

TRIBHUVAN UNIVERSITY

INSTITUTE OF ENGINEERING

PULCHOWK CAMPUS

B-10-BME–2015/2019

Design and Test of Search and Rescue Unmanned Aerial Vehicle

by

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A PROJECT REPORT

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF BACHELOR OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

LALITPUR, NEPAL

AUGUST,2019

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**ABSTRACT**

Unmanned Aerial Vehicles possess characteristics that make them suitable for use in areas of difficult access. UAVs can be great aid in Search and Rescue either operating standalone or in conjunction with traditional manned aircrafts employed in SAR. This project aims to aid in the SAR operation in Nepal by developing a design and a working model of SAR UAV. The design is developed performing aerodynamic, structural and stability analysis using analytical methods as well as commercial code. The design is then fabricated into a physical model.

Nepal is prone to several natural calamities that take lives of thousands of people. More than a million of tourist come to the country every year and a significant number of trekkers go missing. The developed UAV will be capable of performing aerial surveillance and support the SAR operation in both scenarios

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**ACKNOWLEDGEMENTS**

We would like to express our sincere gratitude to the Department of Mechanical Engineering for providing us the opportunity to undertake this project. We are indebted to our supervisor Asst. Prof. Kamal Darlami for mentoring us in academic and finer technical aspects of our project. We express our deepest thanks to Dr. Nawraj Bhattarai, Head of Department, Department of Mechanical Engineering and Assistant Prof Sanjaya Neupane, Deputy Head of Department, Department of Mechanical Engineering for their tireless effort in bringing the best out of us through this project. We would also like to thank Asst. Prof. Hari Bahadur Dura, Deputy Head of Department (aerospace faculty), for his guidance during the development of the project.

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**LIST OF SYMBOLS**

�� = Weight

�� = Density of air

λ = Taper ratio

���� = Coefficient of lift of airfoil

���� = Coefficient of lift of wing

���� = Coefficient of drag of airfoil

���� = Coefficient of drag of wing

α = Angle of attack of aircraft

���� = Reynold’s number

�������� = Slope of coefficient of lift of wing

������ = Slope of coefficient of lift of airfoil

�� = Aspect ratio

��0�� = Zero lift angle of attack

���� = Wing referential area

�� = Wing span

�� = Oswald efficiency number

��0���� = Zero lift angle of attack of wing

�������� = Distance of aerodynamic center of wing from the leading edge of root chord

�������� = Moment about the aerodynamic center of wing

�������� = Slope of coefficient of lift of horizontal stabilizer

�������� = Aerodynamic center from leading edge of root chord of horizontal stabilizer

�������� = Moment about aerodynamic center of horizontal stabilizer ����0�� = Coefficient of moment about cg due to fuselage at zero-degree angle of fuselage reference line

�������� = Slope of coefficient of moment

���������� = Slope of coefficient of yawing moment in sideslip because of wing and fuselage

�������� = Slope of coefficient of lift of vertical stabilizer

������ = Area of vertical tail

������ = Distance from cg to aerodynamic center of vertical stabilizer

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�������� = Coefficient of yawing moment with sideslip angle due to vertical stabilizer

������ = Yawing moment with sideslip angle

����′���� = Coefficient of rolling moment with sideslip angle due to fuselage ����′���� = Slope of coefficient of rolling moment due to vertical stabilizer Γ = Dihedral angle

����′���� = Slope of coefficient of rolling moment due to wing

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**LIST OF ACRONYMS AND ABBREVIATIONS** UAV = Unmanned Aerial Vehicle

SAR = Search and Rescue

VTOL = Vertical Take –off and Landing

SMC = Standard Mean Chord

MAC = Mean Aerodynamic Chord

CFD = Computational Fluid Dynamics

RPM = Revolutions per Minute

MPH = Miles per Hour

HP = Horse Power

ESC = Electronic Speed Controller

BLDC = Brushless Direct Current Motor

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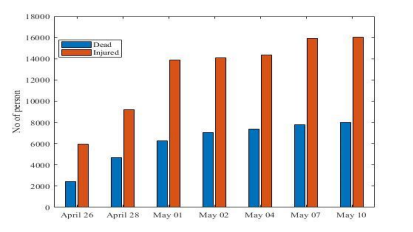
**CHAPTER ONE: INTRODUCTION**

**1.1 Background**

The earliest use of unmanned aerial vehicles (UAVs) was made in military in mid nineteenth century. However, the concept of remotely piloted UAVs is relatively new. It was conceived in the late 1970s, and it was in the mid-1980s that the first UAVs of such type completed their first official test flights. Since then, the technology has been substantially refined and improvements have been accomplished; non-military use of UAVs is growing and the possibilities are endless. The use gained further scale after 2006 when government agencies began using UAVs for disaster relief, border surveillance and wildfire fighting, while corporations to inspect pipelines and spray pesticides on farms.

One of the primary roles attributed to aircraft is the provision of airborne Search and Rescue (SAR) capabilities. Airborne systems are capable of covering large areas in a short time span, thereby improving the chances for success of a SAR mission. Pertaining to SAR mission, we have identified following possible areas of use of UAVs in context of Nepal.

**1.1.1 Disaster Management**

The earthquake on April 25 of magnitude 7.6 struck with epicenter in Barpak, Gorkha district tolled thousands of death and injuries and hundreds of people went missing. *Figure 1: Casualties due to earthquake on Baishak 12, 2072 (“Situation Report of Earthquake”, 2015)*

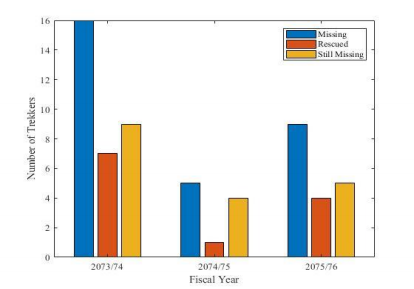
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The chance for survival of the people trapped in collapsed buildings depends mainly on the damage types of the affected buildings and the quickness of SAR. The increasing number of deaths and injuries after a week of incident points to the harsh reality of ineffective SAR.

Since UAVs can be advantageously used for aerial surveillance, they can be used for rapid mapping of the affected areas. After the rapid mapping affected buildings can be characterized by an international standard. This can be important for rescue teams to

optimize their work especially because limited resources are available in disasters. The UAVs can further be equipped with payloads and medical supplies to the remote areas where land transportation either takes too long or is blocked and other aerial resources are limited or not feasible due to topography or weather. **1.1.2 Tourism**

More than a million tourists visit Nepal every year, and the number is expected to rise even higher as the country is planning visit Nepal 2020. Thus, the need of identification of new trails and effective SAR has risen more than even before for which UAVs can be employed.

Problems faced by trekkers and probable ways UAVs can come into aid: *Figure 2: Trekkers details according to year (“Missing trekkers report”, 2019)*

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A significant number of trekkers go missing every year in one or other trekking routes in Nepal (“Missing trekkers report”, 2019).

*Table 1: Missing trekkers*

| Fiscal Year | missed | rescued | still missing |
| --- | --- | --- | --- |
| 73/74 | 16 | 7 | 9 |
| 74/75 | 5 | 1 | 4 |
| 75/76 | 9 | 4 | 5 |

The UAVs can be of great assistance in locating the missing trekkers. ▪ Trekkers generally suffer from Acute Mountain sickness and in worst cases form High Altitude Pulmonary Edema (HAPE) and High-Altitude Cerebral Edema (HAPE). Apart from these medical conditions such as back pain, frost bite, etc. can occur. UAVs can be deployed to have medical and rescue supplies delivered to alleviate the situation.

▪ UAVs can support helicopters greatly in search and rescue missions. Chances of the manned aircrafts meeting another accident in bad weather conditions are high thus leading to delayed searches. Searches with UAVs can be quick and cost effective since a large number of small UAVs can be deployed and since they are inherently unmanned further casualties are prevented.

**1.2 Objectives**:

**1.2.1 Main Objective:**

The main objective of the project is:

• To design and test the Search and Rescue Unmanned aerial vehicle **1.2.2 Specific objectives:**

The specific objectives of the project are:

• To perform aerodynamic and structural analysis of the UAV.

• To carry out stability analysis of the UAV.

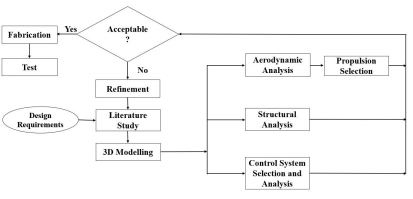
• To select propulsion system for the UAV.

• To fabricate and test the flight of the UAV.

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**1.3 Methodology**

The design of Munal M-72 started from conceptual design. Review of the literatures and analysis of preliminary design were performed to assure the project is on the right track. Design modifications were done as required and detailed design were carried out such that it would be easy to manufacture parts. After acceptable design was produced, Munal M-72 was fabricated and tested.

*Figure 3: Methodology flowchart*

**1.4 Limitations and Expected Outcome**

• The design is based on analytical and computational results.

• The design is inherently constrained due to the availability of only limited type of material and machine for manufacturing.

• The design parameters are subjected to change due to the iterative design process. By the completion of the project, it is expected to have a flying model of search and rescue UAV.

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**CHAPTER TWO: LITERATURE REVIEW**

The general scope of this literature review is to explore the UAVs in general and those developed for SAR operations.

**2.1 Classification**

The UAVs developed so far can be broadly classified into two categories: **2.1.1 Rotary Wing**

Rotary wing UAVs consist of a number of rotors which are turned by electric motors. The rotors have 2 or 3 rotor blades which produces the required airflow over the blade airfoil to generate lift. The rotary wing UAVS have the capability of VTOL. They can hover and perform agile maneuvering. However, they impose mechanical and electrical complexity and are limited by their lower speed and shorter flight range.



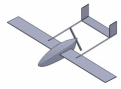
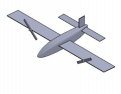
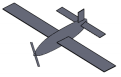
*Figure 4: Quadcopter- a rotary wing UAV(“http://www.dji.com”,2019)***2.1.2 Fixed Wing**

Fixed Wing UAV consists of a rigid wing that has a cross-section of an airfoil. Lift is generated as the UAV moves forward in the air. The forward thrust is usually achieved by means of a propeller turned by internal combustion engine or electric motor. Fixed Wing UAV consist of simpler structure which can be designed to ensure efficient aerodynamics that can lead to longer flight time and range. These are also able to carry greater payloads on longer distances on less power.

One of the leading professional UAV manufacturer and operator is Zipline. Zipline designs, manufactures and operates delivery drone that deliver medicine to people in hard to reach places. It is currently operating in Rwanda and Ghana. The UAV uses launcher pad to propel the aircraft into the air, then it uses its electric powered propulsion when in air.

Figure 5 is a representation of different configuration of widely used fixed wing UAVs.

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*Figure 5: Fixed wing configuration.*

**2.2 Propeller Configuration**

The fixed wing configuration may further be classified into following two configurations based on the position of propeller.

**2.2.1 Tractor configuration**

In tractor configuration, the propeller is at front of the fuselage. It offers following advantages.

i. The motor and the propeller are at the front which helps to move the center of gravity forward and therefore allows a smaller tail for stability considerations. ii. The propeller is working in an undisturbed free stream.

The configuration has following disadvantages:

i. Propeller slipstream disturbs the quality of the airflow over the fuselage and wing root.

ii. The increased velocity and flow turbulence over the fuselage due to the propeller slipstream increase the local skin friction on the fuselage.

**2.2.2 Pusher configuration**

In Pusher configuration, the propeller is at the back of the fuselage. It offers following advantages:

i. Higher-quality (clean) airflow prevails over the wing and fuselage. ii. The inflow to the rear propeller induces a favorable pressure gradient at the rear of the fuselage, allowing the fuselage to close at a steeper angle without flow separation. This in tum allows a shorter fuselage, hence smaller wetted surface area.

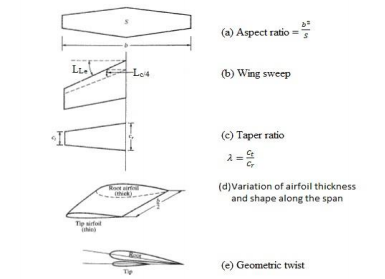
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Pusher configuration also has one important disadvantage that the motor and propeller shift the center of gravity rearward, hence reducing longitudinal stability. **2.3 Wing Configuration**

Wing configuration is the arrangement of its lifting and related surfaces.

**2.3.1 Wing geometry**

The wing geometry is described by (a) aspect ratio, (b) wing sweep, (c) taper ratio, (d) variation of airfoil shape and thickness along the span and (e) geometric twist. (Anderson, 2012)

*Figure 6: Various characteristics to define wing shape(Anderson,2010)*

**2.3.2 Location relative to the fuselage**

There are three basic vertical locations of the wings relative to the fuselage: i. High wing

High wing allows the fuselage to be placed lower and is more stable in terms of lateral and rolling motion. This stability is, however, sometimes a disadvantage since it makes difficult to maneuver.

ii. Mid wing

Mid wing offers the lowest drag of the three positions. However, it poses structural complexity in connecting with fuselage.

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iii. Low wing

In this configuration, landing gear can be retracted directly into the wing. The problem, however, is that the landing gear be long enough to provide sufficient ground clearance.

**2.4 Tail Configuration**

The common tail configuration of various UAVs can be categorized into following configurations:

i. Conventional tail

The conventional location for the horizontal tail is centered on the tail end of the fuselage, and the vertical tail is mounted on the horizontal tail at the center. ii. T-tail

The horizontal tail is mounted at the top of the vertical tail.

iii. V-tail

A tail in the shape of letter V which can function as both horizontal and vertical tail.

iv. Inverted v-tail

This configuration is common in UAVs where tail booms are taken from each wing and stabilizers at the end of each boom meet in the shape of inverted V. v. Twin tail

This configuration is similar to conventional tail but instead of one vertical tail mounted at the center of horizontal tail, it has two vertical tails one at each end of horizontal tail.

**2.5 Primary Search Equipment**

Primary search equipment required for a SAR UAV includes Forward Looking Infra Red sensors, Electro-Optical & Infra-Red sensors.

**2.5.1 Forward Looking Infra-Red sensor**

FLIR sensor is used to detect and identify warm objects under low light conditions, and is therefore ideal and essential for locating objects or persons at night or in bad weather conditions, offering low visibility (Meredith,2011). A FLIR sensor operates in the Infrared (IR) bandwidth of the light spectrum.

**2.5.2 Electro-Optical and Infra-Red Sensor**

An EO/IR sensor turret incorporates an IR thermal sensor and a high-resolution optical color camera. Both the IR sensor and color camera are housed in the same turret. Once

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radar has detected and located an object, the sensor turret can be slaved to the radar. Depending on range, light and environmental conditions, either the IR, or the optical camera, or both, can be directed and zoomed onto the object for detail identification. **2.5.3 Real time video broadcasting Setup**

It is essential that the UAV feeds live data to the control room. Various methods of wireless data transmission are available. In one popular method called First-person view (FPV), the UAV is controlled from pilot’s view. The UAV piloted remotely from a first-person perspective via an onboard camera, fed wirelessly to video FPV goggles. More sophisticated setups include a pan-and-tilt gimbaled camera controlled by a gyroscope sensor in the pilot's goggles.

**2.6 Additional equipment**

**2.6.1 Search and Rescue Direction Finder**

SAR DF intercepts emergency beacon signals emanating from distressed individuals. However, it is necessary that the person in distress is in possession of PLB. PLBs operate on 406 MHz. The signal of a PLB is detected by the COSPAS-SARSAT satellite network anywhere in the world. The network passes the alert to the nearest rescue authority. Based on this information, the SAR UAV can be taken to the vicinity of the signal origin. The SAR UAV is then assisted by the low-power "homing" signal on 121.5 MHz which allows them to pinpoint the distressed individual.

**2.7 Shortcomings**

To minimize the time to find the victim, one of the fundamental parameters that needs to be accounted for in the design of the search algorithms is UAVs energy limitations (Waharte &Trigoni, n.d.). In other words, increasing the flight time of SAR UAV would greatly increase the probability of finding the victim. However, Jagegera & Adairb (2016) and Capta &Scuibba (2019) point out that UAVs of the modern world is not of high endurance which is due to unavailability of lighter power sources. To push the boundaries of UAV flight performance, batteries must become smaller and lighter. However, the world has reached a limit when it comes to power density of the batteries. Lithium-Polymer (Li-Po) and Lithium-Ion (Li-ion) batteries have become very small and affordable and about 96% of commercial unmanned aerial vehicles uses batteries as a power source. Simply adding more batteries to the system will not create the flight times and payload capacities we are looking for. Thus, this raises the need for efficient aerodynamic and structural design of the UAV.

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**CHAPTER THREE: CONCEPTUAL DESIGN**

**3.1 Design Requirements**

The SAR UAVs should be equipped with some payload to the site of distress. The structural weight adds to the weight of the payload. Wing must provide sufficient wetted area to generate the lift. The wing span should be such that it results in higher aspect ratio typical of high endurance UAVs.

Thus, the requirements of UAV are tabulated below:

*Table 2: Design requirements*

| Wing span | 2 m |
| --- | --- |
| Endurance | ≥30 min |
| Payload | ≥1 kg |
| Mass | ≤3.5 kg |

**3.2 Possible configuration**

While developing Munal M-72, a number of different configurations were considered. A visual representation of some of the configurations is presented in Literature review (chapter 2).

Tractor configuration was the first basic configuration considered. In tractor configuration propeller is mounted in font of aircraft so that the aircraft is pulled through air. But this configuration was rejected so as to place camera at the nose of fuselage. This left us with two configurations: either to use two propulsive systems on either side of wing or to use a pusher configuration. If the former was considered, then it would increase complexity in fabrication. Moreover, single propulsive system could be chosen so as to produces enough thrust for small UAVs. Thus, it was decided to go with pusher configuration. In pusher configuration it’s better to use twin tail as it minimizes the influence of the propeller on aircraft’s tail. V- tail configuration will increase complexity in control while two booms from wing will increase complexity in fabrication. Thus, it was finally decided to go with following configuration for Munal M-72



*Figure 7: Final configuration*

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**CHAPTER FOUR: PRELIMINARY DESIGN**

**4.1 Wing**

The wing generates most of the lift to hold the UAV in the air. The selection of the airfoil and the sizing of the wing is described in following sections. **4.1.1 Airfoil Selection**

Different airfoils that are used in UAVs were considered while selecting airfoil for our UAV. Some of the airfoils that are mostly used are listed below,

• Clary Y

• MH 115

• NACA 6411

• Eppler 214

• FALCON

The selection was done by comparing graph between coefficient of lift (����), coefficient of drag (����) and ����

����for different angle of attack (��). The comparison was done using XFLR5. First, lift and drag coefficient at different angles of attack were calculated using XFLR5 then these points were plotted using MATLAB.

Airfoils characteristics are strongly affected by Reynolds number (����). Reynolds number defines whether the flow over airfoil will be laminar or turbulent. While comparing ���� of 200,000 was used. This was the approximated Reynolds number while cruising.

11

*Figure 8:*���� *of different airfoils*

Based on the above comparison, coefficient of lift of NACA 6411 and MH 115 were found to be almost same for different angles of attack. NACA 6411 has maximum lift coefficient and stalls earlier but MH 115 has greater stall angle.

*Figure 9:* ���� *of different airfoils*

In the figure 9, Clark Y and Eppler E214 have low drag coefficient as compared to others in the range of 0 degree to 8 degrees.

12

*Figure 10:* ����/���� *of different airfoils*

For almost all angle of attack, coefficient of lift to drag ratio was found to be maximum for MH 115.

3

In battery powered aircraft, maximum endurance of the aircraft occurs when is ����

2/����

3

is maximum. Thus, ����

2/����was also compared. Figure 11 shows the graphical

comparison between different airfoils.

3

*Figure 11:* ����

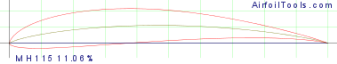
2/���� *of different airfoils*

3

����

2/���� is also maximum for MH115 so, MH 115 was selected for our UAV

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*Figure 12: MH 115*

*Table 3: Geometric properties of MH 115*

| Parameters | Percentage of chord length |
| --- | --- |
| Maximum Thickness | 11.08% |
| Location of Maximum Thickness | 29.29% |
| Maximum Camber | 5.57% |
| Location of Maximum camber | 46.47% |

**4.1.2 Sizing**

Wing span was specified as design requirement. Aspect ratio, root chord length, taper ratio, sweep angle and dihedral angle were the parameters that were to be defined. In the design phase, it was decided not to use landing gear in the UAV so it’s better to have stall speed as low as practicable. To have low stall speed, aspect ratio should be low. But low aspect ratio means higher drag force. Thus, a balance has to be maintained between stall speed and drag. At stall, induced drag is more dominant. Thus, a MATLAB script was to see the relationship of aspect ratio with stall speed and induced drag of wing.

For the program, lift curve slope of wing (��������) is needed which depends upon the aspect ratio (��) and lift curve slope of airfoil (������). In the program different aspect ratios were defined and �������� for each aspect ratio were calculated using the formula,

�������� =2���� 2 + √(2����

������)

(1)

2

+ 4

In the above formula, Clα was estimated using graphs given in the Pamadi (1998) which was found to be 5.95 ������−1. This value was found very close to the value of XFLR5. Zero lift angle of attack (��0��) was assumed to be −5 ������������. Then, coefficient of lift at stall angle (12 ������������) was calculated. The wing area (����) corresponding to each aspect ratio was calculated using the wing span (��),

14

���� =��2 ��

(2)

This area and maximum lift coefficient were used to calculate the stall speed of wing for weight of 34.335 ��. In this analysis, the lift force generated due to empennage and fuselage were ignored.

*Figure 13: Stall velocity for different aspect ratio of wing*

In the analysis of induced drag and aspect ratio, need Oswald efficiency number (��) is required. Oswald efficiency number depends upon aspect ratio, sweep angle and taper ratio. But it was assumed to be 0.85 for all aspect ratio just to keep things simple. So, induced drag for low aspect ratio will be even higher than shown in the figure 14.

15

*Figure 14: Induced drag at stall for different aspect ratio*

Increasing aspect ratio increases structural difficulty and problems in fabrication. Thus, it was decided to keep stall speed around 10 ��/�� and corresponding aspect ratio around 11. By increasing taper ratio, elliptic lift distribution could be approached. But higher taper ratio increases complexity in fabrication. Considering these factors, taper ratio of 0.6 was chosen.

Although swept wing has higher directional and lateral stability, it was decided not to keep swept wing just to keep things simple.

Dihedral increases lateral stability and dihedral angle of 5 �������������� was selected. The reason for this is explained in chapter 7.

Considering different factors, following wing configuration was selected, *Table 4: Wing configuration*

| Span (��) | 2 �� |
| --- | --- |
| Root Chord Length ( ����) | 0.225 �� |
| Tip Chord Length (����) | 0.135 �� |
| Taper ratio (λ) | 0.6 |
| Referential Area (����) | 0.36 ��2 |
| Standard Mean Chord (SMC) | 0.180 �� |
| Mean Aerodynamic Chord (MAC) | 0.184 �� |
| Aspect Ratio (��) | 11.11 |
| Dihedral | 5 �������������� |

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Above wing was modelled and analyzed using XFLR5. Following graphs show results obtained from the analysis.

*Figure 15: Variation of* ���� *with angle of attack at constant lift*

Figure 15 shows that slope of coefficient of lift (������) for the wing is 0.088 ������������−1 and the stall angle is around 15 ��������������.

*Figure 16: Variation of* ����/���� *with angle of attack at constant lift*

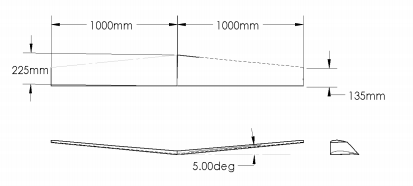
For 1 ������������ angle of attack ����/���� is maximum for the wing. Thus, default angle of incidence of wing (����) should be 1 ������������.

17

*Figure 17: Variation of velocity with angle of attack*

Figure 17 shows that the stall velocity of the wing is 10 ��/��. This is the minimum velocity at which the wing can generate 34.335 �� of lift.

The figure 18 shows orthographic view of wing in third angle projection which was modelled in SOLIDWORKS 2016.

*Figure 18: Orthographic projection of wing*

The parameters for the wing external shape definition are the span, area, the aspect ratio, the taper ratio, the sweep angle, and the airfoil. The parameters for the structural layout include the number of spars, the number of ribs, and the locations of the front spar and the rear spar.

18

*Table 5: Wing design variables*

| Variable | Design 1 | Design 2 | Design 3 | Design 4 |
| --- | --- | --- | --- | --- |
| Number of spars | 1 | 1 | 1 | 2 |
| Number of ribs | 6 | 10 | 16 | 10 |
| Location of front spar | 0.20 | 0.20 | 0.20 | 0.20 |
| Location of rear spar | - | - | - | 0.30 |

Design 4 is the final design used in the development of our UAV. **4.2 Fuselage**

Fuselage should be designed in such a way that it has enough space for battery, esc, wiring, and payload with minimum drag. Rectangular (200mm x 150mm) cross section was used for fuselage so that optimum utilization of space could be made. Moreover, rectangular shaped fuselage is easier to manufacture and payload releasing doors are easier to operate. The edges were filleted with radius of 20mm so that it will minimize drag under sideslip. The tail of fuselage was designed so that the propulsion system could be mounted easily and propeller fits completely with good amount of clearance with the boom. The next challenge was to design the nose of fuselage. The nose was designed with very gradual change in area and the overall fuselage was designed to give good streamline shape. The isometric view and orthographic projection of fuselage is shown in figure 19 and figure 20 respectively which was modelled using SOLIDWORKS 2016.



*Figure 19: Isometric view of fuselage*

19

*Figure 20: Orthographic projection of fuselage*

**4.3 Empennage**

The empennage, also known as the tail or tail assembly, is an arrangement of stabilizing surfaces at the rear of an aircraft that provides stability during the flight. Its conceptual design involves following steps:

**4.3.1 Airfoil Selection**

As the horizontal tail does not experience twist and stress like the main wing, it could be designed to be relatively simple. Symmetric airfoil was chosen for horizontal stabilizer so as to avoid the unwanted lift forces which would be produced if used a cambered airfoil. NACA 0012 airfoil was selected considering the maximum thickness it offers for the ease of the fabrication.

For the vertical tail, NACA 0012 was chosen due to its symmetrical properties; that would help minimize the drag and avoid unwanted yawing moment produced, and the maximum thickness it offers for the ease of fabrication. The symmetrical airfoil will also aid to the stability of aircraft due to the acceleration of airflow around the airfoil shape which will then improve the performance of the rudder.

20

**4.3.2 Sizing**

The center of gravity (��. ��.) of the wing is estimated to be at the 25% of the mean aerodynamic chord of the wing for preliminary sizing of the empennage. The empennage was designed to have a single horizontal stabilizer and twin vertical stabilizers. Also, the concept of twin vertical tail would avoid the air downstream of the pusher propeller from striking the vertical tail directly. The horizontal tail plane was designed to have a rectangular span. The vertical tail planes are made tapered as seen on many aircrafts and UAVs previously built. As from (www.fzt.haw-hamburg.de), for aircrafts with “low airspeeds”, the sweep angle of the vertical tail plane should be less than 20°.

The dimensions of the vertical and horizontal tail planes are determined by using the following equations (Daniel P. Raymer, 1992)

(3)

(4)

Where,

���� =����ℎ���� ����

���� =���������� ����

���� and ���� are the surface areas of horizontal and vertical stabilizers respectively �� is the mean aerodynamic chord of the wing

�� is the surface area of the wing

���� and ���� are the moment arm of horizontal and vertical stabilizers respectively �� is the wing span of the aircraft

����ℎ and ������ are the tail volume coefficients for horizontal and vertical stabilizers respectively.

Raymer (1992) suggests the values of the tail volume coefficients and the wing area, wing mean aerodynamic chord and wing span can be taken from the wing sizing, the relations discussed above now contain two dependent variables each. Determination of the tail plane area would require the value of moment arm which in turn would require the value of tail plane area to be calculated. So, a mathematical model is developed where the moment arm is varied so as to give numerous options for the sizing which were then limited by the manufacturing and aerodynamic constraints.

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The input parameters are:

• Mean aerodynamic chord of the wing of the wing: 0.184 ��

• Wing span: 2 ��

• Wing area: 0.36 ��2

• Tail volume coefficients: 0.5 and 0.04 for horizontal and vertical tails respectively

• Position of center of gravity on wing from trailing edge of the wing: 75% of mac = 0.165 ��

For the calculations, a number of variables were considered as:

• Horizontal stabilizer chord length (����)

• Vertical stabilizer root chord length (����)

• The positions of the ��. ��. of the tail planes are considered to be at 25% of their respective mean aerodynamic chord

• The distance between trailing edge of the wing to the leading edge of the tail (��[��−��]) is varied to obtain different output variables

**Calculations:**

Moment arm for horizontal tail

(����): ��[��−��] + 75% ���� �������� ��. ��. ��. +25% ���� ���������� ��. ��. �� (5) Moment arm for vertical tail

(����): ��[��−��] + 75% ���� �������� ��. ��. ��. +25% ���� ���������� ��. ��. �� + �� ∗ �������� (6) The parameter x arises from the vertical tail plane geometry as shown in figure 21: 

*Figure 21: Vertical tail geometry*

22

The mean aerodynamic chord length of a tapered wing geometry is given in equation7: ������ =23���� (1 + �� + ��2

1 + ��)(7)

where,

λ is the taper ratio

����is the root chord

Few decisions were made on the chord length of horizontal tail and the root chord of the vertical tail and were chosen to be 11 and 16 centimeters respectively. As the distance between the trailing edge of the wing and the leading edge of the tail plane (��[��−��]) was varied, the selection was made based on the manufacturing and aerodynamic constraints obtained from several sources:

• Raymer (1992) suggested an Aspect ratio for the horizontal stabilizer of (3-5) • Raymer (1992) suggested an Aspect ratio for the vertical stabilizer of (1.3-2) • The sweep angle for vertical stabilizer of low airspeed airplanes should be less than 200

• The moment arm should be preferably 3 times farther than the mean aerodynamic chord of the wing from the airplane center of gravity

To determine how the different parameters are changing with respect to the variables, a spreadsheet model was created which is presented in the appendix section. Following results were plotted using MATLAB after analysis of the data: The green part of the horizontal axis represents the allowable range of values for ��[��−��] based on the discussed constraints.

Similarly, as the sizing of the vertical tail is determined by two constraints (Aspect ratio and Sweep Angle), following results were obtained:

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*Figure 22:* ��[��−��] *vs area and aspect ratio of horizontal tail*

*Figure 23: Sizing of vertical stabilizer*

24

As determined by the constraints, the allowable range for the values of ��[��−��]is analyzed to be from 0.56 �� to 0.62 ��. The former value was selected considering the bending moment that the empennage would produce on the fuselage-empennage joint. The final decisions on empennage sizing are as follows:

*Table 6: Empennage sizing*

| Parameters | Value |
| --- | --- |
| Horizontal tail chord | 0.11m |
| Vertical tail root chord | 0.16m |
| Vertical tail taper ratio | 0.6 |
| Individual vertical tail height | 0.192m |
| ��[��−��] | 0.56m |
| Horizontal tail span | 0.415m |
| Sweep angle for the vertical tail | 18.3940 |

**4.3.3 CAD Model**

On the basis of the sizing of the empennage the CAD model of the horizontal and vertical tail planes are presented below:

*Figure 24: Orthographic and isometric views of the horizontal tail*

**

*Figure 25: Orthographic and isometric views of the vertical tail*

25

**4.4 Control Surfaces**

**4.4.1 Aileron**

The roll or lateral control of the UAV requires the aileron. Structurally, the aileron is a part of the wing which consists of two pieces, each placed on the trailing edge of outer portion of the right- and left-wing sections. In the design process of an aileron, four parameters need to be determined (Sadraey, 2013, p.655). They are:

i. aileron planform area (����);

ii. aileron chord/wing chord (����/��);

iii. maximum up and down aileron deflection (����������);

iv. location of inner edge of the aileron along the wing span (������). The figure 26 shows necessary parameters that define an aileron in relation to the wing.

b



����

����/2 

*Figure 26: Aileron layout*

������/2

Raymer (1992) provides a graph to estimate the aileron area. The graph is obtained by plotting historical data of the aileron chord to wing chord ratio (����/��) and total aileron span to wing span ratio (����/��). Sadraey (2013) lists these two parameters for a number of aircrafts which closely match with the graph. The table 7 lists the characteristics of aileron for MUNAL M-72.

*Table 7: Aileron design parameters*

| �� | Span Ratio | | Chord Ratio ����/�� | Area Ratio  ����/�� | ẟAmax | |
| --- | --- | --- | --- | --- | --- | --- |
| ������/�� | ����/�� | Up | Down |
| 2000 | 0.694 | 0.302 | 0.28 | 0.06998 | 20 | 15 |

26

With equal up and down movement, the down-going aileron produces more drag than the up-going aileron which causes adverse yaw. Hence, aileron differential-- different value of maximum up and down deflection-- was chosen to remedy this problem. **4.4.2 Elevator**

The important parameters for the sizing of the elevator are:

• Elevator area as percentage of the total area of the horizontal stabilizer • Elevator chord length as percentage of the chord length of the horizontal stabilizer • Elevator span

The normal sizing of the elevator suggests the area to be 25 − 45% of the total area of the horizontal stabilizer. The lower value of elevator area would result in higher deflection for the same amount of control and vice-versa. So, an area 30% of the horizontal stabilizer was chosen. The span of elevator was made to match the span of the horizontal stabilizer so that the resulting chord length of elevator would be 34 ����

which is 30.9% of the total chord length. This chord length is also suitable through fabrication perspective.

**4.4.3 Rudder**

The rudder design of rectangular shape was chosen over swept rudder design in regards to the easiness it offers in fabrication. Sizing of the rudder is suggested to have 30 − 50% of the total area.

The sizing procedure is similar to that of the elevator where the rudder was made 35% of the area of the vertical stabilizer with span as that of the vertical stabilizer. The chord length was then calculated to be of 48 ���� length.

**4.5 Final Configuration**

With the development of the conceptual configuration, the major design changes were over. This configuration and its associated characteristics as explained in chapter two were frozen. Preliminary design of the Munal M-72 followed this work. Figure 27 is the orthographic view of the Munal M- 27 ready for detailed design.

27

*VA*

*U*

*e*

*lo*

*h*

*w*

*f*

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*o*

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*p*

*c*

*i*

*hp*

*a*

*r*

*g*

*o*

*ht*

*r*

*O*

*:*

*8*

*2*

*e*

*r*

*u*

*g*

*i*

*F*

28

**CHAPTER FIVE: DETAILED DESIGN**

**5.1 Wing**

Detailed design of the wing is essentially design for manufacturing. The wing must transfer the wing loads to the fuselage. The weight of the wing is minimized by cutting holes in the rib wherever possible without compromising its structural integrity. Wing must also allow for attachment of the control surfaces (aileron) and actuators.

**5.1.1 Ribs**

The ribs were designed so as also to provide space for spars (front, middle and ailerons) and stringers. The front spar was placed at 20% of the chord length of the first rib which was then run parallel to the leading edge. This would, in addition to providing structural support, would help in putting the skin cover on the wing. The rear spar was located at 30% of the chord length of first rib and run parallel to front spar. The choice of this location is due to the fact that the chosen airfoil has maximum thickness at 29.8% chord and placing at this location assured maximum thickness between the cut in the rib and rib edge.



*Figure 29: Root rib*

Later, hole was cut 15% of chord and rounded rectangle at 50% of each rib to minimize weight.



*Figure 30: Wing rib along aileron*

The aileron spar was located at 72% of the chord and hence the ribs at those locations (8th and 9th) were cut at 70% chord so as to provide spacing for spar rotation. The aileron would be supported by 7th and 10th rib. The holes were cut in these ribs at 73.4% to allow support as well as rotation.



*Figure 31: Aileron holding rib*

**5.1.2 Spar**

Spar are required to carry flight loads or weight of the wing while on ground.

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**5.1.2.1 Front Spar**

The front spar, in addition to carrying the load, holds ribs in position. The front spar was cut alternatively at 10 locations as specified in the following drawing. The height of the spar ranged from 23.66 mm at front rib to 14.69 at rear rib. The width of the spar remained constant 5 mm along the span.

*Figure 32: Orthographic view of front spar*

**5.1.2.2 Rear Spar**

Rear spar was used to reduce deflection of the wing and strengthen the structure as necessitated by analysis. An 8mm sq. carbon tube with 6mm hole was placed at 30% of chord of first rib and was run parallel to LE from fuselage centerline up to 5th rib. **5.1.3 Stringers**

Stringers are primarily used to transfer wing bending loads to ribs and spar. Secondarily, they help in attaching skin to the wing. One stringer of 3mm depth and decreasing height was used in the LE. A pair of stringers, each 2mm thick and 3mm deep, was placed at 40% chord, one at upper profile of rib and other at lower. Another pair was placed at 60% chord.

**5.2 Fuselage**

It was decided to use 8 x 8 mm carbon tube with 6 mm circular hole as the major load bearing component of fuselage and 5 mm balsa wood to give streamline shape as well as bear small loads. Frame of carbon rod was covered using rectangular shaped formers made up of balsa and these formers were also connected using balsa. The bottom portion of fuselage was made free from any structural members so that payload can be dropped easily. The following figure shows the structural layout of the fuselage. In the figure 33, black color represents carbon rod whereas brown color represents balsa.

30

*Figure 33:Structural layout of fuselage*

**5.2.1 Payload**

A slider crank mechanism was made for payload release. The payload is initially aligned with center-line of fuselage.

The dimension of payload box is 210 ���� × 110 ���� × 80 ���� which was supported by two carbon-fiber rods attached to the frame. One of the two bars is fixed, while the other bar is made to slide sideways which will facilitate the drop. A servo motor is used to control the sliding motion of the sliding bar. Sliding bar and servo motor is connected with the connector as shown in figure below. Before releasing the payload, servo would open the door sideways.

The 3D CAD model of the Payload drop mechanism is shown in figure 34. 

Payload Box

*Figure 34: Payload release mechanism*

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**5.3 Empennage**

The different parts that make the empennage were designed so that it would be viable to fabricate without compromising the functionality. Considerations were also given to the fuselage-empennage connection during the process.

**5.3.1 Horizontal Stabilizer**

As stated above, the horizontal tail has a chord length of 110 mm and a span of 415 mm:

*Figure 35: Horizontal stabilizer*

The structure consist of 10 ribs, one 5 ���� thick balsa wood spar running through the ribs at 38.63% chord length where it has a thickness of 12.81 ����, a carbon rod of 8 ���� × 8 ���� cross- section that runs through 6 ribs; three to each side from the center and an elevator spar to hold the elevators that lies at 73.64% of the chord length of the end ribs where the rib has a thickness of 7.26 ����. The carbon rod was placed to pass through only six of the ribs so as to minimize the potential weight of the empennage. Running lengthwise wouldn’t be necessary from structural point of view as aerodynamic loads experienced by ribs toward end is small.

The ribs used are of 2 ���� and 5 ���� thickness. Ribs of 5 mm thickness were put at the tip of the tail plane to support the elevator spar and at the center to facilitate the placement of the servo motor. Other ribs are of 2 mm thickness. According to the cuts designed in the airfoil ribs to fit into the structure, there are three types of ribs used in the horizontal tail plane:

**End ribs:**

****

*Figure 36: End rib*

32

End ribs were designed considering the placement of the main spar and to support the elevator spar.

**Ribs holding carbon rod and main spar:**

****

*Figure 37: Connecting rib*

These ribs are 6 in number; 3 on both sides of the center. They are cut so as to go into the structure along with carbon rod and the main spar. The rib is 76 mm in length. **Ribs with cuts for main spar only:**

****

*Figure 38: Main spar rib*

They are 2 in number and have cuts for the main spar only.

**Spar:**

The main spar was designed to run through all the ribs to provide structural strength to the structure. It would have a thickness of 5 mm.

*Figure 39: Main horizontal spar*

The spar was designed to hold all the ribs in place and alternate cuts were provided in upper and lower part of the face for robust assembly. The main spar is at 42.5 mm longitudinal distance from the leading edge of the airfoil.

**5.3.2 Vertical tail plane**

As mentioned above the vertical tail plane has a root chord of 160 ���� and a vertical span of 190 ���� with 0.6 taper ratio and a sweep angle of 18.39 ��������������. The structure contains 5 ribs of different sizes due to the tapered structure, one tapered main spar that runs through the ribs, one end spar and a rudder spar that holds 5 rudder ribs in place. The main spar was designed so as to pass through 27.5% chord length of the root chord airfoil rib and 26.5625% of the chord length of the tip chord airfoil rib and is inclined at 76.53 degrees with the horizontal. The main spar was designed so as to pass through 27.5% chord length of the root chord airfoil rib and 26.5625% of the

33

chord length of the tip chord airfoil rib and is inclined at 76.53 degrees with the horizontal. The main spar was designed so as to pass through 27.5% chord length of the root chord airfoil rib and 26.5625% of the chord length of the tip chord airfoil rib and is inclined at 76.53 degrees with the horizontal.



*Figure 40: Vertical tail plane*

The main spar was designed so as to pass through 27.5 % chord length of the root chord airfoil rib and 26.5625% of the chord length of the tip chord airfoil rib and is inclined at 76.53 degrees with the horizontal. As the horizontal and vertical tail planes were designed to be connected by attaching the respective main spars, the location of the main spar of the vertical tail plane should match to the location of the main spar of the horizontal tail plane longitudinally. This is the reason behind the geometric orientation of the main spar so that it passes at same longitudinal distance (as the main spar of the horizontal tail plane passes) from leading edge of the root chord airfoil of the vertical tail plane. But as 20 ���� extension further beyond the root chord rib is provided to connect the two spars, a little but not significant deviation of 2~4 ���� occurs. The middle rib is made 5 ���� thick for the placement of the servo for rudder deflection.

**Ribs:**

The root chord airfoil rib and the tip chord airfoil rib are each 5 ���� thick and the other three ribs are placed at 45 ���� vertical spacing so as to make the height of the vertical

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stabilizer a total of 190 ����.

**Spar:**

The spar is as tapered as the ribs from the root chord airfoil to the tip chord airfoil and has cuts to hold the airfoils into the structure.

*Figure 41: Vertical main spar*

The spar is as tapered as the ribs from the root chord airfoil to the tip chord airfoil and has cuts to hold the airfoils into the structure.

The tail end spar is also tapered and runs through the airfoils. This is vertical in orientation which passes at 112 ���� longitudinal distance from leading edge of the root chord airfoil and has got cuts to support the 3 airfoils sandwiched by the tip airfoils of 5 ���� thickness.

*Figure 42: End spar*

**Design for manufacturing:**

Inclined cuts in the spar and the ribs were required for the assembly to be in a perfect fit. However, the cuts that a CNC laser cutting machine would produce can’t have inclined profiles along the thickness. Due to this very reason, design for manufacturing approach was adopted in which cuts normal to the geometry were provided so as to hold the structure in place:

*Figure 43: Spar-rib alignment*

**5.4 Control Surfaces**

The detail design of control surfaces from manufacturing point of view and attachment to respective UAV part is made in this section.

**5.4.1 Aileron**

One aileron is placed on trailing edge of each wing. The differential deflection of the ailerons is achieved by using hinged movement of the ailerons.

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**5.4.1.1 Ribs and Spar**

Aileron on each right- and left-wing section consists of four ribs, each 2 ���� thick, attached to a spar webbing. The attachment, however, poses a problem as the spar webbing runs not perpendicular to the ribs but an angle greater than 90 ��������������. So, with manufacturing in mind, a rectangular cross-section is cut through spar such that rib has enough space to go through spar as shown in the top view in figure 44.

*Figure 44: Aileron-spar alignment*

The spar webbing is then inserted between 7��ℎand 10��ℎrib of the wing. The end of the spar on the wing root side has a protrusion to connect to the actuator mechanism. 

*Figure 45: Aileron spar*

**5.4.1.2 Actuator Mechanism**

The actuator mechanism of aileron is a four-bar mechanism in which the input is the rotation of the second link by servo motor and output is the rotation of 4��ℎlink (the aileron itself). The 7��ℎrib on which the servo is attached acts as ground for the mechanism.

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*Figure 46: Actuator mechanism*

**5.4.2 Elevator**

The elevator consists of an elevator spar holding 8 ribs as shown. The circular cross section that goes into the end ribs is for structural support as well as to facilitate the rotation of the component.

*Figure 47: Elevator spar*

**5.4.3 Rudder**

Being relatively shorter than the elevator, the rudder is provided with only 4 ribs. The thickness of the spar is 5 ����.

*Figure 48: Rudder spar*

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**CHAPTER SIX: AERODYNAMIC AND STRUCTURAL ANALYSIS 6.1 Aerodynamic Analysis**

UAV was first analyzed using XFLR5. The analysis was done at constant lift and in the analysis contribution of fuselage was not considered. This analysis was done to obtain the cruising velocity of UAV so that analysis could be done using ANSYS Fluent. From the analysis velocity was found to be 15.96 ��/��.

Due to the symmetric nature of the problem domain, analysis was done in ANSYS Fluent Solver for half portion of the UAV. Fluid domain of 16 �� × 12 �� × 10 �� was defined.

*Figure 49: Fluid domain*

In the analysis, an automated default tetra mesh was generated. Default tetra mesh on the fluid domain is shown in figure 50.

*Figure 50: Mesh*

In setup, density and viscosity of air were defined as 1.225 ����/��3and 1.7894�� − 05 ����/���� respectively. Inlet velocity was defined and standard atmospheric

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pressure(101 ������) was used at the outlet. Laminar model was used in the analysis because of low Reynold’s number. In this analysis, the main concern was with the lift and drag forces on different parts of the UAV. Total lift and drag forces were found to be 17.29 �� and 1.06 �� respectively. This lift and drag forces were acting only on the half portion of the UAV thus, total lift and drag forces were 34.58 �� and 2.12 ��. Lift to drag ratio of the UAV was found 16.31

*Figure 50: Lift and drag forces on different components*

*Figure 51:Pressure contour*

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**6.2 Structural Analysis**

Structural analysis was performed to determine the effects of aerodynamic and structural loads on the wing.

**6.2.1 Preprocessing**

Preprocessing is the first step in solving a problem in Finite Element Analysis. Here the entire domain is discretized into elements. These elements form the building block on which the boundary conditions and external effects are specified.

**6.2.1.1 Geometry**

CAD model of the wing structure was generated using SolidWorks. The parameters for the structural layout were taken as design variables in the wing design; a different number of ribs and spar combination were designed for the analysis.

*Figure 52: Geometric model*

In the final design, the first rib was placed at 75 ���� from the fuselage center line and the spacing between the mid-planes of the adjacent ribs was maintained a constant distance of 102.78 ���� for 2 ���� thickness ribs. However, the spacing changed slightly as the first rib and rib carrying the servo were thickened to 5 ����. The following CAD model is the geometric model of the wing of our UAV.

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**6.2.1.2 Material Properties of Elements**

Mechanical and physical properties of the materials that were used in analysis are presented below:

*Table 8: Material properties of elements*

| Material | Property | Value |
| --- | --- | --- |
| Carbon Fiber | Tensile Strength (������) | 2550 |
| Tensile Modulus (������) | 135 |
| Elongation (%) | 2.1 |
| Density (��/����3) | 180 |
| Carbon Content (%) | 93 |
| Balsa Wood | Tensile Strength (������) | - |
| Elastic Modulus (������) | 3000 |
| Density (����/��3) | 160 |

**6.2.1.3 Mesh**

ANSYS was used to automatically generate mesh for the geometry. The wing cover was face meshed to generate fine mesh. The large number of automatically generated elements were tetrahedral. Hexahedral and wedge constituted the remaining. *Table 9: Mesh statistic*

| Number of Elements | 58152 |
| --- | --- |
| Number of Nodes | 122400 |

**Mesh Quality**

The following table lists average values of three important mesh quality parameters for the wing. These parameters play a significant role in accuracy and stability of numerical solution.

*Table 10: Mesh quality*

| Criterion | Average Value |
| --- | --- |
| Aspect Ratio | 15.92 |
| Skewness | 0.94 |
| Orthogonal Quality | 0.21 |

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*Figure 53: Mesh on wing*

**6.2.1.4 Boundary Conditions**

For the analysis, the spars which would connect to the fuselage were taken as cantilevers and they were fixed.

**6.2.1.5 Loadings**

The loads acting on wing are aerodynamic loads and structural weight. The aerodynamic load was imported from ANSYS fluent.

*Figure 54: Pressure distrbution on wing*

**6.2.2 Post Processing**

In reference to the designs described in preliminary design, structural analysis was performed. One important criterion of selection of geometry and material of the

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component part is deflection. The displacement of the wing tip was to be less than or equal to 5% of the semi-wing span i.e. 50 ����.

*Table 11: Tip deflection for different wing configuration*

| Design | Material | | | Maximum Deflection(mm) | |
| --- | --- | --- | --- | --- | --- |
| Front Spar | Rear Spar | Other | LE | TE |
| 1 | Balsa | - | Balsa | 81.33 | 86.81 |
| 2 | Balsa | - | Balsa | 80.63 | 85.28 |
| 3 | Balsa | - | Balsa | 79.51 | 84.88 |
| 4 | Balsa | Balsa | Balsa | 64.49 | 67.07 |
| 4\* | Balsa | Carbon Fiber | Balsa | 12.48 | 12.63 |

Design 4\* is same as design four except for the material of the rear spar. It was observed that the deflection decreased only slightly when the number of ribs was increased from 6 to 16. The 10 ribs were chosen for final design such that spacing would be convenient for putting skin cover on the wing.

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**CHAPTER SEVEN: STABILITY**

**7.1 Longitudinal Static Stability**

Contribution of different components were considered separately and their contribution were combined in the MATLAB code to check the longitudinal static stability. XFLR5 was used to get the aerodynamic center and moment about the aerodynamic center of wing, vertical and horizontal stabilizer. Lift curve slope and zero lift angle of attack were also estimated using XFLR5. Though XFLR5 could be used to check the stability, it was performed manually to get the basic idea and concept of stability. Moreover, the contribution of fuselage is not considered in XFLR5.

Zero lift angle of attack and coefficient of lift curve slope of the wing are: ��������= 0.088 ������������−1

����0�� = −6.4 ������������.

Distance of aerodynamic center of wing from the leading edge of root chord (Xacw) and moment about the aerodynamic center of wing (Macw) are:

�������� = −1.64 ����

�������� = 0.04327.

The above relation showed that the aerodynamic center is at 23.5% of mean aerodynamic chord for wing.

And for horizontal stabilizer,

Slope of coefficient of lift (��������) = 0.0625 ������������−1

Aerodynamic center from leading edge of root chord (��������) = 0.0244 �� Moment about aerodynamic center (��������) = 0 (symmetric airfoil) Fuselage also contributes to the longitudinal stability of aircraft. As the fuselage is cambered, coefficient of moment about cg due to fuselage at zero-degree angle of fuselage reference line (����0��) and slope of coefficient of moment (��������) can be calculated using empirical formulas and graphs as presented by Pamadi (1998). To get equations of camber line and thickness of fuselage, different points were considered and polynomial equations were fitted using Microsoft Excel. For camber line polynomial equation of 6��ℎ order was used whereas 2���� order equation was used for thickness. The integration was performed for three segments of fuselage. The integral was calculated using MATLAB.

The result obtained are:

����0�� = −0.0552

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�������� = 0.0026 ������������−1

In MATLAB, graphs for different default angle of incidence of horizontal stabilizer were plotted. In the program distance was measured from the nose of fuselage. The moment due to drag forces were neglected. For each angle of incidence point with zero moment were found. Then the slope of coefficient of moment with respect to angle of attack about the point was calculated.

*Figure 55: Coefficient of moment for different angle of attack*

It was decided to keep -2 degree as the default angle of incidence of horizontal stabilizer. For the configuration the cg of the UAV should be located at 0.39425m from the nose of fuselage. The mass of the UAV should be arranged as:

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*Table 12: Mass, centroid and position status of different component*

| S.N. | Component | Mass(gram) | Centroid X(mm) | Position status |
| --- | --- | --- | --- | --- |
| 1. | Fuselage | 200.32 | 368.27 | fixed |
| 2. | Wing | 180.74 | 401 | fixed |
| 3. | Empennage | 114 | 938.52 | fixed |
| 4. | Payload System | 2179.14 | 299.20 | variable |
| 5. | Brushless Motor | 60 | 650 | fixed |
| 6. | Battery | 720 | 550 | variable |
| 7. | Servos (Aileron) | 18.32 | 390.42 | fixed |
| 8. | Servo (Horizontal  Stabilizer) | 9.16 | 1165 | fixed |
| 9. | Servos (Vertical  Stabilizer) | 18.32 | 1190 | fixed |

In the above mass arrangement, payload system includes both Payload releasing mechanism and payload. Small components like wires were not considered in the above table.

**7.2 Directional Static Stability**

As mentioned earlier, there is no contribution of wing to the directional static stability if it does not have swept wing.

The contribution of fuselage and wing are considered together. Hoak, et al., (1960) provide relations for the calculation of the contribution. Slope of coefficient of yawing moment in sideslip because of wing and fuselage (����������) was found to be −0.0003 ������������–1.

For the contribution of vertical tail, two units were considered as the single unit. For the single unit,

Slope of coefficient of lift (��������) = 0.056 ������������−1

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Mean aerodynamic chord = 0.131 ��

Area (������) = 0.048��2

Aerodynamic center = 22.13% of mean aerodynamic chord

Distance from cg to aerodynamic center (������) = 0.7447 ��

It was assumed that the vertical stabilizer experiences same dynamic pressure. Then slope of coefficient of yawing moment with sideslip angle due to vertical stabilizer (��������) was found to be 0.00278 ������������−1. The overall slope of coefficient of yawing moment with sideslip angle (������) was found to be 0.00248 ������������−1.

**7.3 Lateral Static Stability**

Munal M-72 has high wing configuration and for high wing configuration, slope of coefficient of rolling moment with sideslip angle (����’���� ) is −0.0006 ������������−1. In the design of Munal M-72 the vertical stabilizer is placed lower. Further, it was assumed that the center of pressure of vertical stabilizer was at 40% of span; then it would be at 51 ���� above the tip of fuselage. But the center of gravity was around 80 ���� above. Thus, the vertical tail has destabilizing effect to lateral stability. The slope of coefficient of rolling moment due to vertical stabilizer (����’����) was found to be 0.000112 ������������−1. In this calculation dynamic pressure is assumed to remain same for the vertical stabilizer.

To increase stability in lateral direction, it was decided to keep dihedral angle (Г) of 5 ��������������. The slope of coefficient of rolling moment due to wing (����’����) was found to be − 0.1 ������−1 or − 0.00176 ������������−1.

**7.4 Longitudinal Dynamic Stability**

To calculate stability derivatives, we used the value of coefficient of lift and drag of whole UAV from the numerical analysis done in ANSYS. From that analysis coefficient of lift and drag were found to be 0.6158 and 0.03775 respectively. Moment of inertia about the y-axis passing through cg (������) was calculated using SOLIDOWORKS and found to be 0.098 ������2. Based on the above data, stability derivatives were calculated.

���� = −0.0379 ��−1, ���� = −1.2383 ��−1, ���� = 0, ���� = 0.4 ��−1(assuming Oswald efficiency factor(��) = 0.9), ���� = −5.899 ��−1, ���� = −2.99 ��−1��−1(������ = −0.4526 per radian), ���� = 0, ���� = 0, ���� = −8.937 ��−1, ��ẇ = 0, ��ẇ = −0.1615 ��−1 Then stability matrix is,

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�� = [

−0.0379 0.4 0 −9.81 −1.2383 −5.558 15.96 0 ]

0.2 −2.0373 −11.51 0 0 0 1 0

Using MATLAB, Eigen values of the matrix were found to be -8.5336 ± 4.8762�� and −0.0194 ± 0.6072��. Using these value half-life of long period oscillation (LPO) and short period oscillation (SPO) were calculated and found to be 0.0812 �� and 35.73 �� respectively.

The response of MUNAL M-72 to disturbance of ∆�� = 0.1��0 = 1.596 ��/�� and ∆�� = 5 ������������ was plotted in MATLAB.

*Figure 56: Response of MUNAL M-72 to disturbance in ∆u and ∆α – change in ∆u Figure 57: Response of MUNAL M-72 to disturbance in ∆u and ∆α – change in ∆α*

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*Figure 58: Response of MUNAL M-72 to disturbance in ∆u and ∆α – change in ∆q Figure 59: Response of MUNAL M-72 to disturbance in ∆u and ∆α – change in ∆θ*

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**CHAPTER EIGHT: PROPULSION SYSTEM**

**8.1 Introduction**

Propulsion is a critical and indispensable module of the UAV structure which provides the necessary thrust to maintain a flight. The UAV performance, effectiveness, and utility strongly depend on the onboard propulsion capabilities. Jointly with other UAV design considerations, the structure and design of propulsion system determines the endurance, size, weight, payload capacity, and the flight time of all UAV classes.

Among several options available for propulsion system, it was decided to select Brushless-Motor driven electric propulsion system for our UAV. Although initially, it was decided to use reciprocating piston engine, the decision was changed due to unavailability and high cost of engine. Electric propulsion has the potential to reach efficiencies of up to 80 − 90 %. Unlike internal combustion engine which decreases in efficiency and reduces output horsepower with increase in altitude, the electric motor power is relatively unaffected by altitude, temperature, and humidity factors. Besides, Electric propulsion system provides also quick response from radio to receiver, which makes UAV more efficient. It also provides quieter and cleaner energy, which is plus point for surveillance applications.

The major components of electric propulsion system are

1. Propeller to convert motor torque force into thrust force,

2. Brushless DC Motor to provide required torque,

3. Brushless ESC to control the throttle,

4. DC Battery as source of power.

**8.2 Design and Selection of Components**

Along with analytical calculations, several online resources, Handbook’s data and online thrust calculator were used to estimate, cross-check and to choose efficient components. The general methodology applied are as described below: - **8.2.1 Power Requirement for takeoff**

Thrust to weight ratio for takeoff is given by

��=0.908 (��~~��~~)

����,max × ������+ �� = 0.0908(3.5

0.35)

��

2.1 × 15 + 0.035 ≈ 0.3232 (8)

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Where, �� = Ground friction coefficient (nearly 0.035)

W/S = Wing Loading (����/��2)

����,������,���� = Maximum coefficient of lift for takeoff

������ = takeoff distance (m)

Minimum thrust is given by

�������� = �� ∗ (����) = 3.5 ∗ 0.3232 = 1.1312 ���� = 1131.2 ��

(9)

= 11.093 ��

Similarly,

Minimum required power for take-off is given by

�������� = �������� × ������������ = 11.093 × 9.4 = 104.2742 Watt (10)

Where, ������������ = Stall speed of aircraft.

This shows that large amount of power is required for take-off. Since battery capacity limits the operation, it was decided to launch Munal M-72 by hand. **8.2.2 Power Requirement during Cruise**

In level flight, the total thrust should overcome the drag forces.

Drag forces is calculated by formula

�� = �������� =12× �� × ��2 × ���� × ��������(11)

From CFD, it was calculated that maximum 3D drag force (Required thrust by propeller) is approximately 3 ��.

The cruise speed is approximated to be 15 ��/��. So, the power required for cruise is given by

��������. = ��ℎ�������� × ������������ ���������� = 45 �������� (12)

It is always recommended to use higher value of motor power (40-50% more) to fly easily at 50 − 60 % throttle. So, we will be looking for motor of power rating around 65 – 70 ��������.

**8.3 Propeller Selection**

Propeller selection is one of the most critical design decisions for a UAV. Often times it is the first component to be selected based on required thrust, and the rest of the UAV

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is scaled around the selected propeller. Due to the complexity of the propeller dynamics, and the many variables involved, there is no simple way of doing this. Although propeller selection often relies on experience, brushless motor and propeller performance prediction tools can also be used to find good propeller-motor combinations by trial and error.

For slow-moving UAVs or for hovering UAVs such as multi-copters, large propellers always give more efficient performance. However, if the UAV is meant to fly fast, smaller propellers with larger pitch will be required. Larger propeller causes larger thrust force and also therefore draws higher current.

It was decided that the propeller should be kept at the rear side of UAV so that front side can be equipped with a camera (unobstructed view). So, a pusher propeller was to be selected our design. Having the propeller mounted quite high makes it easy to hand launch.

**8.3.1 Calculation and Selection of Diameter of Propeller**

Propeller diameter is the mean diameter of imaginary circle scribed by the blade tips as the propeller rotates. The diameter of the Propeller was calculated from the formula provided by Falk (1944). The formula is as follows

�� = ��1(������) × ��2(����ℎ. ) × ��3(ℎ��) (13)

Where, *D*is diameter of propeller (ft.),

��1(������) is factor from ������ curve.

��2(����ℎ) is factor from ����ℎ curve.

��3(ℎ��) is factor from (ℎ��) curve.

The curve in the textual reference, Falk (1944), for the rpm, mph and hp are limited in between 1000-3000,50-3000 and 50-3000 respectively which is not in accordance with our requirement. So, the curve is revised for small UAV which has power requirement lesser than 50 ���� and fly at speed lesser than 50 mph. The propeller’s rotational speed is also more than 3000 ������. So, the curve is modified by picking different data coordinates from the curve provided by Cook (2007) and these data were extrapolated in MATLAB. The extrapolated curve along with the coordinates are shown in figure 60:

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*Figure 60: Extrapolated curves for propeller diameter calculation*

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Following parameters were considered for the calculation of above factors, Flight Speed = 15 ����−1 = 33.554 ����ℎ

Required Power = 45 �������� = 0.060346 ℎ��

Rotational Speed = 9000 ������,

Based on the above curves, the factor ��1(������), ��2(����ℎ), ��3(ℎ��) were calculated and finally the diameter of propeller was calculated as: -

�� = 3.866 × 1.58 × 0.1395 = 0.852 ���� = 10.23 ������ℎ

Since, 10.23 inch. diameter propeller is not manufactured commercially,11-inch diameter was selected at initial phase as diameter of propeller.

**8.3.2 Calculation and Selection of Pitch of Propeller**

Pitch is the linear distance that a propeller would move in one revolution with no slippage.

The Pitch can be calculated by formula

�� =336 �� × ��

��=336 �� × 33.554

8000 = 4.427 ������ℎ(14)

where, �� = Pitch of Propeller (������ℎ)

�� = Forward Speed (����ℎ)

�� = Rotational speed (������)

For pitch too, since 4.427 − ������ℎ pitch is not manufactured commercially, propeller with 5 ������ℎ pitch was selected.

**8.3.3 Tip Speed Limitations of Propeller**

When the axial velocity or aircraft speed equals to zero.

������������,������ = ���� = 0.0254 × �� × �� = 0.0254 × �� ×2���� 60

(15)

Here, ����is tip speed of propeller on the ground which should in range of 180 - 200 m/s to keep it within noise limits.

When the aircraft flies, the total tip speed increased to

������������,������ = √����2 + ������������2

(16)

where ������������ is speed of UAV.

Then the rotational speed of propeller in rpm is given by:

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�� =60 ∗ ������������,������

0.0254 × 2�� × ��=60 ∗ ������������,������

(17)

0.0254 × �� × ��

Here, r and D is radius and diameter of propeller (in inch) respectively. The graph between rotational speed limitation and diameter of propeller is shown in figure 61.

*Figure 61: Diameter vs Speed limit of Propeller*

Hence for 11 \* 5 Propeller, the maximum rotational speed is limited to approximately 13709.54 rpm.

**8.3.4 Static and Dynamic Thrust Calculation**

The static thrust (thrust produced at zero speed of aircraft) and dynamic thrust generated by the propeller depends on more on diameter and rotational speed of propeller. Due to complexities of geometry, there is no general formula can be derived for calculation of thrust for commercial propeller that fits for all other. Besides all these, an empirical formula (16) extrapolated from the experimental data is used for initial guess of thrust. This formula is accurate within +/- 26% of the actual thrust for 95% of all cases, and accurate to within +/- 13% for 68% of the cases for static thrust and more or less accurate for dynamic thrust also.

This formula will be used for rough estimation of propeller rpm for the given set of Propeller size that can produce required thrust

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The empirical formula is as follows:

��ℎ��������(��) = �� − �� (18)

Where,

60 )2× (��

�� =��(��(0.0254×��)2)

4× (��×0.0254×��

�� =��(��(0.0254×��)2)

4× (��×0.0254×��

3.29546×��)1.5 3.29546×��)1.5

�� = density of air (kg/m3)

60 ) �� × (��

D = diameter of propeller (inch)

N = rotational speed of propeller (rpm)

P = pitch of propeller (inch)

V = aircraft speed or propeller forward speed (m/s)

When V= 0 m/s, thrust produced will be *static thrust*, else it will be *dynamic thrust*. The table of estimation of static thrust and dynamic thrust for different size of propeller was generated from above formula with the help of Excel. During the formula setup, density of air was chosen to be 1.225 ����/��2, rotational speed was chosen to be 9000 ������ which should be in range of rpm as guided by tip speed limitations and airspeed was chosen as 12 ����−1.

The tables for static thrust and dynamic thrust for different values diameter and pitch were tabulated as in appendix-2

The required thrust for our UAV was calculated to be approx. was in the range of 300 − 400 ����. Based on above table, 10× 5 ,11 × 4.7 propeller was selected and static thrust was tested using these propellers.

**8.3.5 Blade Number of propellers**

In general, 2-blade propellers are light weight and slightly more efficient. However, efficiency doesn’t propel an airplane, thrust does. Thrust is needed to overcome drag and weight, helping the aircraft climb. Choosing the right number of propeller blades depends on certain parameters, including a given aircraft’s engine power (motor power), operating RPM for the propeller, diameter limitations, and performance requirements. If these factors were held constant, the efficiency of a propeller would decrease as more blades are added. However, as engine power increases, additional blades were generally required to efficiently utilize the increased power and producing required thrust.

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Keeping all these in mind and looking the general trend in manufacturing of UAV, it was decided to use 2 blade propellers.

**8.4 Thrust Test**

Static thrust testing was done through physical setup while dynamic thrust test was done using ANSYS.

**8.4.1 Static-thrust Testing**

A physical setup was made to measure the static thrust by the above selected propeller. Weighing Machine is used to measure the thrust and tachometer is used to measure the rpm of propeller. A 3S LIPO battery is used to power the brushless motor. Along with this 60 ������������ ESC is used as speed controller and a 2212/10 T 1400 ���� BLDC motor is used in this setup

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*Figure 62: Static Thrust vs RPM graph for propeller*

The graph showing the results of static thrust vs thrust is as follows: - The static thrust by both of these propellers are enough for flight. But during flight, airspeed comes into play and net dynamic thrust decreases. Since, physical setup for dynamic thrust testing was beyond the scope of project, to counterbalance this, CFD analysis was done using ANSYS Fluent Solver.

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**8.4.2 Dynamic-Thrust Analysis**

Dynamic Thrust analysis was done from ANSYS Fluent Solver. A 1147 Propeller is used for the analysis. The rotating domain as well as static domain were made as shown in figure 63

*Figure 63:Geometry of Propeller and its Domain*

Tetra mesh were used for meshing. Since, the domain was too large, 40 ���� element size was selected for meshing to reduce the computational cost. The average skewness of meshing was 0.202242

*Figure 64: Mesh of Domain*

In setup, inlet velocity of air was chosen to be as 10 ms-1and rotational speed of propeller was selected as 10000 rpm. Furthermore, pressure-based solver was used and K-epsilon model was used for analysis. The density of air was 1.225 kg/m3 and viscosity of air was 1.7894�� − 05 ����/����.

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The figure 65 is velocity contour from CFD analysis of propeller which shows variation of velocity along the radius

*Figure 65: Velocity contour of propeller*

*Figure 66: CFD result as thrust*

From above CFD analysis, net thrust was found to be 4.26 N. This thrust was in the range of required thrust.

**8.5 Motor Selection**

Due to better performance (Better speed vs torque characteristics, High dynamic response, high efficiency, Long Operating Life, Noiseless Operation) as compared to other brushed motor and induction Motor, Brushless DC (BLDC) Motor is used to popularly in UAV industries. There are two types of BLDC motor: Outrunners (outer casing rotates around center) and Inrunners (shaft rotates inside outer casing). Generally, Inrunners are used in RC helicopters as it is easily mountable.

The brushless motor is characterized by its size, KV rating, number of turns of coil, maximum current rating. By KV rating we mean, number of rotations per minute when powered by 1-volt source.

The BLDC motor should be chosen in such a way that it should provide the required rpm without any damage. The size of motor determines the torque it provide and its

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maximum current handling capacity. The maximum current rating of motor should be chosen such that it should under the 1.2 − 1.5 times under the maximum. The propeller size also dictates the sizing of motor. In general, for high KV, low diameter high pitch propeller is used and vice versa. But it should be checked whether the torque produced by propeller is compatible by motor or not. Else it will be over prop and motor will burn out.

Keeping all these things in minds, it was decided to choose 3548 1100 ���� BLDC motor. Here, 3548 represents the size of motor. The size of stator diameter is 35 mm and length of motor is 48 mm. Similarly, 1100 ���� means it can be rotated at 1100 revolutions per minute when powered by 1-volt source.

**8.6 Battery Selection**

BLDC needs high amount of current. The current flow capacity depends on the discharge rate (C-rating) of battery. Thus, due to high discharge rate, high power to weight ratio, LIPO battery was used. LIPO battery is specified by C-rating (which determines the maximum current flow) and its capacity mAh (which represents total milliampere current that can be continuously drawn for 1 hour).

If the battery is 2600 ����ℎ 25 ��, the maximum current is 2.6 × 25 = 65��. If battery operates under the maximum current, the life of battery will be shortening. Endurance of battery powered UAV depends on the mAh of battery. So, while choosing the LIPO battery, endurance of UAV should be kept in mind. But just adding piles of battery wouldn’t increase endurance as it will also increase the weight of UAV.

**8.6.1 Endurance**

Endurance (time of flight) is only affected by capacity (mAh) and current drawn by the system if all the other factors remains constant. The maximum current drawn was 7 − 9 ��. Choosing 10 �� as maximum current, the endurance can be found out by

������������������(������������) =���������������� ���� ��������������(����ℎ)

1000 × ��× 60(19)

The minimum time of flight was decided to be about 40-60 min. To achieve that goal, it was decided to choose battery in between 7000 mAh – 10000 mAh. The capacity of battery may be increased by parallel combination of two batteries.

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**8.7 Electronic Speed Controller (ESC) Selection**

An electronic speed control or ESC is an electronic circuit that controls and regulates the speed of electric motor. To run brushless motor, brushless ESC was required. Brushless ESC systems basically create three-phase AC power, as in a variable frequency drive, to run brushless motors.

The electronic speed controller was selected based on its Ampere rating. This should be greater than ampere rating of the motor.

������ ������������ = (1.2 ���� 1.5) × ������. ������������ ������������ ���� �������� ���������� (20) There are 2 current ratings to an ESC: continuous and burst. Continuous current rating indicates the maximum amount of continuous current which the ESC can safely handle. And Burst current rating is higher current it withstands for short periods of time (10 ��������������).

Since, the maximum current flow in our designed propulsion system is 10 ��, the ESC should handle at least 10 A. As a matter of safety, to prevent the system from burning out, generally ESC of rating of 20 − 30�� was selected. Larger ESC also generates less heat as compared to small one and thus providing higher efficiency.

Along with ESC, Battery eliminator circuit (BEC) should be used to cut-off the voltages for elevator and rudder servos.

**8.8 Final Propulsion Configuration**

The final propulsion system configuration based on the above analytical calculation were cross checked and compared with online calculators that finds the best match of Motor, Propeller, ESC and battery. Then, on the basis of its availability in local market and its cost the final configuration was selected.

The final configuration of propulsion system satisfying above requirement is shown in table 13.

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*Table 13: Final configuration of propulsion system*

| **Brushless Motor** | | | | |
| --- | --- | --- | --- | --- |
| EMAX 1400KV Brushless Moto | KV rating | Voltage range | Power range | Weight |
| 1400 KV | DC 8-12 V | 95.2-247.2 W | 52 grams |
| **Brushless Propeller** | | | | |
| EP 1147  Propeller | Diameter | Pitch | Material | Shaft  Diameter |
| 11 inches | 4.7 inches | Plastic | 3.2 mm |
| **LIPO Battery** | | | | |
| 5000 mAh  LIPO Battery | C-rate | Rated capacity | Size (mm) | Weight |
| 25 C | 10000 mAh  (3s) | 36 × 59  × 170 | 442 grams |
| **ESC** | | | | |
| Sky Walker 40A ESC | BEC | Output Amp. | Burst | Weight |
| 2A/5V | 40 A  continuous | 40A /10 secs | 37 grams |

**8.8 Basic Propulsion and electronic system schematic Diagram** The basic wiring of the important part is shown in figure 67.

BATTERY

MOTOR ~~~~ESC

RECEIVER

*Figure 67: Basic propulsion and electronic system*

**8.9 Other Electronics Used:**

**Servo Motor:**

Servo Motor is used when it is required to rotate or move with great precision. In fixed wing UAV, servos are used to rotate the control surfaces (elevator, rudder, aileron,

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flaps). They can also be used to release the payload and to control landing gear precisely. These servos are connected with receiver and then controlled through transmitter’s stick. Altogether eight servos are used in our design; two for ailerons, two for rudders (twin tail), one for elevator, one for landing gear, one for payload release mechanism and one for opening door during payload release.

**Transmitter:**

Transmitter is hand-held controller with joysticks, knobs and switches in it that takes the user input and transmits wirelessly to the UAV’s receiver. Transmitters have programming functionality which allows custom mixing and adjusting the channels. **Receiver:**

Receiver is small electronic component integrated with UAV that receives transmitter’s signals, interprets it and control the components in the UAV accordingly. Receivers are mainly used to control the servos and to control the speed of motor through ESC. The receiver used in Munal M-72 is powered through ESC with integrated BEC. The transmitter and receiver used to control Munal M-72 is FlySky FS-i6 2.4GHz

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**CHAPTER NINE: FABRICATION**

After complete design and analysis, the fabrication of Munal M-72 was started. Plywood (density 534 kg/m^3) was used instead of the balsa wood as the latter was not shipped in 2 months procurement period. The fuselage components, ribs and spars of the wing and empennage were laser cut. Polyurethane foam was used wherever it was required to give the shape and then covered with tape to provide smooth finish. The details of fabrication of each part is described below:

*Figure 68: Laser cut parts*

*Figure 69: Hot wire setup*

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