fiber
Cost	1	2	3
Manufacturability	1	3	3
Strength	3	2	1
Manufacturing Cost	1	2	3
Total Score	6	9	10

There are many different steps in manufacturing process using composite material as stated in [20], such as 3D CAD shape design, wet lay-up, CNC mold milling, prepreg laminating, high-temperature curing and off mold dressing. In [19], the vacuum forming method is used in fabrication due to its good finishing result. It is a considerable technique to fabricate my UAV.

Based two references above, carbon fiber tube support is selected as main support frame materials of my fixed-wing hybrid UAV while Balsa wood or plywood will be selected as materials for frame ribs. For skin materials of aircraft, it is yet to be decided later. Kevlar tow and thin cyanoacrylate are selected as lashing materials.

2.7 Electronic components

According to Figure 2.9, main electronics components generally found in all battery powered UAV consists of a lithium-ion-based battery, electronic speed controller (ESC), motors, flight controller and RF receiver. Other parts that are not mentioned are optional depends on an individual's design.

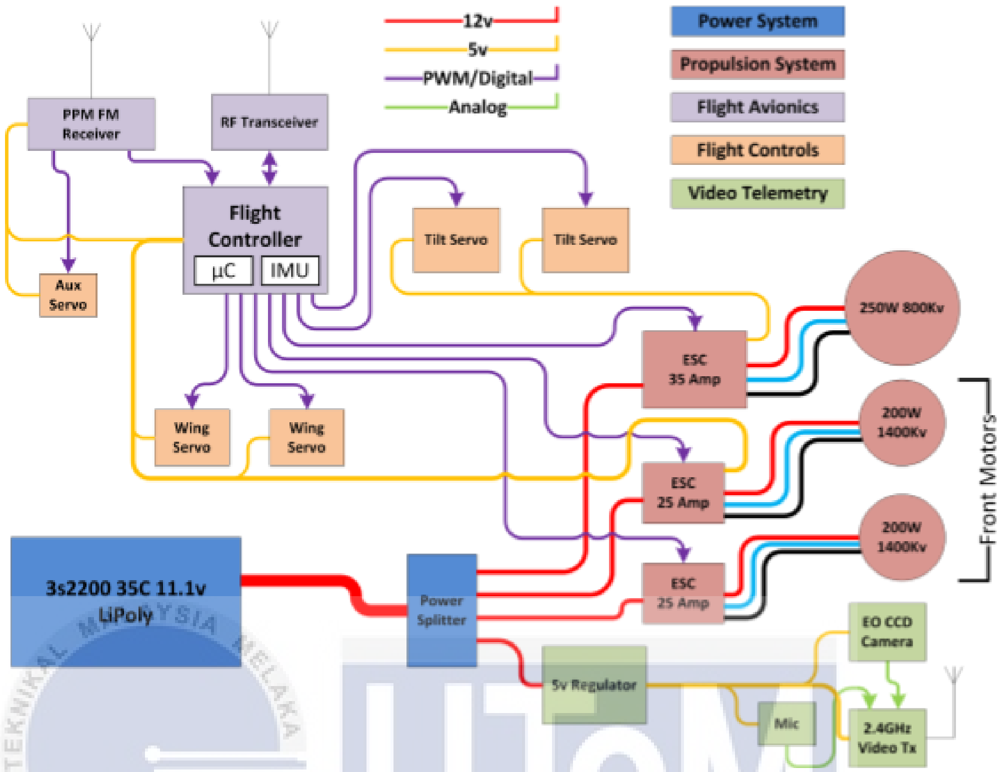


Figure 2.9 System Diagram Example for Battery Powered UAV [18]

2.7.1 Electrical Propulsion

Electrical propulsion is better than internal combustion engines in aspects of gaseous emissions, heat, and noises generated [21]. Electric motors are also noted for their relatively high efficiency and low level of maintenance [22]. The electric propulsion system generates mechanical power in the form of thrust by converting electrical power from a battery.

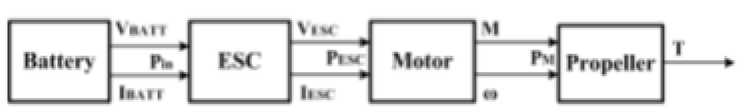


Figure 2.10 Transfer of power through propulsion components

The power derived from the battery source is given by:

$$P_{batt} = V_{batt} \times I_{batt} \qquad (2.1)$$

Where:

V_{batt} = Battery voltage [V]

I_{batt} = Battery current [A]

Pulse Width Modulation (PWM) throttle control signals either from an auto-pilot system or an onboard Radio Frequency (RF) receiver receives by the ESC. The ESC controls the motor speed according to the percentage duty cycle. Quasi-three-phase AC power architecture is the form of power during transfer from ESC to the motor, given by:

$$P_{esc}(RMS) = V_{esc}(RMS) \times I_{esc}(RMS) \quad (2\text{-}1)$$

V_{esc}(RMS) represents ESC voltage in volts (V) and I_{esc}(RMS) is the ESC current in ampere (A).

The motor converts the electrical power to mechanical power in the form of torque (M) on its output shaft at a specific angular velocity (ω) given by:

$$P_M = M \times \omega \quad (2\text{-}2)$$

M denotes torque in Newton meter (Nm) and ω denotes angular velocity in radian per second (rad/s).

The propeller converts the torque (M) and rotational speed to an aerodynamic thrust (T). The required thrust is determined from the UAV platform specifications [21].

2.7.2 Lithium-Ion Battery as Power Source

A Li-ion battery is constructed by connecting basic Li-ion cells in parallel or series. Meanwhile, parallel cells increase the battery current yet series cells increase the battery voltage. Battery cells can be integrated into a module, then modules can be integrated into a battery pack. For example, a typical Tesla car contains 7104 cells to supply 85-kWh of power in total. Typically, a positive electrode (cathode) and a negative electrode (anode) can be found in a basic Li-ion cell. They are contacted by an electrolyte medium containing lithium ions. A separator is used to isolate the electrodes from each other, such as microporous polymer membrane, which allows the exchange of lithium ions between the two electrodes while preventing the electrons do the same. The design of Li-ion cells still remains the same as those cells Sony commercialized two decades ago, although various kinds of electrode materials, electrolyte, and separators have been explored [23]. Advantages of Lithium-Ion Batteries stated in [24]:

- Light in weight among the other rechargeable batteries.
- Made of lightweight lithium and carbon lead to high energy density (energy stored to weight ratio).
- Low charge loss as 5 percent per month as compared to 20 percent charge loss per month by NiMh. Batteries.
- Do not need to be discharged completely while not using.
- Capable of countless charge and discharge cycle.

Among all types of Li-ion batteries, the most commonly known one is cobalt based Li-ion battery (18650)[24], because it is rated as high power battery as it has large energy density.

2.7.3 Electronic Speed Controller (ESC)

An ESC is a component found in an electric UAV that connects the power source and the motor. It functions as the controller to the output power and rotational speed of motors, responding to the throttle commands from pilot. Generally, the ESC converts the direct current (DC) electricity from a battery to 3-phase alternating current (AC) to drive a brushless DC motor. This is achieved via high-frequency electronic switching, which could yield considerable efficiency losses [25].

2.7.4 Flight Controller

Flight controller chosen for this project is Pixhawk 2.1 as shown in Figure 2.11 that support Ardupilot firmware (APM).

Figure 2.11 Pixhawk 2

PIXHAWK2.1 is the latest version of Pixhawk, which is an independent, open-hardware project. Its design is directed to provide a high-end autopilot hardware to the academic, hobby and industrial communities at low costs and high availability. With the help of APM firmware, PIXHAWK2.1 turns any RC plane, copter, or rover into a full-featured personal drone [26].

2.7.5 Radio Control (RC) Transmitter

Radio control (RC) is a controlling method by transmitting or receiving signals from a device through radio signals. It is often used for controlling model vehicles from a hand-held radio transmitter that normally operating at frequency of 2.4GHz[27].

From [22], there are two precautions need to be taken during the use of RC Transmitter :

Receiver Inundation – Signal strength from RC can be significantly reduced while placing it near to another high-power transmitting source. This is due to inundation of the receiver and the other independent of frequencies. As receiver inundation is independent of frequency, the direct-sequence spread spectrum (DSSS) modulation utilized by the RC receiver would not be effective. For example, the modem transmits at a much higher power than the RC transmitter, which greatly reduced the efficiency of transmission and receiving of signals by RC.

Shadowing – Since RC is using the electromagnetic wave, dense or conductive materials, like carbon fiber, copper, aluminum, and steel, reduce the efficiency of RC by shielding electromagnetic waves from passing through them. This is a crucial issue to drones design because most of the materials preferred to manufacture them are carbon fiber, which significantly reduce the strength of RC.

2.8 Research Gap

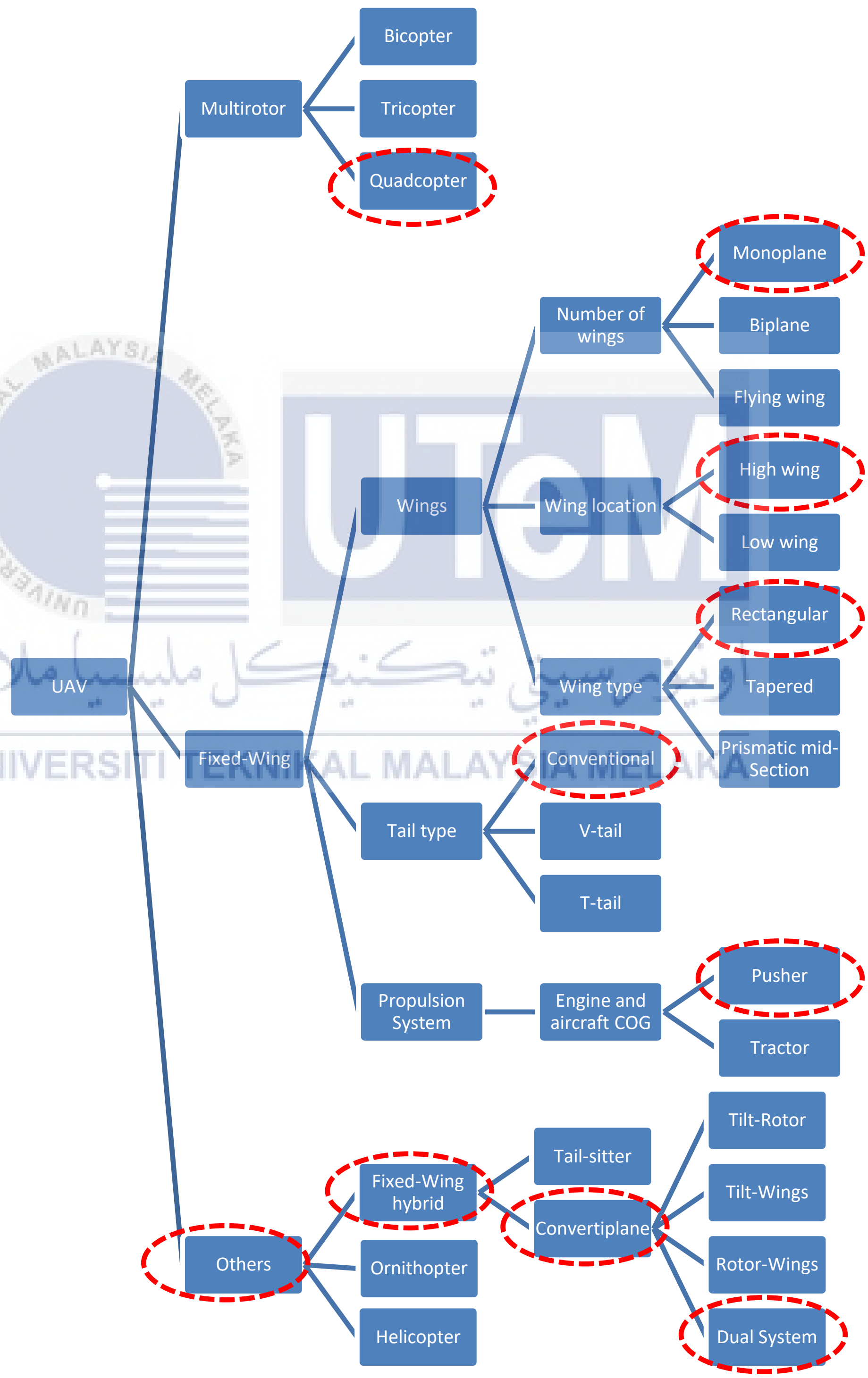
According to [9], more preferable configurations for wing design of fixed-wing aircraft are monoplane (one-wing plane). Likewise in [10], rectangular wing is chosen for its higher manufacturability and easier to determine its aerodynamical performance. In the same journal, conventional tail type aircraft is suggested as well for its lower structure weight. To decide placement of motor for fixed-wing part of UAV, [9] is referred, as it stated that tractor type of aircraft has a greater efficiency. Furthermore, in the same journal stated that airfoil MH114 outstands the other four types of airfoil compared in terms of lift to drag ratio, as well as relation of lift coefficient with angle of attack of the aircraft.

For design on multirotor part of UAV, X-4 quadcopter configuration is chosen due to its mechanical simplicity as [11] mentioned. This multirotor type is capable of high payload yet gyroscopic effect is reduced based on [14]. This is the first attempt of mine in building UAV, so the easiest configuration of fixed-wing hybrid aircraft is selected for this project [15].

Materials selection for manufacturing is as important as choosing configurations, hence journals are reviewed to determine the most suitable ones according to project limitations and purposes, which mainly concern about cost, manufacturability as well as availability. Based on [18], light plywood and carbon fiber tube as frame structure are selected, where Balsa wood is used to build fuselage of low cost fixed-wing aircraft in [19]. However, carbon fiber is chosen as skin material since it has been chosen as frame structure in earlier, even though in [19], fiber glass reinforced plastic has a higher score. By referring to [24], cobalt based Li-ion battery (18650) is chosen as power source for this project, since it has large energy density yet being widely used.

Summary Diagram

The diagram below higlights all the configurations chosen for fixed-wing hybrid UAv of this project. In short, UAV desgined and developed is a high wing monoplane with rectangular wing and conventional tail, a pusher type aircraft hybrid with a quadcopter system to enable vertical takeoff and landing



Chapter 3

METHODOLOGY

3.1 Overview

In this chapter, methods to achieve the objectives of the project as stated in Chapter 1 will be discussed and presented. Thus, this chapter can be divided into 3 main parts, designing, manufacturing and evaluating fixed-wing hybrid developed in this project. All mathematical equations needed in design, materials, and methods in manufacturing, methods to evaluate UAV performance are stated in detail within this chapter.

3.2 General Project Flowchart

Based on Figure 3.1, first thing to start in this project is estimating the maximum takeoff weight of aircraft, this is due to the whole design process are going to refer to this parameter estimated in earlier stage. Then, design is started from fixed-wing part. Wings, tails, and fuselage are determined through calculations and being explained in detail later, as this is the most difficult and challenging part of this project. After that, the propulsion power for both forward transitioning and VTOL are calculated, continue with deciding motors to generate power required. By this stage, all the electronics components are decided since they are all related to motors. Moreover, once all the parts are selected, new total weight of aircraft is measured to ensure it fell into design range. After the actual weight being assured, fabrication process is carried out as the next stage in this project. Next, the real weight of aircraft is measured again to ensure it fits the design.

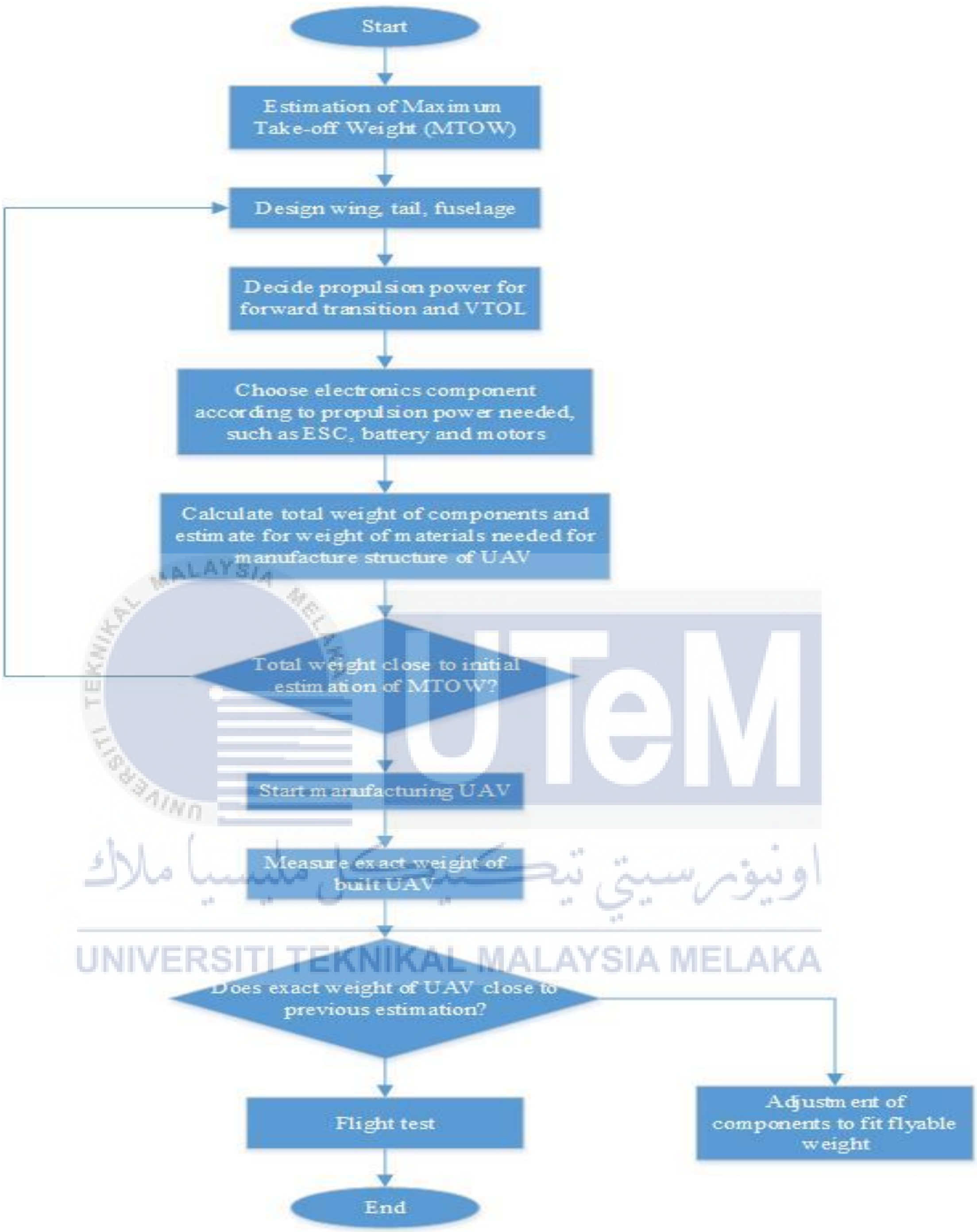


Figure 3.1 General Project flowchart

3.3 Designation of Fixed-Wing part of UAV

There are three general design phases for fixed-wing aircraft as shown in Figure 3.2.

Conceptual Design Phase – A phase is the aircraft design at the concept level, all the configurations for a wing, tail, motor, structural and mechanisms are decided in this stage.

Preliminary Design – A phase that determines aircraft maximum take-off weight (MTOW), hence deciding wing area (S_{ref}), motor power (P) and thrust (T).

Detailed Design – In this phase, all the detailed design of wings, tails, and fuselage are determined with calculations based on [6].

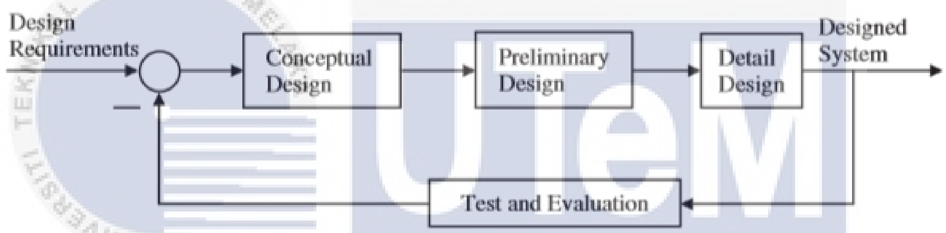


Figure 3.2 Block diagram of four major design activities for fixed-wing aircraft[6]

3.3.1 Maximum take-off weight (MTOW)

Maximum take-off weight for UAV in this project consists of weight from electronics component and structure materials. The components are consisted of flight controller, ESC, servo motors, brushless DC motors, and batteries. Structure materials weight are depended on the final decision in choosing materials during fabricating UAV. However, the weight of motor and batteries rely on how much thrust is needed for UAV, where thrust power calculation is related to maximum take-off weight. This causes an infinite loop in the calculation, hence an estimated MTOW is set to bring on the designation phase to the preliminary design phase. To estimate MTOW, weight, and sizes of fixed payload such as flight controller, ESC, servos is measured, while brushless DC motors and batteries are estimated at first.

3.3.2 Wing

Figure 3.3 shows the flow of designing wings for an aircraft. In Chapter 2.3.1, wing types have been reviewed in several papers to choose best-fit configurations for this project. The number of wings is chosen to be monoplane type, while the vertical location of wing is high wing type. Meanwhile, airfoil type is selected to be MH114. UAV in this project supposed to be capable of VTOL, thus no high-lift devices needed as they are for taking-off horizontally. For simplicity purpose in manufacturing, sweep, dihedral, twist and incident angle of aircraft are all set to 0°, so calculations of those angle will not be involved. Since rectangular wing is chosen, taper ratio of wing (λ) is set to 1.

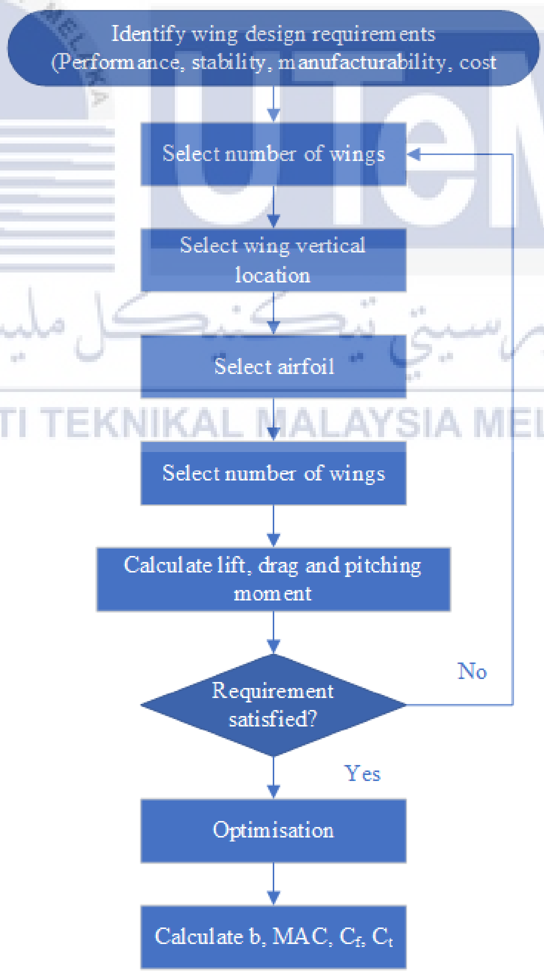


Figure 3.3 Wing design flowchart [6]

3.3.2.1 Wing Area

Wing area needs to be calculated during preliminary phase in designing an aircraft. To calculate wing area required to generate enough lift for aircraft weight, there are supposed to have 5 equations according to [6], which take account of stall speed (V_s), maximum speed (V_{max}), maximum climb rate (ROC_{max}), take-off run (S_{TO}), and ceiling height (h_c). However, aircraft in this project doesn't concern of ROC nor h_c, therefore, only equations of V_s and V_{max} S_{TO} are listed as below. Firstly, find the stall speed ($V_{s)}$ contribution by using Equation 3.1 shown. Then maximum speed contribution is calculated by using Equation 3.2 followed by calculating take-off run with Equation 3.3 and all the equations are plotted into a match plotting graph to obtain desired wing area.

$$\left(\frac{W}{S}\right)_{V_s} = \frac{1}{2}\rho {V_s}^2 C_{L_{max}}(\qquad (3\text{-}1)$$

Where:

Air density, $\rho = 1.225 kg/m^3$ (chosen at sea level since it is highest, also denotes as $\rho_{o)}$

$\left(\frac{W}{S}\right)_{V_S}$ is wing loading (Weight to Wing Area ratio) for V_s

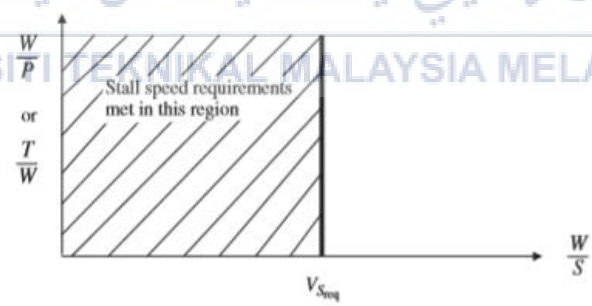


Figure 3.4 Stall speed contribution in constructing a matching plot

$$\left(\frac{W}{P}\right) = \frac{\eta_P}{\frac{a{V_{max}}^3}{\left(\frac{W}{S}\right)} + \frac{b}{V_{max}}\left(\frac{W}{S}\right)}(\qquad (3\text{-}2)$$

Where:

$a = \rho_o C_{D_0}$

$$b = \frac{2K}{\rho \sigma V_{max}}$$

$$K = \frac{1}{\pi . e . AR}$$

Wing aspect ratio, AR = 4 to 7 (for home built)

(ρ_o) is air density at sea level, σ is the ratio of air density at specific altitude, (ρ) to air density at sea level (ρ_o), (C_{D0}) is zero-lift drag coefficient which needs to be estimated under preliminary design by calculating several aircraft that have similar performance characteristics and configurations. (η_p) is the efficiency of power.

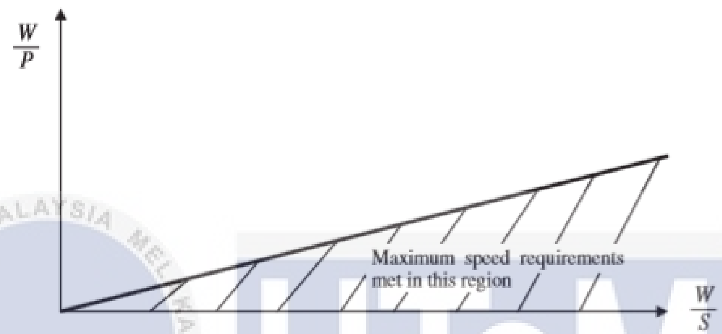


Figure 3.5 Maximum speed contribution in constructing a matching plot for a prop-driven aircraft

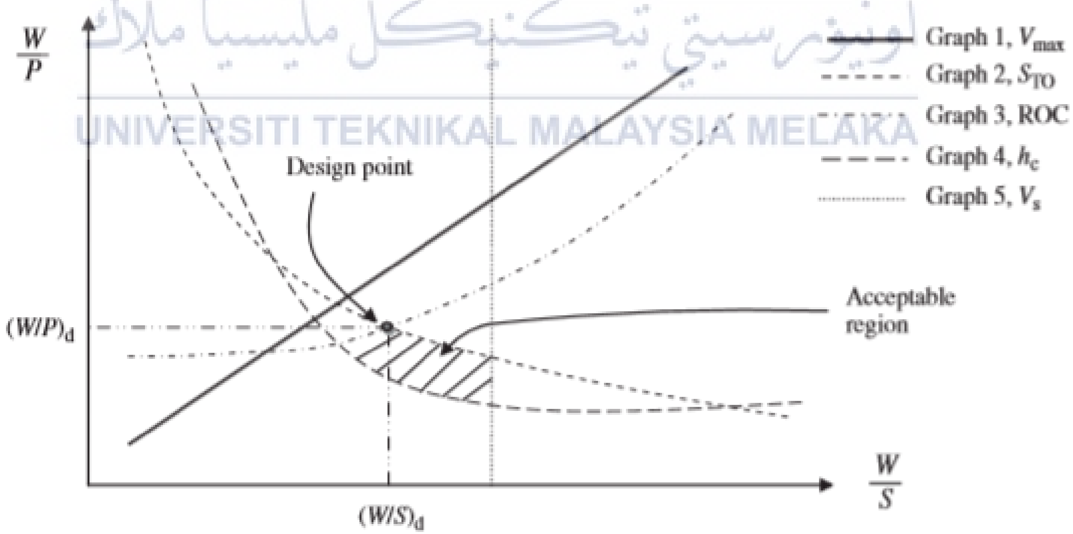


Figure 3.6 Example of a matching plot for prop-driven aircraft

$$\left(\frac{W}{P}\right)_{S_{TO}} = \frac{1-\exp\left(0.6\rho g C_{D_G} S_{TO}\frac{1}{W/_S}\right)}{\mu-\left(\mu+\frac{C_{D_G}}{C_{L_R}}\right)\left[exp\left(0.6\rho g C_{D_G} S_{TO}\frac{1}{W/_S}\right)\right]}\frac{\eta_P}{V_{TO}} \quad (3\text{-}3)$$

After finding matching contribution from stall speed and maximum speed, a matching plot similar as Figure 3.6 needed to find out design power loading, $(W/P)_d$ and wing loading, $(W/S)_d$, which means aircraft weight to power of motor ratio and aircraft weight to wing area ratio respectively. To calculate estimated wing area, S, use Equation 3.4 below.

$$S = {W_{TO}}/{\left(\frac{W}{S}\right)_d} \quad (3\text{-}4)$$

3.3.3 Tail

Figure 3.7 presents the design flow of fixed-wing's tail. Both horizontal and vertical tail have similar flow of design. Like wing design, tail design starts with identifying design requirement such as trim, stability, control, manufacturability and so on. Then, select the configurations according to requirements stated. Next, by presetting tail volume coefficient, determine optimum tail arm and planform area required. Then, select airfoil, calculate setting angle (preferred to be 0° for easing manufacture process), and all the tail parameters.

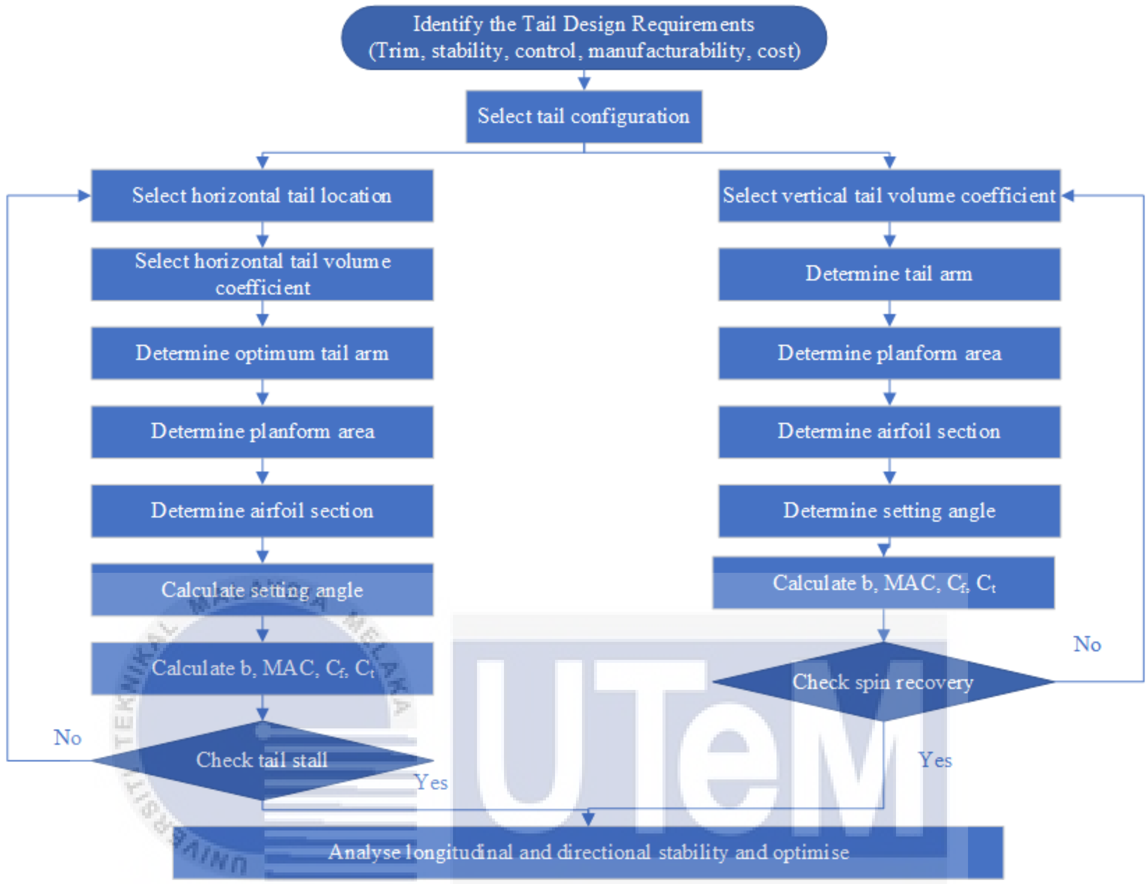


Figure 3.7 The tail design flowchart

As in the flowchart above showed, the tail in a conventional aircraft has two components, a horizontal tail, and vertical tail, and carries two primary functions:

- Trim (longitudinal and directional).
- Stability (longitudinal and directional). Since two conventional control surfaces (i.e., elevator and rudder) are indeed parts of the tail to implement control, it is proper to add the following item as the third function of a tail.
- Control (longitudinal and directional).

Note that during tail design procedures, taper ratio, sweep angle, settling angle and twist angle are not considered as they will be set to simplest configurations. Taper ratio will be set as 1, and all the angles are set as 0 as wing design does.

3.3.3.1 Horizontal Tail Design

The optimum tail arm (l_{opt}) shown in Figure 3.8 is calculated with Equation 3.5.

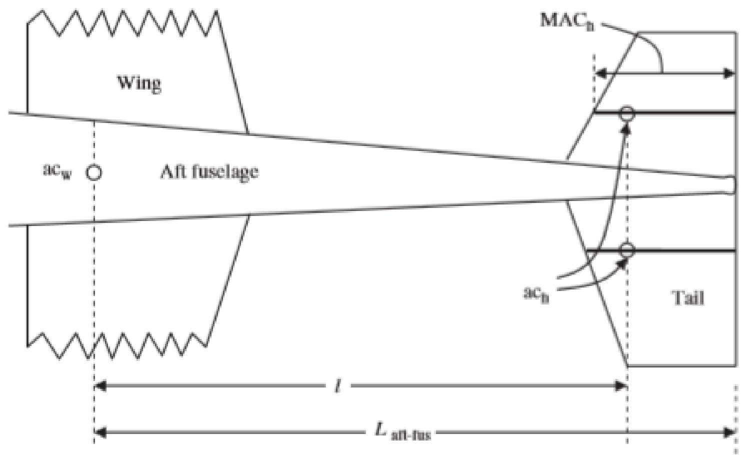


Figure 3.8 Top view of an aft portion of aircraft

$$l_{opt} = K_C\sqrt{\frac{4\bar{C}S\bar{V}_H}{\pi D_f}}(\qquad (3\text{-}5)$$

K_c is a correction factor that varies between 1 (when aft portion of the fuselage is conical in shape) to 1.4 (when aft portion goes further away from conical shape). K_c = 1.1 (as a general rule for single-seated single engine prop-driven GA aircraft) but 1.4 for transport aircraft with the cylindrical fuselage. D_f denotes the maximum fuselage diameter.

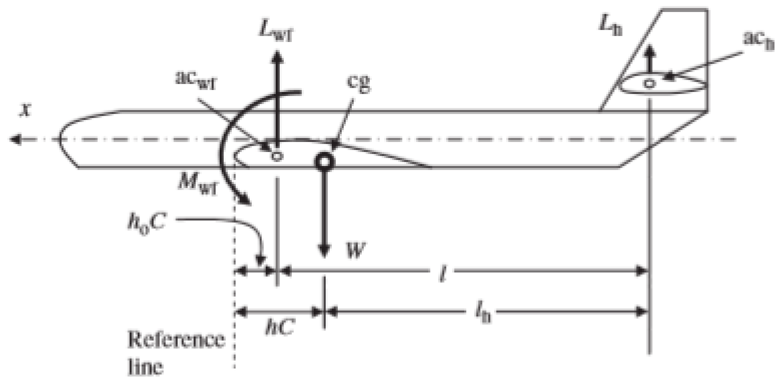


Figure 3.9 A conventional aircraft in longitudinal trim

$$\bar{V}_H = \frac{l}{\bar{C}}\frac{S_h}{S}(\quad (3\text{-}6)$$

All variables in Equation 3.6 are denoted as following, horizontal tail volume coefficient ($\overline{V_H}$), distance from cg to ac of horizontal tail (l), mean aerodynamic chord for wing ($\bar{C}$), horizontal tail planform area (S_h), wing planform area (S),

3.3.3.2 Vertical Tail Design

Designing vertical tail is similar to horizontal tail. Planform area of vertical tail is preliminarily determined based on selection of vertical tail volume coefficient ($\overline{V_v}$)

$$\bar{V}_v = \frac{l_v S_h}{bS}(\quad (3\text{-}7)$$

By using Equation 3.7 above, the vertical tail volume equation, planform area S_v can be obtained since vertical tail arm l_v is assumed to be equal to the horizontal tail arm while b and S are wingspan and wing reference area respectively.

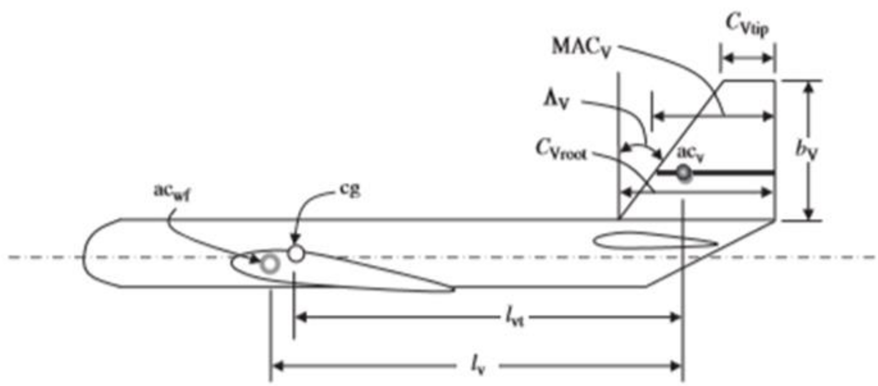


Figure 3.10 The vertical tail parameters

Note that while choosing airfoil for vertical tail, a symmetrical airfoil shape is recommended since it has more advantages. The incidence angle of vertical tail is considered to change to 1° or 2° to nullify rolling moment produced by prop-motor.

3.3.4 Propulsion for Fixed-Wing part of UAV

Motor power required is calculated with design power loading obtain in matching plot as Figure 3.6, using equation below.

$$P = W_{TO} \Big/ \left(\frac{W}{P}\right)_d \qquad (3\text{-}8)$$

While P is required power, W_{TO} is take-off weight, $\left(\frac{W}{P}\right)_d$ is the desired power loading (aircraft weight to power ratio that obtain from matching plot graph)

To know the exact cruising speed needed for an aircraft to generate enough lift for overall weight of it, Equation 3.9 is derived from ideal cruise lift coefficient equation.

$$V_C = \sqrt{\frac{2W}{\rho C_{L_C} S}} \qquad (3\text{-}9)$$

3.4 Designation of Multi-rotor part of UAV

3.4.1 Propulsion for Multirotor part of UAV

As propulsion for multirotor is similar to propulsion for fixed wing part of UAV. The only difference with propulsion in fixed wing is total thrust needed in multirotor is shared by four identical motor, which means each of them only need to support a quarter of thrust needed to perform VTOL. As in [27], only half throttle of motors are used for hovering as this is the optimum. Selection for suitable propulsion from VTOL motors are simple, as estimated weight of an aircraft is 2.5kg, then the total thrust provided from 4 motors have to be around 5kg. Motor thrust can be obtained from experimentally which mostly can be found in datasheet of it.

3.5 Fabrication of Fixed-wing hybrid UAV

3.5.1 Materials Chosen for Fabrication

The materials chosen to fabricate fixed-wing hybrid UAV are listed as below :

- i) Carbon fiber tubes as main supporting frame (round tubes and square tubes.)
- ii) 5mm thick Balsa wood as ribs
- iii) 1mm waxed polyester braid as lashing material
- iv) Thin cyanoacrylate and epoxy as adhesive material
- v) Heat shrink plastic film as skin of UAV
- vi) PLA 3D print for several mounting, sockets and vertical tail.
- vii) M3 black steel bolt and nut
- viii) Aluminum spacer

3.5.2 Motors and Propellers Selection

Motor selection process is crucial in building an UAV. In 3.3.4 and 3.4.1, result calculation thrust needed for UAV is needed here to choose appropriate motors. Hobby motor commonly used in building mini UAV, they are rated in Kv ratings and current ratings [27] which mean RPM per volt supplied and maximum current can be drawn safely. There are suggested propellers size paired with suitable rating of ESC in motor data sheet, for aircraft designed in this project, the total all up weight of it is measured as 3.4kg. The fixed wing motor is selected to be brushless d.c motor, Dualsky XM3542EA-5(950Kv), rated with 2.03kg thrust together with 3 cells battery (12.6V when fully charged) and 12x6E APC propeller [28]. By using this motor in forward transitioning, the thrust to weight ratio is 0.5971, that is quite enough for a remote-controlled aircraft. Then, VTOL motors are selected to be brushless d.c motors, Turnigy D3536/6 (1250Kv), rated with 1.27kg thrust each together with 4 cells battery (16.8V when fully charged) and 10x4.7 propellers.

3.5.3 Battery selection

After choosing motors and propeller, voltage and current required is known, therefore number of battery cells can be easily predicted as one 18650 Li-ion cell provides 4.2V at fully charged condition with around 20A maximum current (depend on brands) can be drawn safely. For example, if 30V is needed for motors, at least 8 cells need to be arranged in series circuit (since voltages add up in series-oriented battery). Normally, batteries are rated in mAh and C which indicates power can be stored in the batteries and maximum current can be discharged respectively. For example, a cell with rating 2000mAh and 5C able to sustain 10A maximum current discharging for 12 minutes.

The fixed wing motor will be using 18650 Li-ion cells with 3 cells in series,4 cells in parallel (3S4P), 12 cells in total that provide 12000mAh in total but VTOL motors are powered by Lithium Polymer battery (LiPo) with 4 cells in series, provide 1500mAh in total. The reason to separate power sources for both system is because VTOL motors need a very high discharge rate, that up to 136A in total at maximum throttle, this discharge rate can be only handle by at least 7 18650 parallel cells (140A total discharge rate), with 4S required meaning that at least 28 batteries needed to provided enough power. A single

18650 cell weights around 45grams, 28 cells will weight 1.26kg, it is way to heavy for battery sources. Hence, LiPo is chosen for VTOL motors as it rated 110C with 1500MAh capacity, it means the discharge rate can be up to 165A. The capacity for VTOL power source is much smaller because it is for taking off and landing only, any excessing capacity will be unused weight on the aircraft. Let say if the VTOL motor is running at full throttle all along, the LiPo is still capable to sustain for 40 seconds, that is reasonably enough for just takeoff and land. The battery pack for fixed wing motor is self-spot-welded into 3S4P configuration, it is capable of 80A discharge rate while the motor is only rated at 37.98A at maximum throttle.

3.5.4 Electronic Speed Controller (ESC) Selection

This component is going to control the speed UAV in term of controlling the speed of rotor. The main concern in selecting an ESC is by ensuring the rated ESC are capable to handle voltage and current drawing from battery to motors at maximum throttle. ESC chosen for plane system is Dualsky 45A ESC whereas HobbyWing 40A ESCs are chosen for the VTOL system respective to the motors current draw and rated voltage.

3.5.5 Electronics Components Schematic Diagram

From Figure 3.11, all the electronics components are shown with their respective connection into the flight controller (PixHawk 2). There are a few features added to support the fixed wing hybrid system such as GPS module, telemetry that transfer data back to ground control station (any PC will do) and low voltage beeper.

The HERE GPS module takes an important role to measure the ground speed of aircraft. The ground speed is then being processed to estimate the airspeed of the aircraft but this is just an estimated value, a proper airspeed sensor (Pitot tube) is more accurate but to reduce the budget, estimated airspeed will do too.

A Telemetry system is used in this project named RFD900x, it is an ultra-long-range radio modem. This telemetry system helps to transmit real-time flight data back to ground control system, such as altitude, groundspeed, battery information, flight health, flight mode and so on. Besides, before taking off, it also shows the motor arming status (armed or disarmed) as only after the VTOL motors are armed, then it allows throttle input. Since this fixed-wing hybrid control system relies on GPS, if the GPS signal is unhealthy, it will not allow pilot to arm the motors, that we can see from the ground control station. Parameters in PixHawk can be amended from ground control station through telemetry, so it is not necessary to detach flight controller all the times for parameters adjustment.

A low voltage beeper is implemented in this project system because the PixHawk can only monitor a single power source, which is decided to reserve it for fixed-wing system for monitoring the cruising endurance. So, another low voltage alarm is needed to notify ground control that the VTOL power source is low. The beeper will start to beep once the LiPo battery drops to 3.7 volt, meaning that the battery is barely left for landing sequence instead of maintain hovering.

Remote control used in this project is T8J by Futaba, this remote offers PPM signal as output signal to PixHawk. Normal PWM remote control is not compatible with PixHawk because it can be paired with PPM remote control only.

There are two types of connectors used in this project, which are XT-60 and XT-90 connectors. These connectors are named after its rated ampere such as XT-60 is rated for 60A current flow. A proper match with possible ampere flow and rated ampere for wires and connectors is important to prevent overheat case. Since the VTOL motors draws 34A at maximum, so 4 motors is split into two pairs when each of the pair will drawn 68A at maximum, 60A rated connector will do as the motor will not draw maximum current constantly. Both pairs will be paralleled together and connect into LiPo battery with XT-90. Even though the maximum current can be drawn by motors is 136A in total, but XT-90 is the highest rated connectors can be found in existing resources I have, after the flight test there are no overload current signs shown as well so it should be comfortable enough for the current draw.

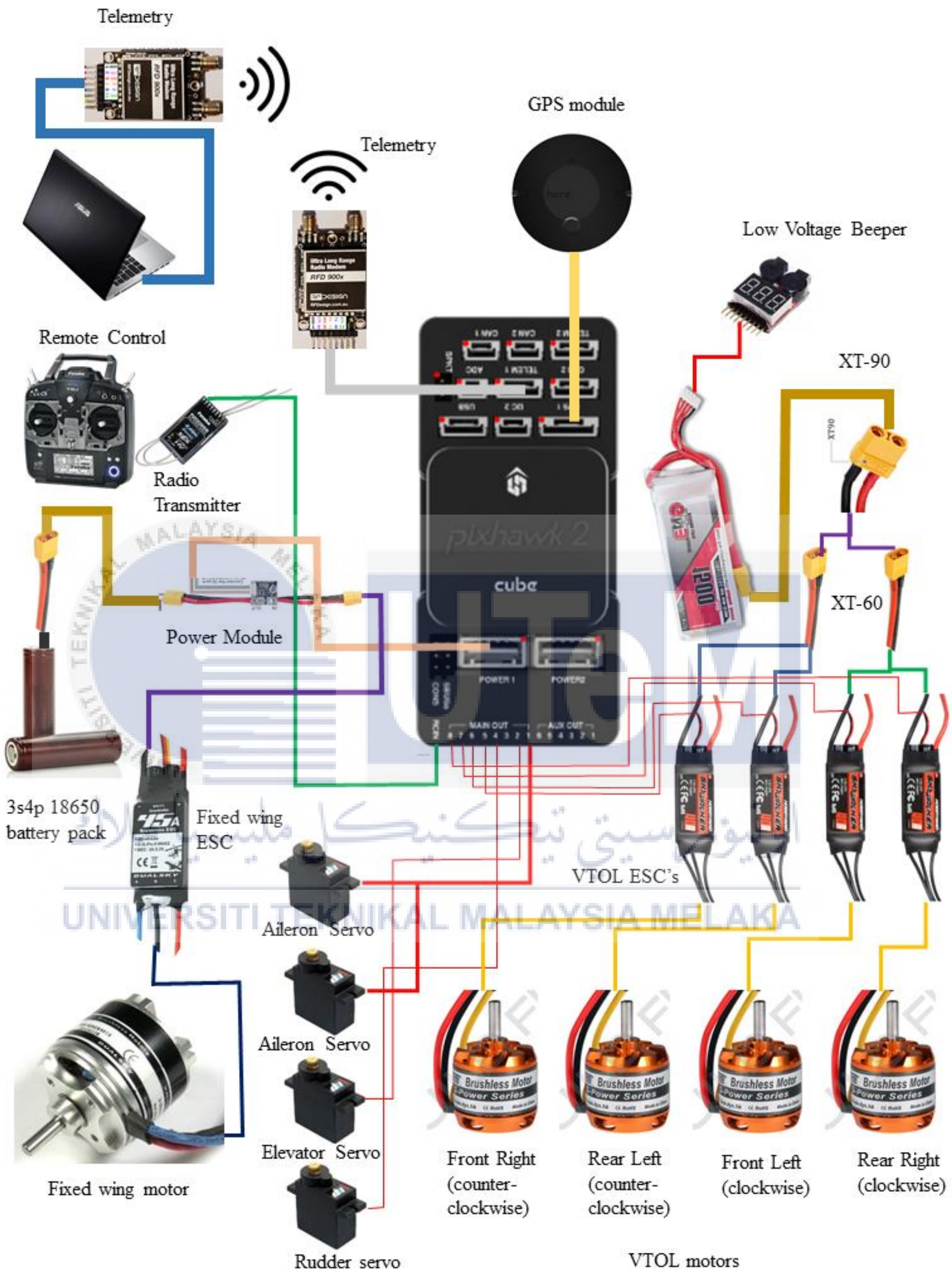


Figure 3.11 Full electronics schematic diagram

3.6 Firmware Settings Procedure

Based on [29] there is a firmware named QuadPlane by Ardupilot is suitable to control fixed wing VTOL. APM:Plane supports QuadPlane mode from version 3.5.0 onwards while the latest version 3.9.8 is used in this project. To enable this mode, Q_ENABKE parameter in the firmware is set to 1, then the QuadPlane parameters appear right after refreshing parameter list. The other changes in parameters are listed as below.

Table 3.1 Parameters in Ardupilot firmware than need to be changed

Parameter	Value	Remark
Q_FRAME_CLASS	1	Declare copter frame class as quad configuration.
Q_FRAME_TYPE	1	Declare quadcopter frame type as X frame.
ARMING_RUDDER	2	To setup for rudder disarm
ARSPD_FBW_MIN	15 (m/s)	Calculated airspeed for aircraft to cruise
Q_ASSIST_SPEED	10 (m/s)	The VTOL motors turn on when the airspeed is below 10m/s to prevent aircraft stall
Q_RTL_MODE	1	To enable hybrid return to launch mode, which means it cruises back to launch pint with plane mode then land with copter hover mode automatically.

3.7 Flight mode used

3.7.1 Quadcopter hover (QHOVER)

QHOVER is very similar to a copter mode named Altitude Hold mode, which means the throttle stick is controlling altitude climb instead of controlling the throttle level. By controlling altitude means the when the throttle stick is raised above 50%, the copter tends to hike in altitude, the higher the throttle level, the greater the climb rate.

When the throttle level is lower than 50%, the copter tends to decent its altitude. At 50% of throttle level, the copter holds its altitude automatically until the next throttle signal given.

Since take off and landing sequences are done with a copter system, QHOVER is the suitable mode to use on.

3.7.2 Fly By Wire-A mode (FBWA)

This is the most popular mode for assisted flying in Plane, and is the best mode for inexperienced flyers. This mode is used in cruising after taking off using VTOL system then after reaching desired airspeed to cruise, the VTOL motors will be turned off after 5 seconds.

In this mode, it will hold the roll and pitch specified by the control sticks. So, the aileron stick is held hard right then the plane will hold its pitch level and will bank right by the angle specified in the LIM_ROLL_CD option (in centidegrees). It is not possible to roll the plane past the roll limit specified in LIM_ROLL_CD, and it is not possible to pitch the plane beyond the LIM_PITCH_MAX/LIM_PITCH_MIN settings.

Holding level pitch does not mean the plane will hold altitude. How much altitude a plane gains or losses at a particular pitch depends on its airspeed, which is primarily controlled by throttle. So, to gain altitude the throttle is raised, and to lose altitude the throttle is lowered. In FBWA mode throttle is manually controlled, but is constrained by the THR_MIN and THR_MAX settings.

3.8 Evaluation of UAV performance

There are many log data recorded in Pixhawk can be retrieve by either using telemetry or extracting SD card from it. There are few important data retrieved as list below.

- Ground speed

  Since there is no pitot tube (airspeed sensor) used in this project, the airspeed in flight controller is estimated from ground speed from GPS module.

- Altitude

  Altitude is measured with built in barometer in Pixhawk. Altitude travelled should be under control since developed aircraft is designed for flying at 100m or below.
- Channel 3 of remote-control input

  As channel 3 of RC input is the altitude control for hover mode and throttle level for plane mode, it is important to retrace this input in order to know the throttle level for the aircraft to cruise and climb, this data is then analyse together with altitude and ground speed recorded.
- Battery voltage during flight

  Battery voltage directly indicates the energy left in the batteries, it is important to know the voltage drop during flight to know the performance of aircraft in term of power spent throughout the flight test.
- Battery current drawn during flight

  Battery current draw is retrieved to make sure the motor and ESC is not overloaded.

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Overview

In this chapter, results that are expected from next phase of final year project is presented, which includes the conceptual design of UAV with all configurations and parts being emphasized.

4.2 Conceptual Design of UAV

Figure 4.1 and Figure 4.2 show the first phase of design in this project. After all the comparisons and reviews, these configurations of fixed-wing hybrid UAV are best fit in term of manufacturability, cost and performance, at the same time, able to achieve VTOL for a fixed-wing aircraft.

To summarize, this UAV is a high wing monoplane, with choosing MH114 as airfoil of wing, conventional tail for longitudinal and lateral trim and stability. This UAV is expected to have wing span less than 1-meter, total weight is less than 10kg so that this prototype will not be oversized for an individual work. Motor placement is going to be tractor type for forward transitioning. In addition, another 4 vertical motors oriented in quadcopter X-4 type for VTOL. Furthermore, electric propulsion is going to be powered by Lithium-ion based battery (18650). Moreover, PixHawk2.1 is chosen as flight controller due to its functionality eases this project’s development. Likewise, this UAV will be featured with video capturing as well, meaning that an action camera is included in payload allocation.

Since there are no specific parameters decided yet upon this stage of project, thus conceptual design is presented in hand drafted form. Detailed parameters and results are going to be shown after hands on work started as all processes are still under planning in conceptual behavior.

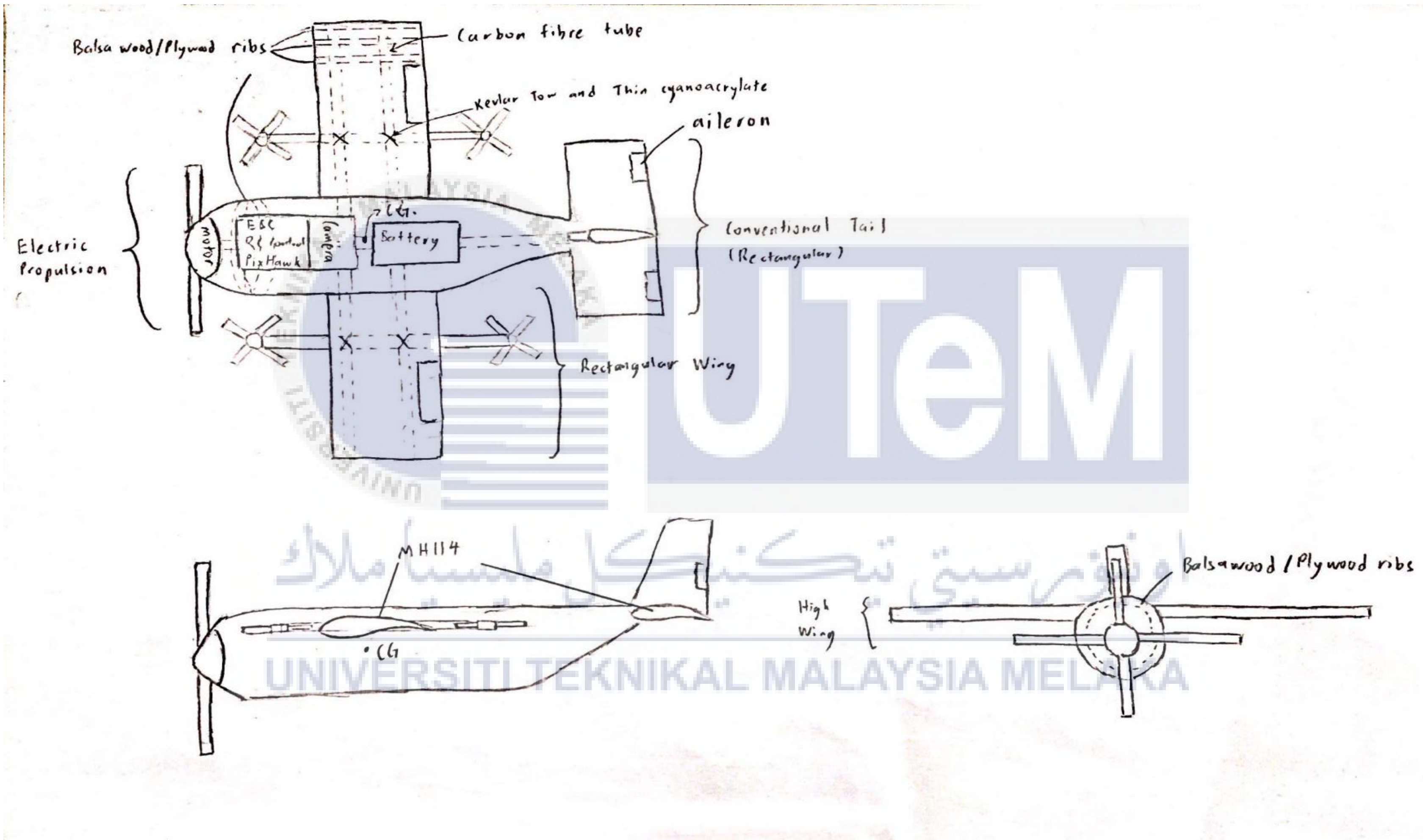


Figure 4.1 Hand drafted Three View of Conceptual Design

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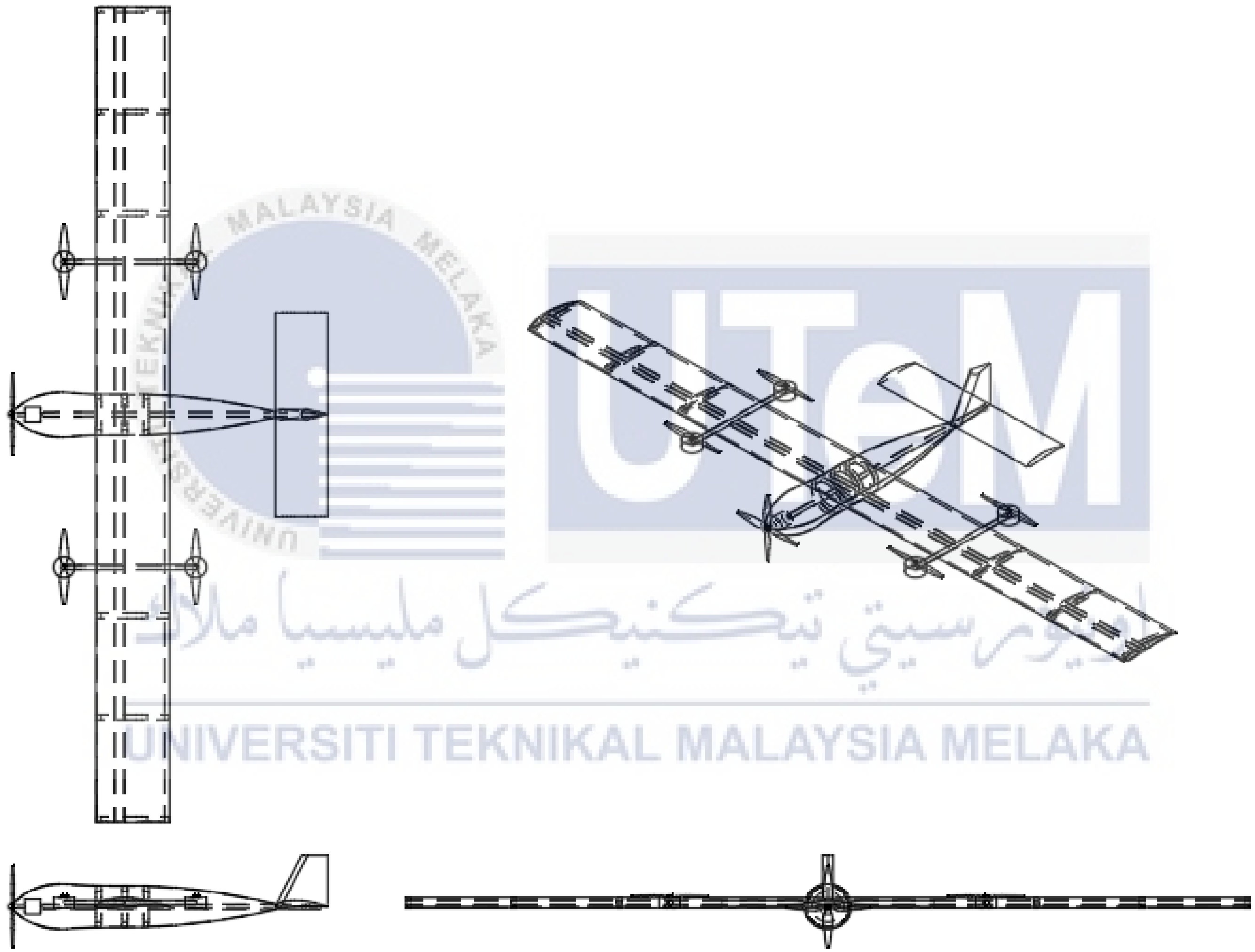

Figure 4.2 Computer-aided design (CAD) of Three View of Conceptual Design

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4.3 Mathematical Results

4.3.1 Wing Design

As in **Error! Reference source not found.** mentioned that in order to get a wing d esign, a few constraints need to be defined first. The constraints are listed as table below:

Table 4.1Constraints for wing design

Parameter	Value	Remarks
Desired maximum takeoff weight, W_{TO}	2.5kg	Estimated weight of aircraft
Desired stall speed, S_{TO}	10m/s	Reasonable value
Cruising speed, V_C	15m/s	Midpoint between stall speed and maximum speed
Desired maximum airspeed, V_{max}	20m/s	Reasonable speed for a prototype
Desired cruising altitude	100m	Above sea level
Oswald efficiency number,e	0.85	Typical values range from 0.7 to 0.95, an average value are chosen
Zero lift drag	0.07	Estimated because it can only obtain from wind tunnel experiment
Aspect ratio for wing	7.3	Similar to glider because similar flight characteristics such as weights and speed
Takeoff speed	15m/s	Once aircraft hits this speed, VTOL motors will be turned off.
Takeoff runway	30m	It requires this distance to hit takeoff speed.
Friction coefficient of runway	0	Due to takeoff in air, friction can be ignored
Estimated drag coefficient	0.17	Estimated with reference to [6]
Lift coefficient at 0° incident angle	0.8289	Obtain from [30]

With the constraints above, calculations are done by MATLAB and plotted in it as shown in Figure 4.3 Matching Plot of Power Loading(W/P) versus Wing Loading(W/S) done by MATLAB. The calculation coding in MATLAB is as following.

```
MTOW = 2.5*9.81; %maximum take off weight
Vs = 10; %stall speed
Vmax = 20; %maximum airspeed
CLmax = 2.5; %maximum lift coefficient
roh_0 = 1.225; %air density at sea level
roh = 1.1682; %air density at specific altitude
e = 0.825; %oswald efficiency number
sigma = roh/roh_0;
W_S_Vs = 0.5*roh_0*(Vs^2)*CLmax; %stall speed contribution
CD_0 = 0.07; %zero lift drag
a = 0.5*roh_0*CD_0;
AR_W = 7; %aspect ratio
K = 1/(pi*e*AR_W); %drag factor
b = (2*K)/(roh*sigma);
np = 0.9; %efficiency of power by motor
V_TO = 15; %take off speed
S_TO = 30;
mu = 0; %friction coefficient of the runway
CD_G = 0.17; %estimated drag
CL_R = CLmax; %lift coefficient at takeoff rotation
W_S = linspace(0,170);
W_P = np./(((a.*Vmax^3)./(W_S))+((b./Vmax).*W_S)); %maximum
speed contribution
W_P_STO = ((1-exp(0.6 .* roh .* CD_G .* S_TO .* (W_S.^(-
1)))))./(mu-(mu+(CD_G./CL_R)).*(exp(0.6 .* CD_G .* S_TO .*
(W_S.^(-1)))))).*(np./V_TO);%takeoff runway contribution
plot(W_S,W_P);
hold on;
W_S_Vs2(1:100) = W_S_Vs;
plot(W_S_Vs2,W_P);
plot(W_S,W_P_STO);
plot([70,70],[0,1]);
```

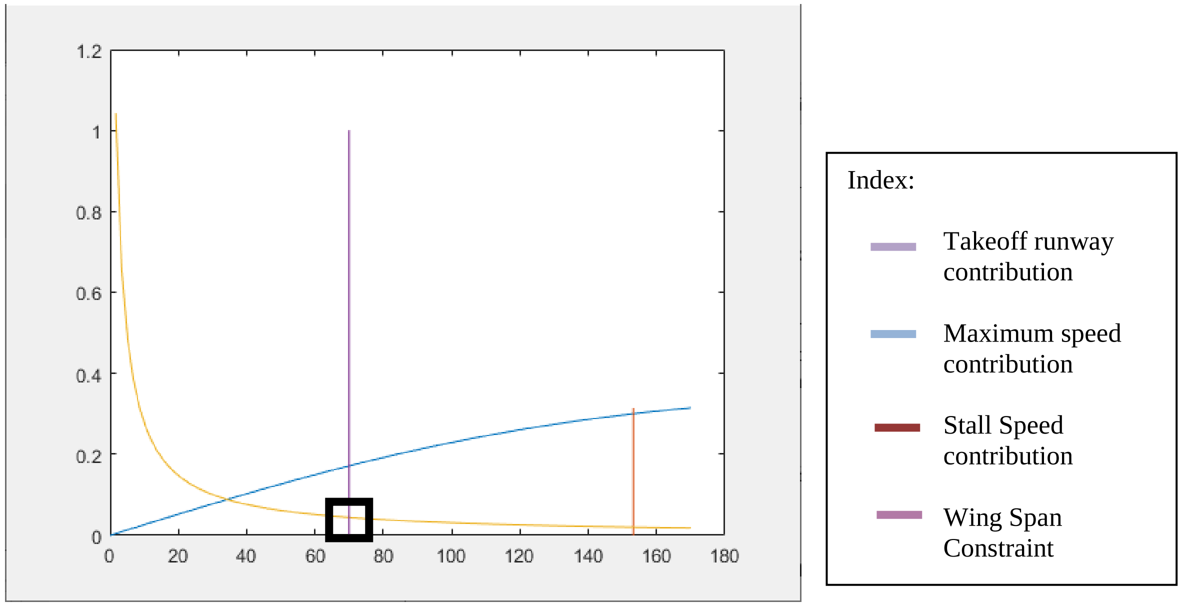

Figure 4.3 Matching Plot of Power Loading(W/P) versus Wing Loading(W/S) done by MATLAB

In Figure 4.3, wing span constraint contribution is added in order to limit the wing span to 1.6m for fixed wing.

Since $\left(\frac{W}{S}\right) = \frac{W_{TO}}{S}$, where S is the wing planform area which is wing span multiply by chord length, this constraint contributed a constant line to (W/S) axis

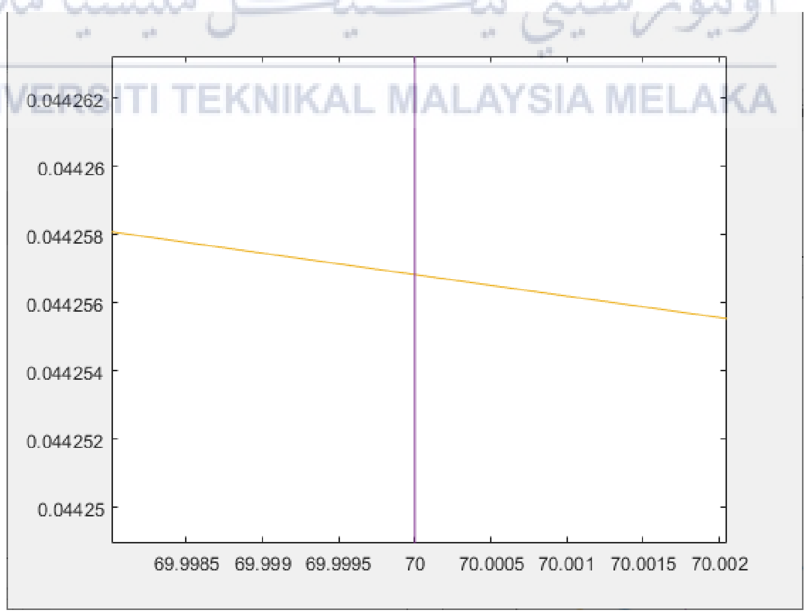

Figure 4.4 Close up view of desired matching plot point in Figure 4.3

From Figure 4.4 two important values are obtained, which is $\left(\frac{W}{S}\right)$ and $\left(\frac{W}{P}\right)$, they are 70 and 0.04426 respectively. These two numbers brought a guide for designing wing and propulsion. From Equation 3.4, wing planform area, S is determined.

$$S = \frac{2.5 \times 9.81}{70} = 0.3504 \tag{4-1}$$

Since aspect ratio, AR is set to 7.3, wing chord is determined.

$$wing\ chord, \bar{C} = \frac{wing\ span, b}{AR} = \frac{1.6m}{7.3} = 0.219m \tag{4-2}$$

4.3.2 Tail Design

Tail Design is critical to obtain enough stability for a fixed wing aircraft. There are few constraints need to be set before proceeding to tail design calculation, the constraints are listed as following.

Table 4.2 Constraint for tail design[6]

Parameter	Value	Remarks
Aspect ratio for tail	4.87	2/3 of wing aspect ratio
Estimated horizontal tail volume ratio	0.5	Typical value for home-built aircraft
Fuselage diameter, D_f	0.01	Estimated according to components size
Estimated vertical tail volume ratio, V_H	0.04	Typical value for home-built aircraft
Correction factor, K_c	1.1	General value for a single-engine prop-driven GA aircraft.

Calculations are done as following MATLAB code to determine suitable parameters for tail configuration.

```
W = 2.5 * 9.81;
Vc = 15;
roh = 1.225;
AR_w = 7.3;
AR_h = (2/3)*AR_w;
W_S = 70;
W_P = 0.04426;
S = W / W_S; %wing planform area
P = W / W_P; %motor power required
w_span = sqrt(AR_w*S);
w_chord = w_span/AR_w;
Vh_est = 0.5; %estimated horizontal tail volume
D_f = 0.10; %fuselage diameter
Kc = 1.1; %correction factor
C_mean = w_span/AR_w;
nh = 0.9; %horizontal tail efficiency
l_opt = Kc * sqrt((4*C_mean*S*Vh_est)/(pi*D_f));
S_h = (Vh_est*C_mean*S)/l_opt;
h_span = sqrt(AR_h*S_h);
h_chord = h_span/AR_h;
Vv_est = 0.04;
S_v = (w_span*S*Vv_est)/l_opt
```

From the codes above, there are few configurations obtained, the optimum tail arm length, l_{opt}, horizontal tail chord and span, as well as vertical tail area. As mentioned earlier, l_{opt} is the distance between tail aerodynamic center to aircraft's center of gravity. The l_{opt} found is 0.7689m. The horizontal tail chord and span are 0.4928m and 0.101m respectively. The vertical tail area is 0.0291m^2. A vertical tail airfoil and shape are not as important as horizontal tail and wing do, so as long as it fulfills the vertical tail area requirement, it provides enough directional stability. The design is decided to be a tapered shape that top width is one-third of base width. The base width is set as 0.175m, hence the other geometry can be easily calculated using trapezium rule.

$$Area\ of\ trapezium = \frac{1}{2}(top\ width + base\ width) \times height \tag{4-3}$$

$$height = \frac{0.0291m^2}{\frac{1}{2}\left(0.175 + \frac{1}{3}(0.175)\right)}$$
$$= 0.249m$$

Next, neutral point and cg of the aircraft needed to be calculated from all the configurations found above. An online calculator are found to achieve this [31]. The neutral point is located at 42% of wing MAC from tip. For a stable aircraft, its cg should be always placed in between neutral point and wing aerodynamic center with a 10% static margin. So, the cg is located at 32% of wing MAC from tip.

4.3.3 Propulsion needed

From Figure 4.4, power loading, $\left(\frac{W}{P}\right)_d$ is obtained with value of 0.04226. With Equation 3.8, power from motor can be calculated.

$$P = W_{TO} \Big/ \left(\frac{W}{P}\right)_d \tag{4-4}$$

$$= \frac{2.5 \times 9.81}{0.04226}$$

$$= 554.11W$$

Even though the maximum power supply from existing fixed wing motor is 502W peak, but it is fine because the aircraft is going to generate forward speed in the air.

4.3.3.1 Actual cruising speed

By using Equation 3.9, the cruising speed of aircraft is calculated as below.

$$V_C = \sqrt{\frac{2 \times 3.4 \times 9.81}{1.225 \times 0.8289 \times (1.6 \times 0.219)}} \tag{4-5}$$

$$= 13.69m/s$$

Now, the cruising speed is found to be 13.69m/s, this is the speed of aircraft need to achieve before transitioning from VTOL hover to plane mode.

4.4 Actual CAD Drawing

4.4.1 Full CAD Orthographic View

Figure 4.5 shows the orthographic view of fully assembled CAD drawing in SolidWorks. All the dimensions are followed as calculations done earlier to illustrate the design in CAD drawing and to make sure all the parts dimensions are correct during fabrication process.

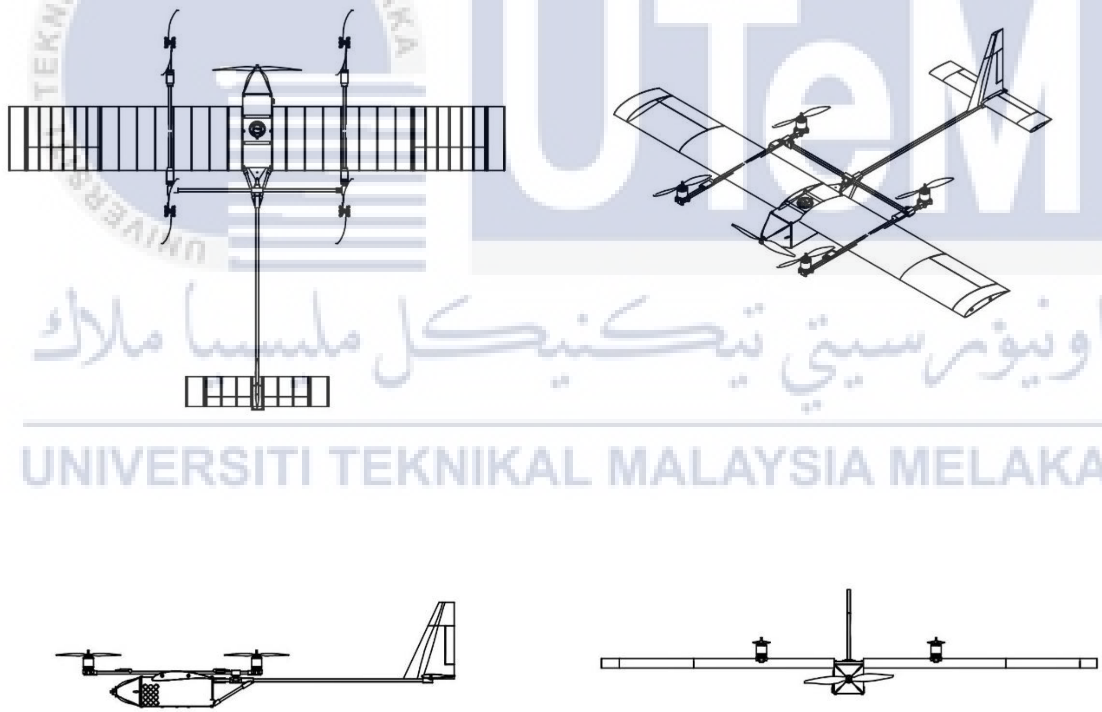

Figure 4.5 Orthographic View from SolidWorks drawing

4.4.2 Views from SolidWorks modelling

Figures following are different views taken from SolidWorks modelling to illustrate fixed wing hybrid UAV of this projects. There are some models are downloaded from online sources, which are propellers, motors, GPS module, ESCs and batteries.

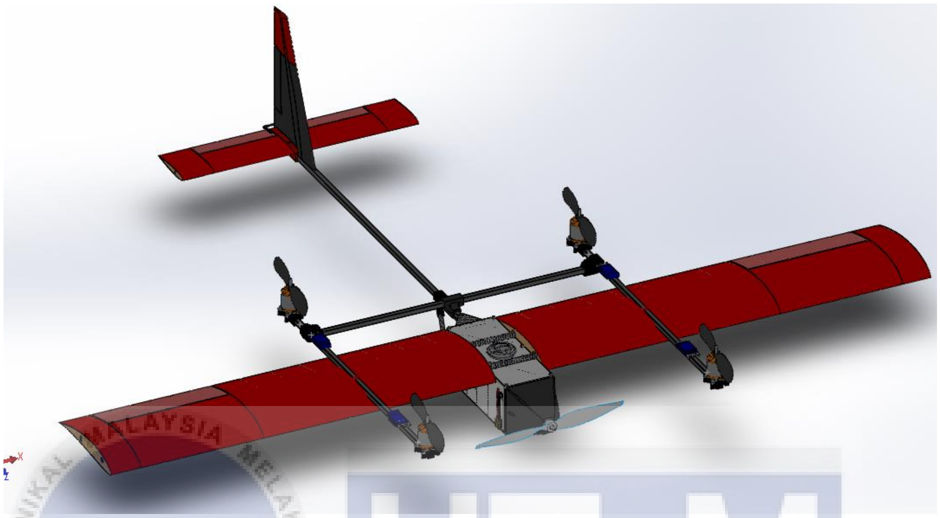

Figure 4.6 View 1 of SolidWorks modelling

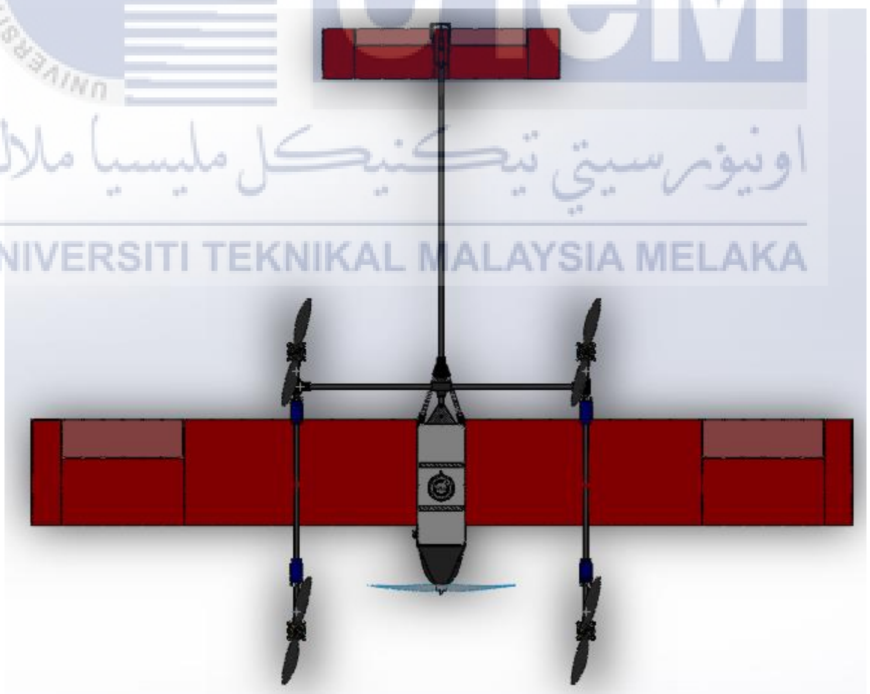

Figure 4.7 View 2 from SolidWorks modelling

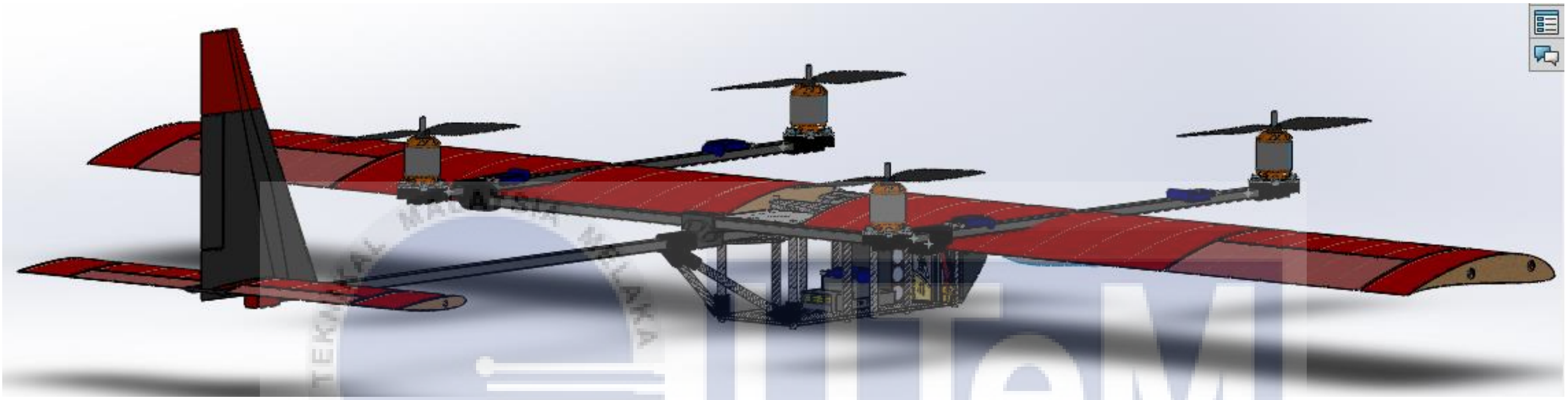

Figure 4.8 View 3 from SolidWorks modelling

4.5 Hardware Fabrication

4.5.1 Wing and Horizontal Tail Fabrication

Both wing and horizontal tail are using the same method to fabricate. Due to the specific airfoils are selected for wing and tail, CNC laser cutting method are chosen to get the balsa wood into desired shapes.

Figure 4.9 CNC machine that laser cut tail rib

The airfoil shapes are drawn into SolidWorks by downloading the airfoil details (geometry data) from http://airfoiltools.com.

Figure 4.10 Ribs are glued onto the carbon fiber rod with epoxy

Cardboard are added to tip and root of wing and tails because extra support need for heat shrinking plastic film as skin of them. This also provides extra strength to the wing to minimize twisting of wing, as twisting is very critical to a VTOL system.

Figure 4.11 Cardboard added to tip and root

Even though epoxy is a very strong adhesive but it might not enough to hold VTOL motors propulsion during taking of and landing, therefore, 1mm waxed polyester braid are chosen to fix VTOL spar onto the wing spar. The lashing used are named square lashing, this kind of lashing enable the braid knotted on so tight that chance of par twisting is minimized.

Figure 4.12 VTOL motor spars are knotted with wing spar using braid

Heat shrink plastic film is chosen for coating aircraft as this is very common way for an ribbed RC plane. Firstly, ironing the film onto the attaching surface is necessary because there is heat sensitive adhesion underneath the film, which is for holding the film position during shrinking. After the film are attached properly onto the surface, heat gun is used to shrink the film to get smooth surface. In Figure 4.13 is the demonstration for ironing the film with a mini soldering iron that is dedicated for heat shrink plastic thin film.

Figure 4.13 Iron plastic film onto surfaces

Before final coating the wings, the cables from servos and ESC's are brought through the reserved cable holes in ribs for assembling electronics part later.

Figure 4.14 Insert cables before final coating

4.5.2 Vertical tail Fabrication

Due to lack of time to get extra balsa wood and doing CNC laser cut in Taylor's University Malaysia, vertical tail is decided to fabricate with 3D printing. 3D printing ease the fabrication process as all kind of structures and shapes can be printed, balsa wood can be only fabricated for 2D parts such as ribs. In addition, vertical tail does not need a strong structure, so it can be thin in width to minimize drag. For such thin in width structure, balsa wood is less suitable. Figure 4.15 shown the design for vertical tail together with its mounting part to attach it onto the carbon fiber square tube tail.

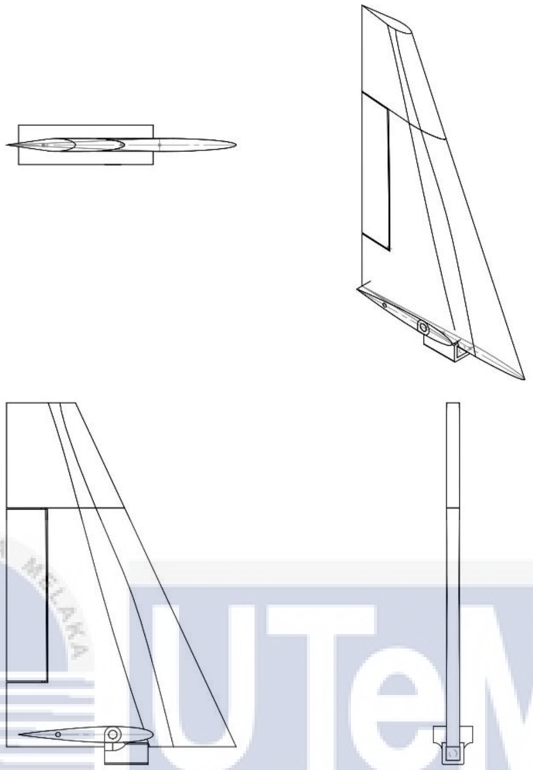

Figure 4.15 CAD orthographic view for vertical tail

Figure 4.16 shown the 3D printed vertical tail. The different in colors indicate the tail is printed in split parts because the are joints for rudder to install to the tail. Thin cyanoacrylate is used to combine all the parts for final assembly for vertical tail.

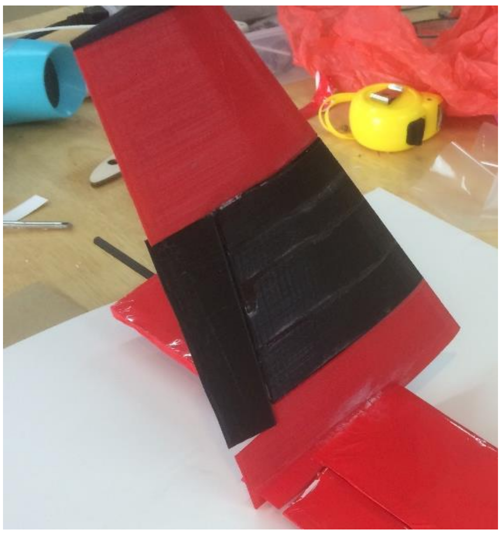

Figure 4.16 3D printed vertical tail

4.5.3 Fuselage Fabrication

Fuselage is the place that stores majority of electronic components of an aircraft. Other than protecting the components from being damaged during accident, fuselage has to be rigid enough for holding lift force from wing and VTOL system. Hence, carbon fiber plate is chosen as the main structure of fuselage. Figure 4.17 illustrates the actual ratio printed model glued on the carbon fiber plate for cutting into desired shape later.

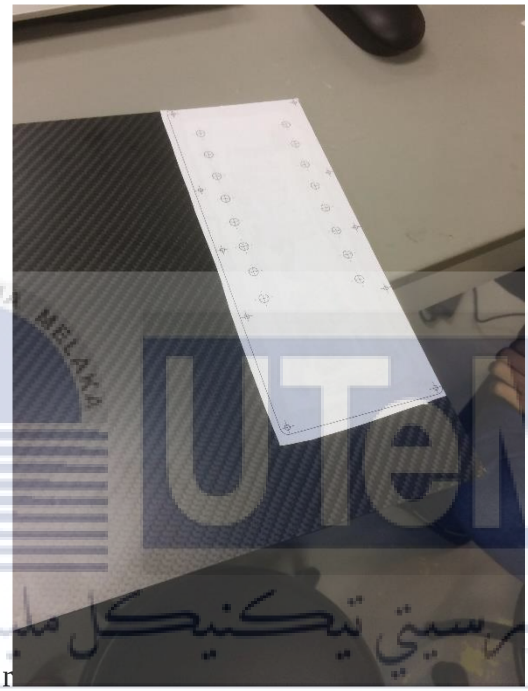

Figure 4.17 Fuselage top and bottom plate

Figure 4.18 shows the cutting process done with band saw, dimension of the fuselage is 10cmx10cmx25cm (height x width x length).

Figure 4.18 Cutting fuselage plates shape with band saw

Even though carbon fiber is less dense in term of its strength, but every grams in an aircraft needed to be considered as this increases the efficiency of overall performance. Figure 4.19 shows that milling process is on going to reduce materials of fuselage by manual milling machine. Different sizes of end mills are used with the rotational speed of 3000rpm, the higher rpm gives the better milling product for carbon fibers because low speed milling causes splinters.

Figure 4.19 Milling holes to reduce redundant materials for top plate

The pattern on fuselage top plate and bottom plate is different as comparing Figure 4.20 to Figure 4.19, this is because fuselage bottom plate pattern is taken consideration for components placing while fuselage top plate does not.

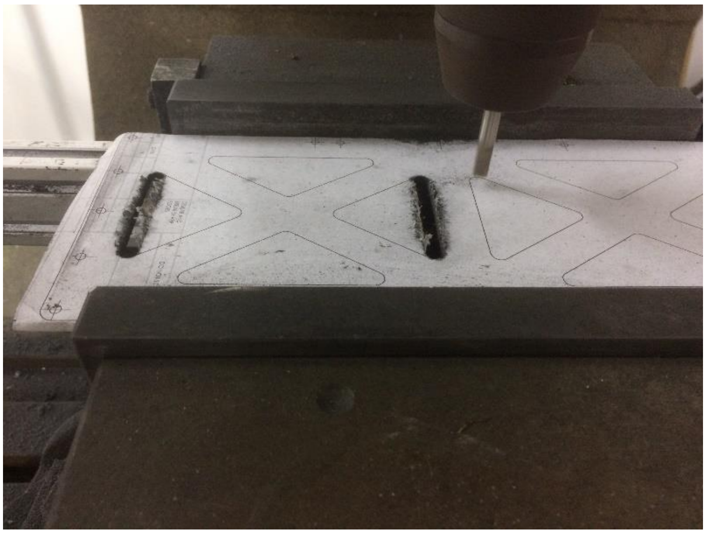

Figure 4.20 Milling off redundant materials for bottom plate

To combine both fuselage plate, carbon fibre rods are used with spacer epoxied inside the tube to create screw thread for bolts later. Epoxy is a very strong adhesive after cured but not very effective on smooth surfaces, thus tapping is done as shown in Figure 4.21 for better adhesion.

Figure 4.21 Tapping carbon fiber rods for better adhesion

As mentioned earlier, epoxy is not as efficient on smooth surface, therefore gloss surface of spacer has been file to create roughness on it for better adhesion into the carbon fiber rods.

Figure 4.22 File spacer surface for better adhesion

Figure 4.23 is the view of fuselage after assembling all the carbon fiber rods as pillars of fuselage, firewall for nose motor mounted with red spacer screw onto the firewall for nose motor. The firewall plate is blind rivet with the pillars since the position of it is planned to permanently fixed.

Figure 4.23 Fuselage halfway assembled

In Figure 4.24 shows that the nose cover CAD drawing. This part is 3D printed as the shape is specifically design to cover the nose motor and create better aerodynamic surface for forward transition. As this structure does not need high strength, it is printed with 1mm thickness to minimize the weight contributed to the aircraft.

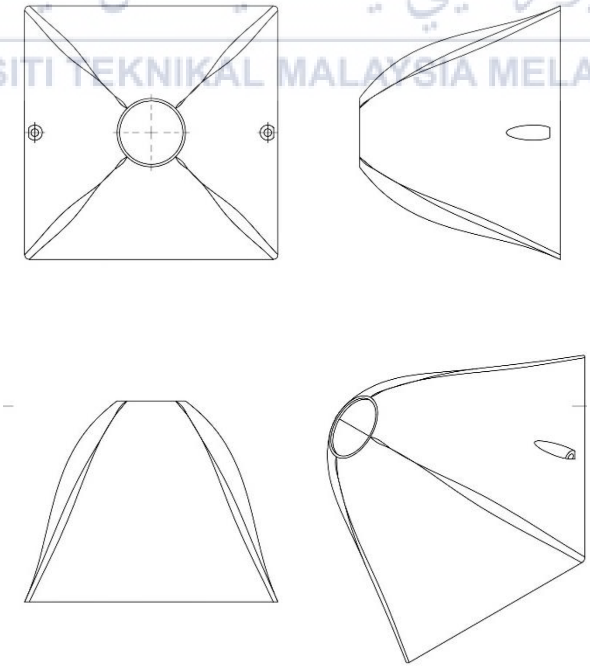

Figure 4.24 CAD orthographic drawing for aircraft nose cover

Figure below shows the 3D printed nose cover mounted on firewall, the height of the nose cover is just nice, distance between the tip of nose and propeller is around 2mm, this optimize the drag induced by thrust produced from propeller.

Figure 4.25 3D printed nose cover

To combine tail with fuselage, carbon fiber tube is use as a spar. A supporting system is designed to reduce tension of tail. The system is designed in SolidWorks then 3D printed. The drawing parts are displayed in Figure 4.26 and Figure 4.27. These two parts are sockets for carbon fiber rods as links as shown in Figure 4.28. These structures are sufficient to withstand bending moment vertically and horizontally.

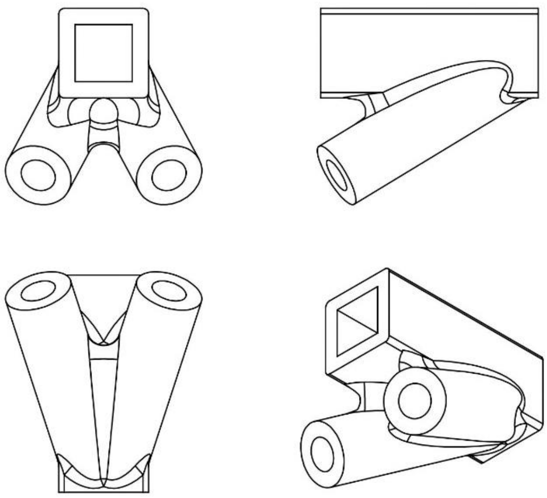

Figure 4.26 CAD orthographic drawing for tail support at tail

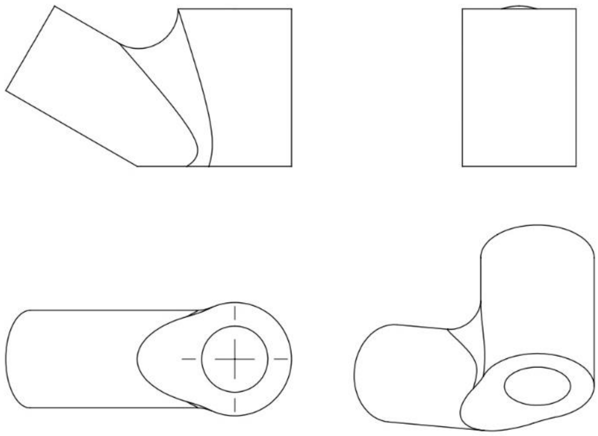

Figure 4.27 CAD orthographic drawing for tail support at fuselage

Figure 4.28 shows the tail mounted on fuselage pillars and supports. Carbon fibers plate are used as the main structure to hold the tail as emphasized with black box. Bolt and nuts with M3 size are used for assembly.

Figure 4.28 tail mount onto fuselage with support

4.5.4 Final Product

Figure 4.29 shows the final assembled product of this project, with all the wires, electronics installed and ready to proceed to test flight.

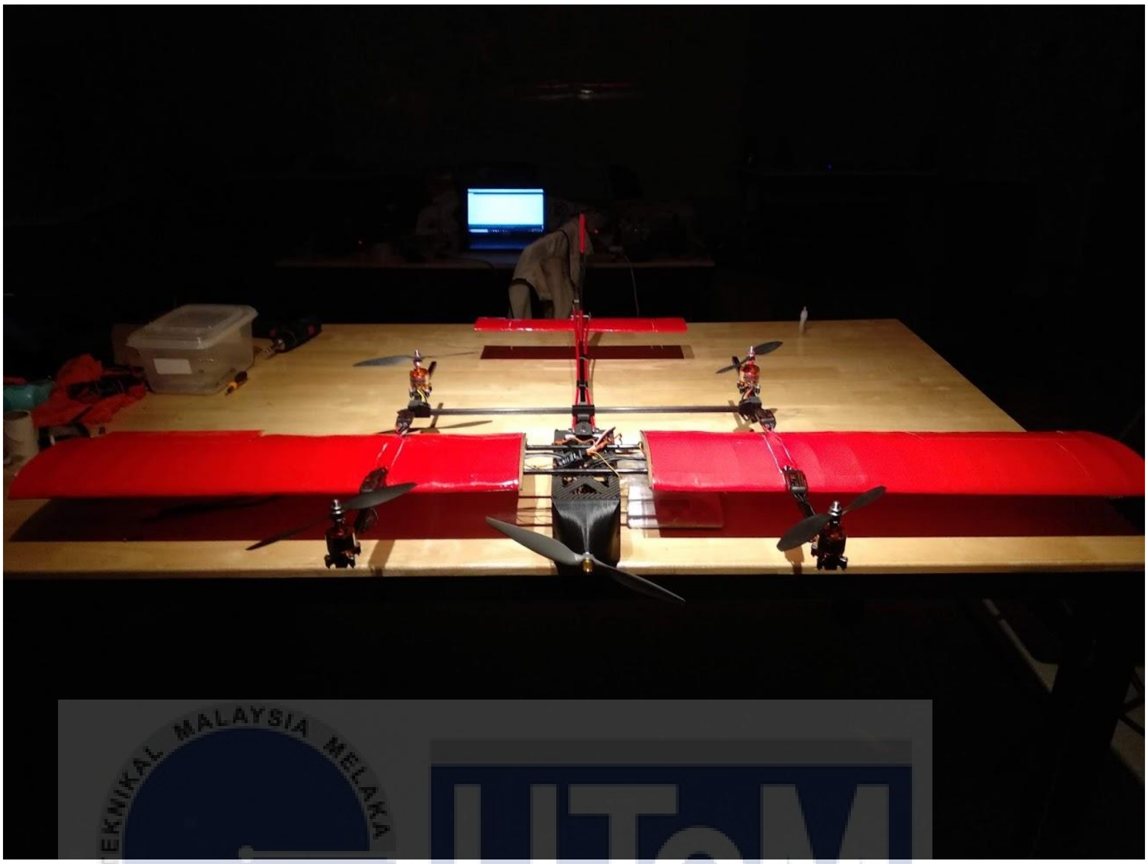

Figure 4.29 All parts and components are finally assembled and ready to be tested.

4.6 Flight Test

Besides stable control system in Pixhawk2.1, the benefit in using this flight controller is it stores all the flight data into a microSD card in it for post flight check. There are 6 data obtain from the controller for post flight analysis, that are ground speed achieved, altitude travelled, throttle input, output signals to VTOL ESCs, battery voltage and current.

4.6.1 Ground speed achieved

Figure 4.30 indicates the ground speed hit by UAV during the flight test. According to the graph obtained, the maximum ground speed hit is 18m/s. The VTOL motors are turned of once the UAV hit 15m/s airspeed. As mentioned earlier, airspeed is estimated from ground speed since there are no air speed sensor installed. It can be seen that ground speed escalated once the UAV switched to FBWA mode because this mode provided forward transitioning thrust by nose motor. The ground speed drop significantly from time to time in the graph, it is due to the pilot input on turning the UAV back to launching spot to prevent it flew out of sight. To perform steering in the air, roll input is given together with pitching upward input because when the UAV roll, lift from wing dropped significantly as the lift direction is slanted, pitch is need in order to keep the UAV to generate enough lift to hold the altitude but this induced drag and lead to drop in ground speed. During transition from FBWA back to QHOVER, the groundspeed dropped significantly as the nose motor has been turned off, the remaining ground speed shown is the pilot adjusted the UAV for a suitable location to land.

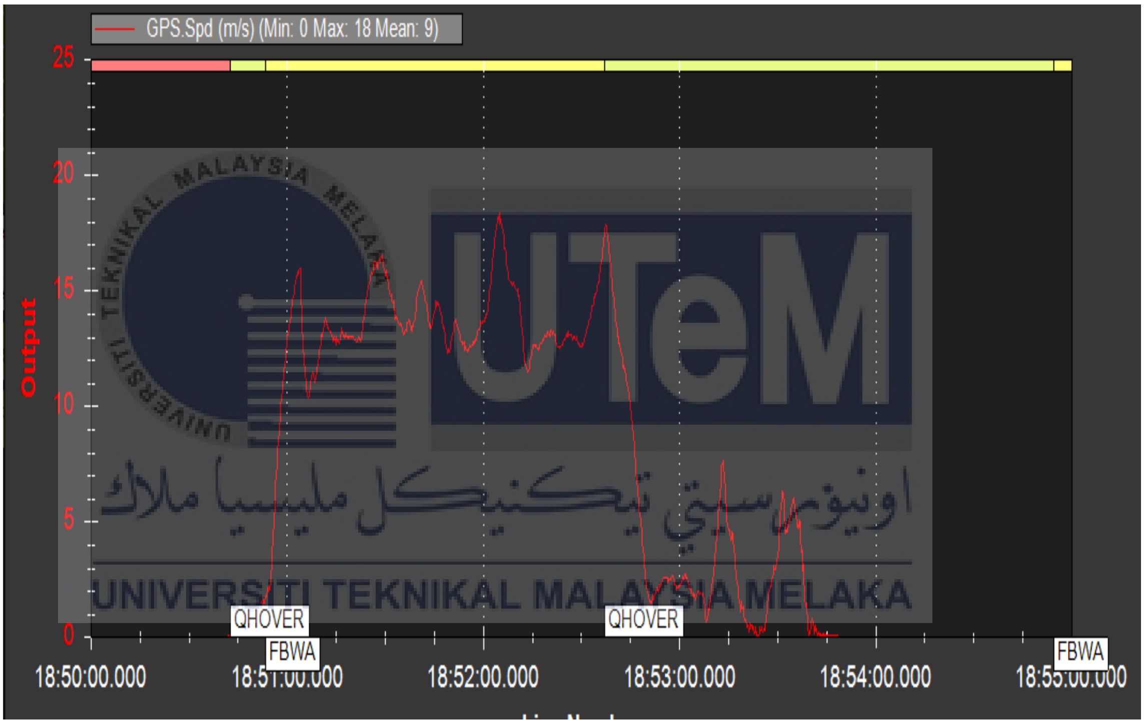

Figure 4.30 Graph of ground speed achieved

4.6.2 Altitude travelled

The altitude from flight controller is measured by built-in barometer in it. From the following graph, it illustrates the highest altitude travelled is 89m. The climb rate is quite constant at around 1m/s for both QHOVER and FBWA mode. The altitude is then dropped for landing sequence. The altitude escalated again at the landing sequence in QOHVER mode because during the flight test, the landing spot is found out not suitable so the pilot immediately input climb signal to UAV, then pick for another good spot to land.

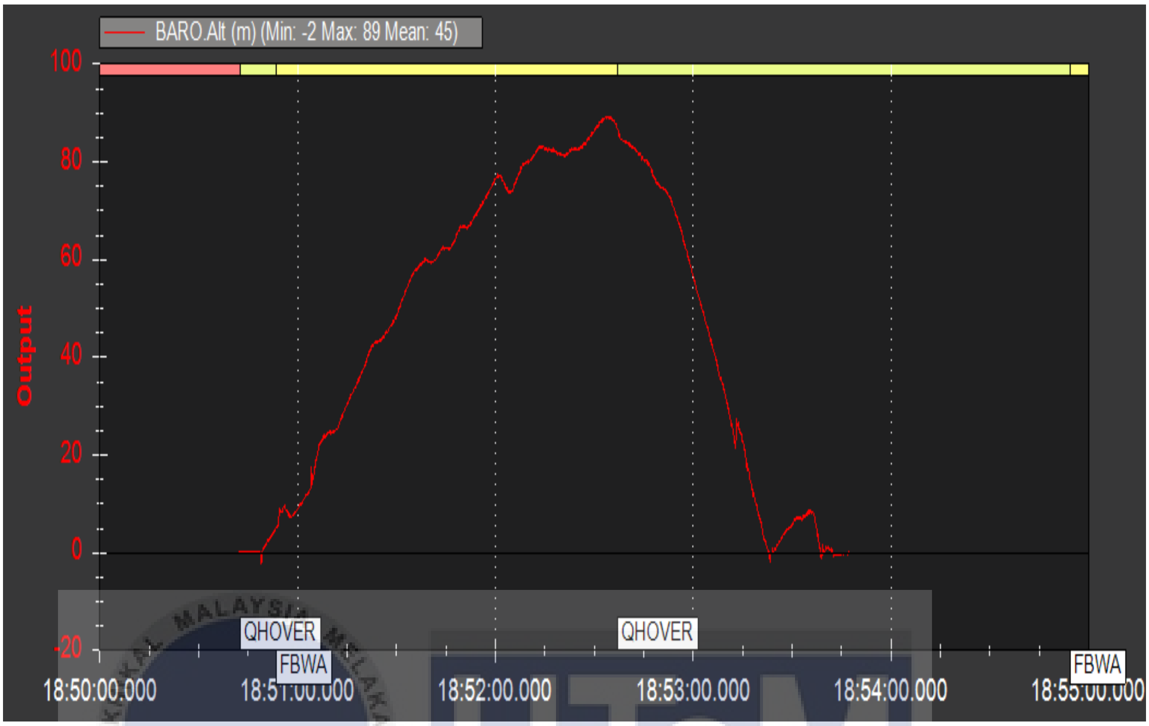

Figure 4.31 Graph of altitude travelled

4.6.3 Remote control input from Channel 3 (Throttle input)

This data is obtained in order to know the throttle level input in different mode then analyze the performance of the UAV. AS shown in Figure 4.32, the minimum input is 1146 (0% throttle level) and the maximum input is 1924 (100% throttle level). During QHOVER, the signal given is 1720 which is around 90% of the total level, but note that throttle level for QHOVER and FBWA is different as throttle in QHOVER point to climb rate while for FBWA simply mean the throttle for nose motor. After transitioned to FBWA from take off sequence, the pilot input 100% of the throttle level to hit the desired cruising speed as soon as possible. This is because the sooner the UAV hit the desired cruising speed, the sooner the VTOL motors turned off, which means more energy left for VTOL system in landing use. At GPS time 18:51:44, the VTOL motors are turned off, this can be proved from the output signal from channel 5-8 which directly control the VTOL motors by ESCs. The graph of output signal from channel 5-8 is shown in Figure 4.33. The significant drop in signal level indicates the motors has been turned off during cruising. The motors are turned back on when the pilot switch FBWA mode to QHOVER for landing purpose, it can be seen in Figure 4.33 as well for the hike in signal level at time 18:52:37.

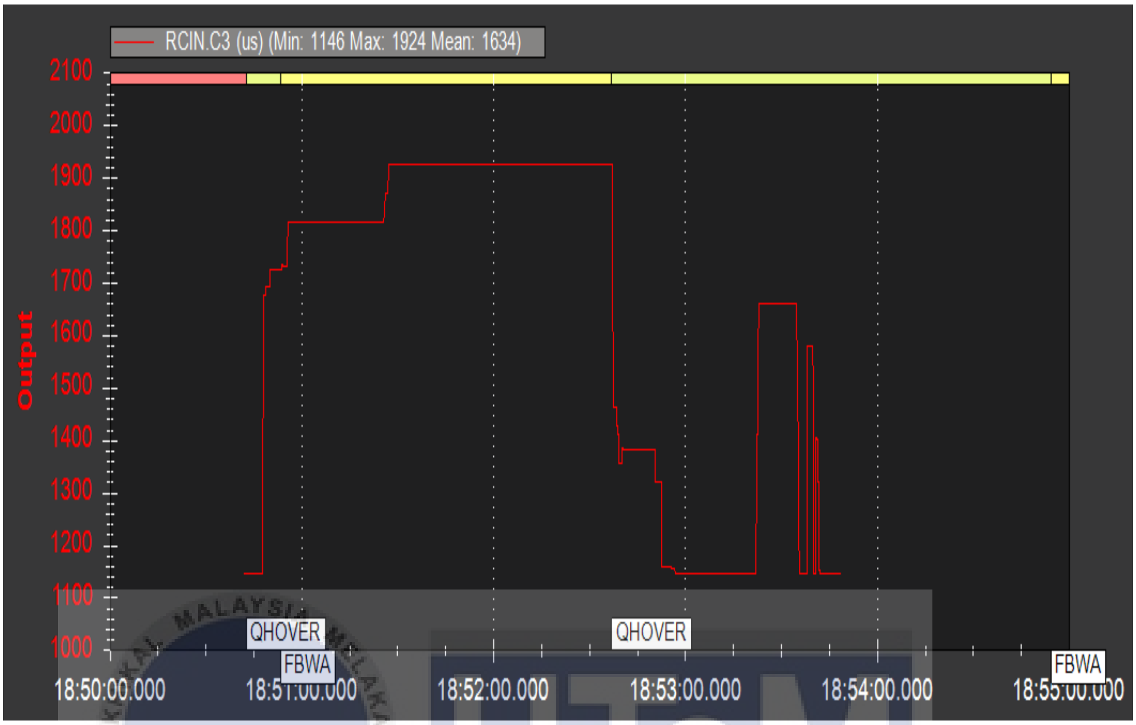

Figure 4.32 Graph of Channel 3 input (Throttle input)

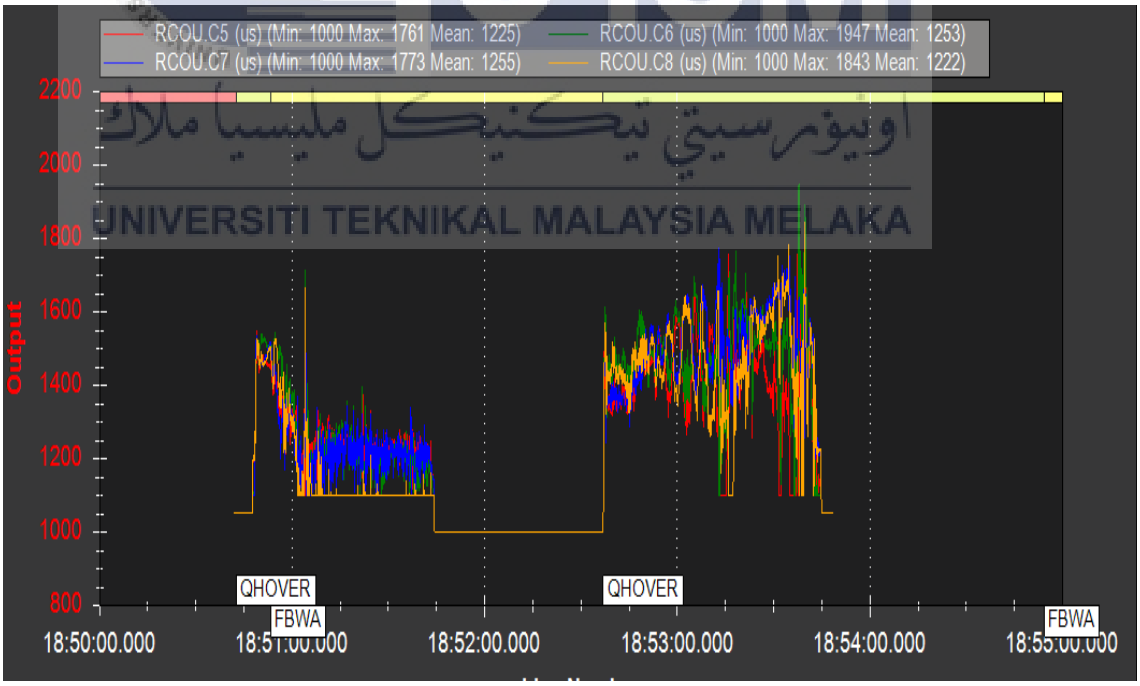

Figure 4.33 Graph of Channel 5 to 8 output signal to VTOL ESCs

4.6.4 Battery condition during flight

To recall, only the battery source for fixed wing motor is being monitored by PixHawk, therefore, there is no changes in battery voltage during QHOVER mode as the VTOL motors used different battery source. The significant drop for battery voltage happened when 100% throttle input is given to nose motor. The voltage drops drastically is not because of energy left dropped as it, but it is because of large current drawn from the battery. This is the common case happens in Lithium Ion battery. 9 volts shown is graph is actually unhealthy for the battery because the battery can be damaged for over low voltage, so in future another series of cells might be installed to improve the battery performance. Another concern is this flight test is carried out before the battery is fully charged, so an accurate flight endurance ca not be obtain from this battery level data.

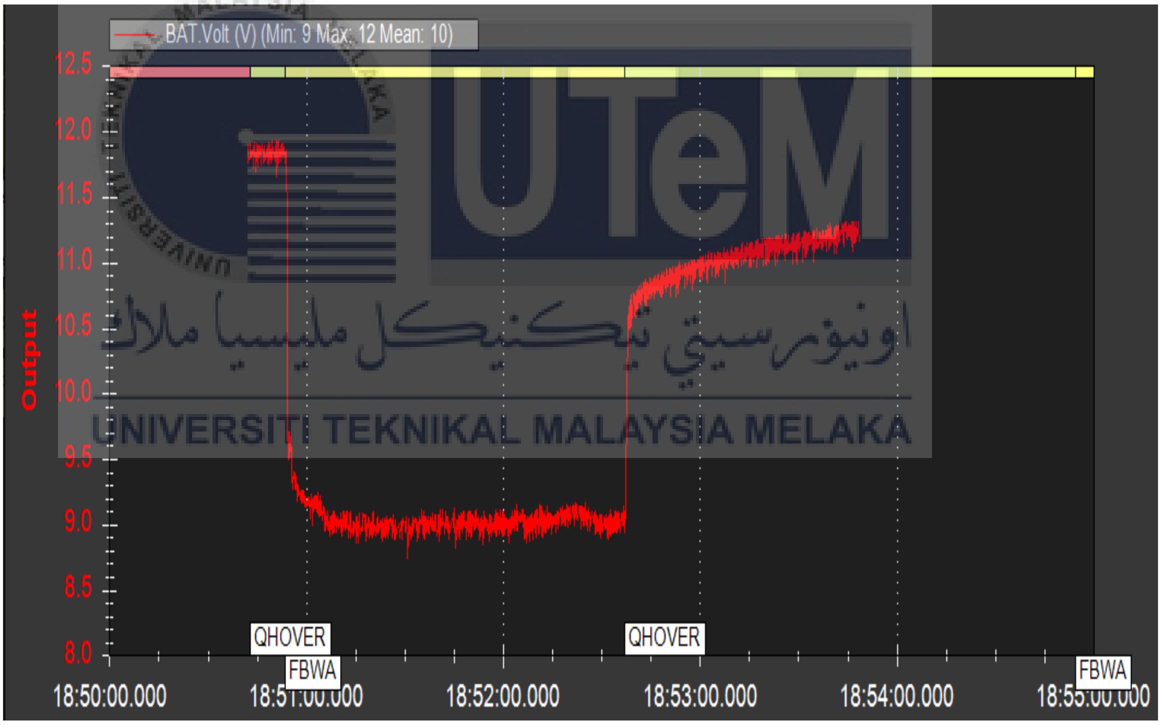

Figure 4.34 Graph of battery voltage

The maximum current drawn as shown in Figure 4.35 is 39A, it spiked to this maximum current drawn right after 100% throttle signal is given due to the inertia of UAV, as the time went through, the current began to drop because the airspeed is increasing, which brought lesser load to the motor. The mean of current draw is 15A so an estimated endurance can be calculated based on this data.

$$Endurance = \frac{Battery\ total\ capacity}{Current\ draw} \tag{4-6}$$

$$= \frac{12000mAh}{15A}$$

$$= 0.8hour$$

$$= 48minutes$$

From [32] shown that rotorcraft endurance are around 20 minutes maximum where fixed wing VTOL UAV built in this project has a theoretical endurance of 48 minutes.

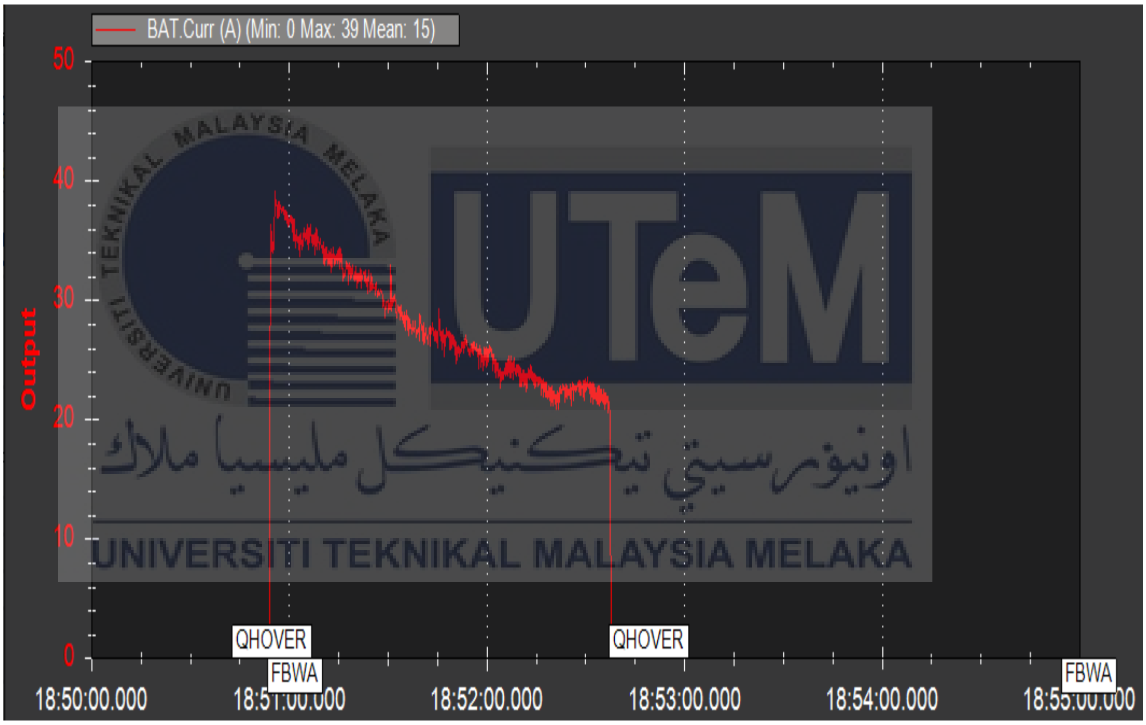

Figure 4.35 Graph of battery current

Chapter 5

CONCLUSION AND RECOMMENDATIONS

5.1 Overview

A conclusion for work has been done upon this phase of Final Year Project is made in this chapter. Outcomes from each chapter are concluded in brief.

5.2 Conclusion

In a nutshell, all objectives are achieved in this Final Year Project. A VTOL fixed wing hybrid UAV is designed and built, with successful vertical takeoff, forward transition without VTOL motors assisting, yet perform vertical landing. The designation process is done with SolidWorks for fabrication with detail planning and proper order. The designed and built UAV has 1.6m wing span, 21.9cm wing chord, 49.28cm and 10.1cm for horizontal tail span and chord respectively. In addition, it has 0.0291m^2 vertical tail area and 76.89cm tail arm. The center of gravity of UAV is located at 32% of wing mean aerodynamic chord. Motor arm of VTOL system is 84.85cm. The total weight of UAV is 3.4kg, with 0.597 and 1.49 thrust to weight ratio for fixed wing motor and quadcopter motors respectively. The flight test performed has been evaluated with data abstracted from flight controller, likewise an estimated endurance of this project's UAV is 48 minutes after analyzing mean current drawn by fixed wing system. The maximum altitude travelled by this project's UAV is 89m while the maximum speed is 18m/s.

5.3 Future work

As this is the first attempt on build an UAV yet it is a fusion of a quadcopter and fixed wing airplane, inexperience causes some design flaws and inaccurate estimations. In the future, there are a few works need to be improved such as design flaws occurred such as in proper center of gravity placing. This is caused by wrongly estimation of center of gravity after allocation of electronics component, even with all the heavy components placed at most front of fuselage, the c.g. is still away from desired position, hence extra weight need to be included during flight to shift the c.g. to designed position. Besides, reduce weight from excessive materials such as fuselage plate. The plate materials can be further reduced since the structure are way stronger than it actually needed. Moreover, there is a need in decreasing overall drag from components exposed in air flow. Combining both battery system into one for more efficient power storing as the power left in VTOL battery after flight is redundant weight that decreases the flight endurance at last. Last but not least, more flight tests are required to get an accurate flight endurance of UAV.

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