# Design and Analysis of Ultra-Light Weighted STOL Aircraft

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***Abstract*** *- The design of Unmanned Arial Vehicle (UAV) is unique at various aspects from conventional aircraft design. Tremendous variation of mission requirements (i.e. user requirements) from military to civil usage makes it almost impossible to adopt a specific design philosophy. Rather, the design is driven by the individual mission targets and optimizing between them. Following by the approximation of a best fitted configuration, a smart starting design point selection is crucial for a successful design. After that multi-disciplinary optimization (MDO) is initiated and expected performance parameters are evaluated to check their relevance to the requirements. This iterative process is continued until the design converges to a best feasible solution. The above steps of aircraft design are covered during aircraft conceptual and preliminary design phase and a successful completion follows the detail design. This paper represents the conceptual and preliminary design of an UAV named "SB-02" manufactured by the team "DREAMERS' FIN" during 17th annual DBF competition.*

## 1. INTRODUCTION

An aircraft design is a separate discipline of aerospace engineering which is both an art and science. The design of aircraft draws on a number of basic areas of aerospace engineering including aerodynamics, propulsion, stability & control etc. Each of these areas involves parameters that govern the size, shape weight and performance of aircraft. Aircraft design philosophy deals with three split phases [1] viz. conceptual, preliminary and detail design. In the conceptual design the basic questions of configuration attachment, size and weight, and performance are answered. During preliminary design the specialists in areas such as structures, landing gear and control system will design and analyze their portion of the aircraft. At last detail design phase begins in which the actual pieces to be fabricated are designed and also focus on design verification and formal approval or acceptance of the designs, prototype manufacture and testing. Following these aircraft design phases the authors have designed a light and short take-off and landing Aircraft for specific missions. After completion of the conceptual and preliminary design an optimized design was proposed. The final design was a high wing monoplane with conventional tail, single tractor propulsion system and a tail dragger landing gear. The design iterations ended with a low wing loading, high lift coefficient and a moderate thrust to weight ratio. This combination leads to the short take-off capability of the aircraft. A careful wing and fuselage design allowed sufficient payload capability. Overall geometry was designed to generate less drag to make the aircraft fly as a fast as possible. Thus, a nearly perfect design to meet all the mission requirements was obtained.

### *1.1 Objective of The Project*

The primary objective of designing a "Ultra-Light Weighted STOL [2] Aircraft" was to participate the 2012-2013 AIAA/Cessna/RMS Student Design/Build/Fly Competition [3] on behalf of Military Institute of Science and Technology. The entire process was totally challenging from the staring date. This year's competition simulates a joint strike fighter [4] accomplishing three different missions. The first mission is short take-off, in which the objective is to fly maximum number of laps within 4 minutes. Second is the stealth mission, where the aircraft has to fly 3 laps with maximum possible internal payload. The last one is the strike mission, where the aircraft takes random payloads and complete three laps as fast as possible. At all missions the aircraft must take-off within 30 ft. and land safely. A careful analysis revealed lowest rated aircraft cost (RAC) as the primary design objective. It has been determined to build an aircraft with minimum RAC that can fly fast, fly with maximum payload and take-off within the marked area of 30 x 30 feet square at all missions.

### *1.2 Purpose of the Paper*

This paper represents the early stage of aircraft design where the initial configuration of the aircraft was to be determined. A rough sketch of the aircraft overall configuration was prepared without any detail of the actual geometry. Mission requirements functioned as the motivating force for the conceptual design. A precise understanding of the mission requirements was instigated at the early stage of initial design, which was followed by a careful translation of mission requirements into design requirements. Several configurations for the aircraft was proposed based on the requirements and a final configuration was selected comparing their merits on different features.

## 2. REQUIREMENTS

### *2.1. Aircraft General Requirements*

General requirements of the aircraft are:

- Aircraft must be AMA legal.
- The aircraft may be of any configuration except rotary wing or lighter than air.
- Aircraft must be designed to be capable of performing all required missions.
- Maximum battery packs(s) weight for propulsions 1.5lb.
- 20Amp fuse limit.
- 5 minutes limit to load the pay load and check out the aircraft system as fully functional.
- Aircraft must take off with in a 30X30 ft. square marked on the runway.
- Must land successfully to get a score.

### *2.2. Mission Requirement*

After the completion of the preceding mission, the Aircraft can be proceeding further for the next mission. A maximum f4 flight attempts can be taken to complete the three missions. Every mission requires stake-off within the prescribed are and a successful landing. In this mission one, the aircraft will take-off within the 30ft*30ft prescribed area & fly with its empty weight. Mission two is a three lap flight with internal payload stores. Payloads must be carried internally with the aircraft in the main fuselage or completely inside the wing. Mission Three is a three lap flight with mixed payload stores, where payload will be a random draw of internal and external stores.

### *2.3. Flight Course Layout*

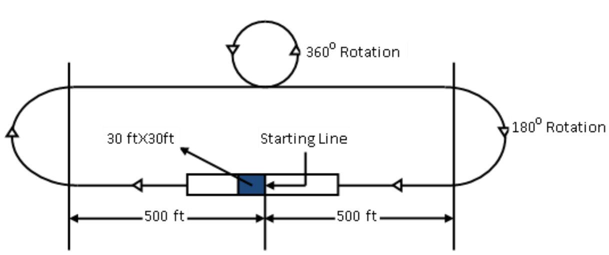



**Fig 1- Flight Course layout shown in scale**

### *2.4. Design Requirements Derived from Mission Requirements*

The main objective was to design a light aircraft with a minimum size factor which can safely accomplish the third mission within the possible fastest time, fly the second mission with maximum possible payload and complete maximum number of laps within 4 minutes in the first mission. The constraints of the respective mission derived the design requirements which are tabulated below.

**Table 1. Translation of Mission Requirements into Key Design Requirements**

| Mission Requirements | Design Requirements |
|---|---|
| Short Take-off (30ftX30ft square area) | High Static Thrust.<br>Low Stall Velocity.<br>Low wing loading. |
| High Airspeed | Minimize parasite drag.<br>Sufficient thrust at high airspeed. |
| High Turn Time | High load factor.<br>Enough thrust to assure sustained turn. |
| High Payload Capability | Large payload compartment.<br>High lift-ability. |
| Stable Flight | Adequate static and dynamic stability. |

## 3. SOLUTION CONCEPTS

Several configurations for the aircraft were abstracted. Finding out the suitable configuration which can best meet the design requirements was done comparing the competitive configurations. Different features of the individual configurations were converted to a mathematical parameter weighted on their efficiency and capabilities. Again these distinct features were weighted based on their importance to achieve design requirements. A scale factor from 1 to 7 was followed for the weighting schedule to assess different configurations. The value "7" signified the most important and"1" the least important.

### *3.1. Aircraft Configuration: Monoplane*

Mono plane is the most conventional practice in the aviation sector. Better aerodynamic characteristics and design simplicity makes it as the best choice for the overall design solution. A comparison of several aircraft configurations have been shown in tabular form in below.

**Table 2. Aircraft Configuration Selection**

| **Figure of Merit** | **Weight** | **Monoplane** | **Biplane** | **Canard** | **Flying wing** |
|---|---|---|---|---|---|
| RAC | 7 | 4 | 5 | 4 | 7 |
| Payload Capability | 5 | 5 | 6 | 5 | 3 |
| L/D | 4 | 6 | 5 | 3 | 7 |
| Stability & Control | 3 | 6 | 4 | 7 | 3 |
| Manufactur-ability | 3 | 6 | 4 | 5 | 3 |
| Total | - | 113 | 109 | 101 | 110 |

*3.2. Component Layout*

*3.2.1. Propulsion: Single Tractor*- Single tractor propulsion system is comparatively light weight and of better propeller efficiency. Although the possibility of certain aerodynamic inefficiencies remains due to the slip stream of the propeller, the system can be considered the most effective one.

**Table 3. Propulsion Selection**

| Figure of Merit | Weight | **Single Tractor** | **Single Pusher** | **Twin-Tractor** |
|---|---|---|---|---|
| Weight | 7 | 6 | 5 | 2 |
| Thrust | 5 | 4 | 4 | 6 |
| Efficiency | 2 | 6 | 5 | 2 |
| Aerodynamics | 2 | 5 | 6 | 2 |
| Total | - | 84 | 77 | 52 |

*3.2.2. Empennage: Conventional*- Conventional tail can provide adequate stability and control at the lowest weight. Although, it may suffer from the wake effect of the wing, but a suitable positioning of the conventional tail can best meet the desired requirements.

**Table 4: Empennage Configuration**

| Figure of Merit | Weight | **Conventional** | **T-Tail** | **V-Tail** |
|---|---|---|---|---|
| Weight | 7 | 6 | 3 | 6 |
| Efficiency | 5 | 5 | 6 | 4 |
| Drag | 3 | 4 | 5 | 5 |
| Total | - | 79 | 66 | 77 |

*3.2.3. Landing Gear: Tail-Dragger*- Tail-dragger gear provides higher propeller clearance, has less drag and weight, and allows the wing to generate more lift for rough field operation than the tricycle gear. Main disadvantage of tail-dragger is that it is inherently unstable. With the assist of an efficient pilot team, the tail-dagger was considered as the best solution.

**Table 5. Landing Gear Selection**

| Figure of Merit | Weight | **Bicycle** | **Tail-dragger** | **Tricycle** |
|---|---|---|---|---|
| Weight | 7 | 7 | 5 | 4 |
| Ground Handling | 5 | 1 | 5 | 6 |
| Drag | 3 | 6 | 5 | 4 |
| Total | - | 72 | 75 | 70 |

*3.3. Overall Conceptual Configuration*

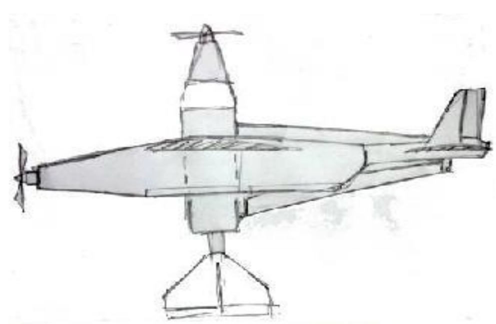


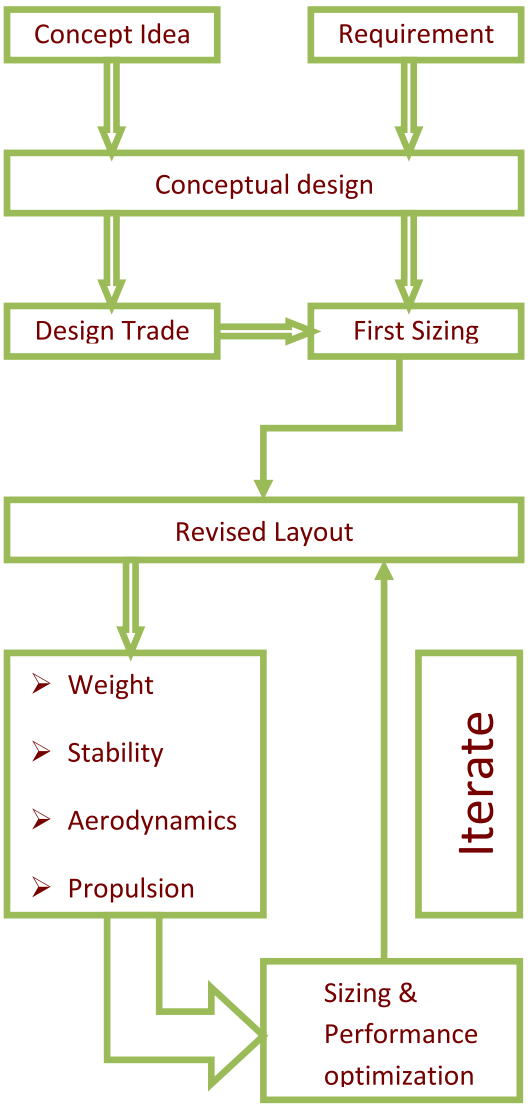
**Figure 2- Conceptual Design**

## 4. PRELIMINARY DESIGN

Following the conceptual phase the preliminary design process starts with the initial airframe sizing. Aerodynamics, propulsion, stability and control and structures are evaluated for every individual design iterations and continues till convergence to a desired point.

*4.1. Airframe Design and Analysis Methodology*

A close loop optimization process was followed during preliminary design. First iteration started with the concept idea developed during conceptual design and initial approximated airframe parameters based upon the design trades. Individual design parameters were used as an input and the performance result was monitored to explore any further improvements. If improvements were monitored at any point, then the next iteration was started from that point.




*4.2. Design Trades*

We adopted the philosophy to define a starting design point as a function of mission parameters. Several curves were plot to generate a design area and a design point was selected from that area considering minimum weigth and size factor (SF).

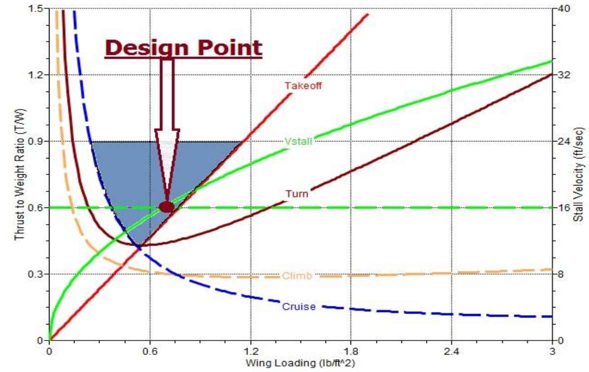



**Fig 3- Design Trades**

An approximated stall velocity of 1**6ft/sec** derived the design point of wing loading around **0.615lb/ft$^2$** and thrust to weight ratio around **0.6**.

*4.3. Airfoil Selection*

*4.3.1. Wing Airfoil-* Effect of lift coefficient on the wing loading for the take- off during mission 3 was analyzed to predict a required lift coefficient for a predefined wing-loading.

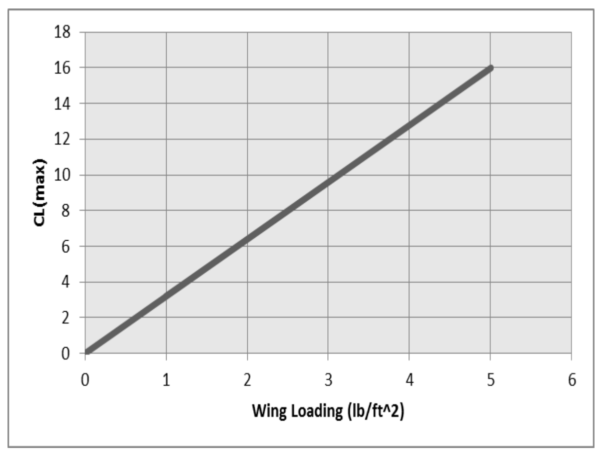



**Fig 4- Effect of CL$_{max}$ on wing-loading.**

Simultaneously, effect of lift coefficient on stall velocity for various wing-loadings was also analyzed for a better understanding of the required lift coefficient.

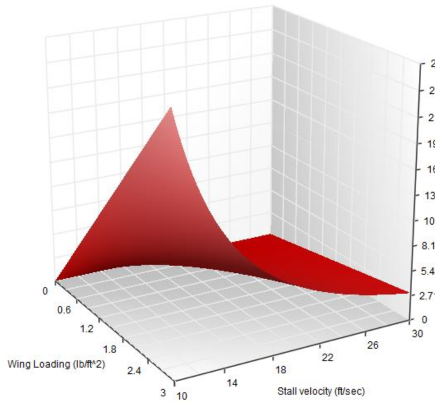



**Figure 5- Effect of $CL_{max}$ on stall velocity for different wing loadings.**

Both the graph influence the team to select an airfoil which will be capable of generating a 3-D lift coefficient of around 2 with some flap deflection. As a result the team searched for airfoil having lift coefficient more than 2.2, while considering some other important aspects follows:

- Drag polar
- Stall characteristics
- Pitching moment coefficient
- Manufacturability

After initial quick review four airfoils were shortlisted for further detail analysis at different flight condition (i.e. different Reynolds number). Javafoil and XFOIL were used to analyze the airfoil. Analyzed airfoils were:

CH10(smoothed)
E423
S1223
WORTMAN FX 63-137

**…………**

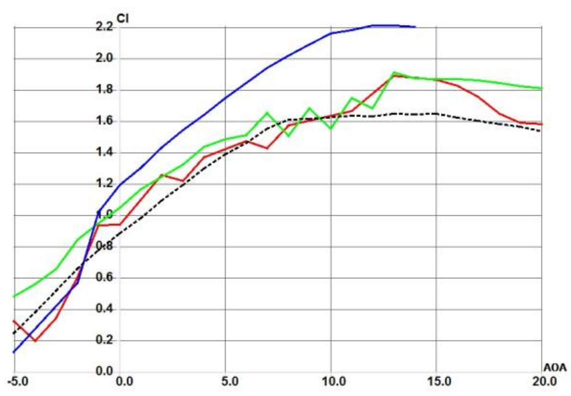



**Figure 6-XFLR5 analysis of lift curve. (Re no: 180,000)**

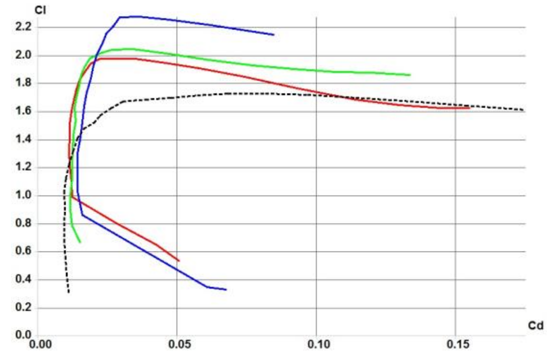



**Figure 7- XFLR5 analysis of drag polar. (Re no: 500,000)**

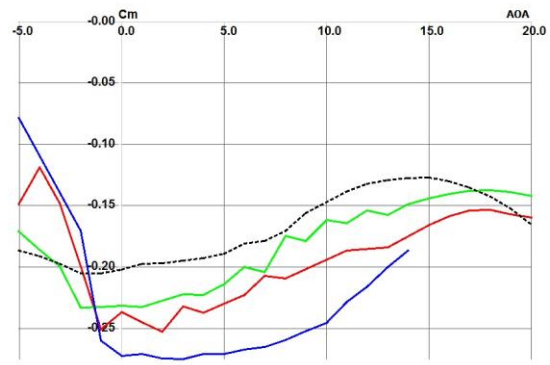



**Figure 8-XFLR5 pitching moment analysis at takeoff condition. (Re no: 180,000)**

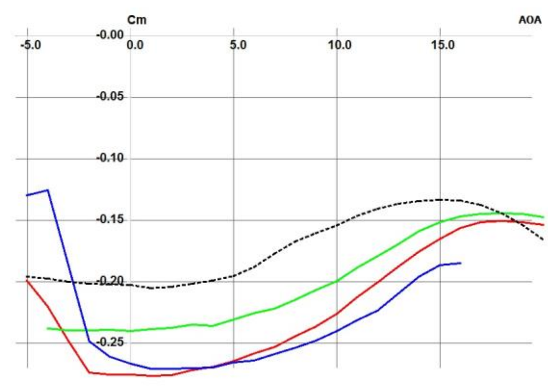



**Figure 9-XFLR5 pitching moment analysis at cruise condition. (Re no: 500,000)**

A figure of merit table was made on the basis of the analysis to find out the best foil for the wing. Various performance parameters of the airfoil were weighted from 1 to 7 based on their importance.

**Table 6. Airfoil Selection**

| Parameters | Weight | CH10sm | E423 | S1223 | FX 63-137 |
|---|---|---|---|---|---|
| $Cl_{max}$ | 7 | 6 | 6 | 7 | 5 |
| (L/D) | 4 | 5 | 6 | 5 | 4 |
| Cl@ $(L/D)_{max}$ | 3 | 6 | 6 | 7 | 3 |
| Stall characteristics | 3 | 4 | 5 | 4 | 7 |
| Manufacturability | 3 | 5 | 5 | 2 | 3 |
| $-dC_m/d\alpha$ | 2 | 3 | 4 | 4 | 4 |
| Total | - | 113 | 122 | 116 | 98 |

Finally the table showed **E423 [**[11] was the best airfoil for the wing which will be able to generate desired amount of lift with good aerodynamic performance.

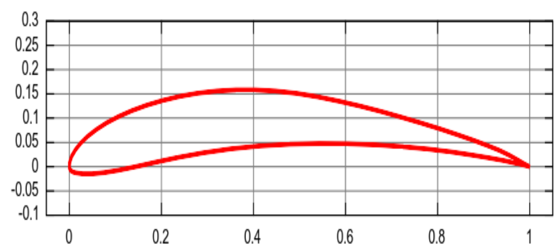



Figure 10: Chosen airfoil for wing (E423).

*4.3.2. Empennage Airfoil* - For simplicity and weight reduction, flat plates were used for horizontal and vertical stabilizer with a curvature shape at the leading edge and sharp edge at the trailing end.

*4.4. Aerodynamic Performance Estimation*

The aerodynamic performance estimation was started from estimating the parasite drag coefficient or zero lift drag coefficient of the aircraft. Raymer's "Component Buildup Method" [1] was applied to estimate the parasite drag. A spreadsheet file named parasite_drag.xlsx was used to estimate the parasite drag from stall to maximum velocity condition. After that another spreadsheet file named CL_CD.xlsx was used to estimate the total drag [12] coefficient and lift coefficient of the aircraft for all the missions and these data were used to plot the drag polar[13] of the aircraft.

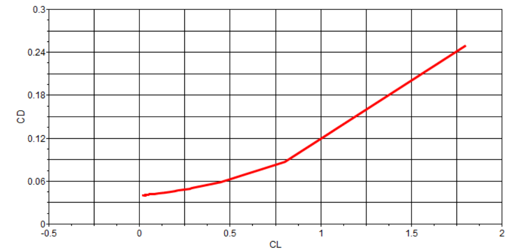



**Figure 10- Mission 1 drag polar.**

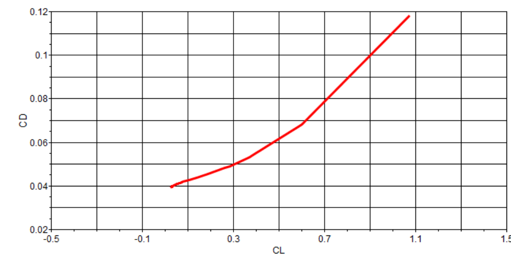



**Figure 11- Mission 2 drag polar.**

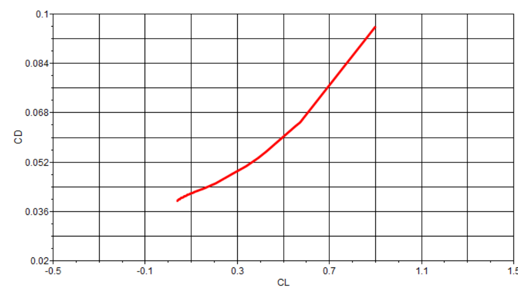



**Figure 12- Mission 3 drag polar.**

Drag and lift coefficient of the aircraft for maximum velocity of mission 1, cruise velocity of mission 2 and cruise velocity of mission 3 are tabulated as below.

**Table 7.Aerodynamic Estimation of Each Mission**

| **Components** | **Mission one** | **Mission Two** | **Mission Three** |
|---|---|---|---|
| $C_{D0}$ (Wing) | 0.0202 | 0.0205 | 0.0207 |
| $C_{D0}$ (Fuselage) | 0.0147 | 0.0162 | 0.0172 |

| | | | |
|---|---|---|---|
| $C_{D0}$ (Stabilizers, landing gears, pylons, Interference ) | 0.0087 | 0.0092 | 0.0095 |
| Total $C_{D0}$ | 0.0437 | 0.0459 | 0.0474 |
| $C_L$ | 0.1680 | 0.6001 | 0.7560 |
| Total $C_D$ | 0.0454 | 0.0681 | 0.0827 |
| $C_L/C_D$ | 3.7 | 9 | 9.1 |

*4.5. Stability & Control*

The aircraft is to be designed in such a way so that it should remain stable in every flight condition and has sufficient control power to perform necessary maneuvers. The major parameters which affect the stability and controllability of the aircraft are static margin and tail plane geometry. Static margin is chosen such that it will give sufficient stability as well as comparatively smaller tail volume co-efficient will be enough to provide sufficient controllability. A static margin of 8% is chosen for mission one, 5% for mission two and 4% to 5% for mission three. Tail Plane's primary function is to ensure longitudinal and directional stability. Design books were followed to design the tail plane to assure desired characteristics.

*4.5.1. Control Surfaces*- Elevator is used to modify tail lift and hence pitching moment of the aircraft. After analyzing, 30% chord of the horizontal tail was made as elevator which is sufficient enough to trim the aircraft in every flight condition. Rudder was sized as 40% chord of the vertical tail using suggested values from Roskam [14] and Raymer [1]. It was sufficiently large to produce required yawing moment to move the aircraft in required direction in both air and ground. At every mission aircraft will require less lateral controllability. That's why Flaperon was used which also saves aircraft weight.

*4.5.2. Stability and Control Derivatives* - To ensure dynamic stability, the aircraft aerodynamic stability derivatives were estimated using equations from Etkin [15].

**Table 8. Stability and Control Derivatives**

| **Alpha derivative** | | **Roll rate derivative** | |
|---|---|---|---|
| $C_{M\alpha}$ | -0.009 | $C_{Lq}$ | 0.071 |
| $C_{L\alpha}$ | 0.084 | $C_{Mq}$ | -0.160 |
| **Control surface derivatives** | | | |
| $C_{L\delta e}$ | | 0.0133 | |
| $C_{M\delta e}$ | | -0.0300 | |
| $C_{L\delta f}$ | | 0.0450 | |
| $C_{M\delta f}$ | | -0.0080 | |
| $C_{\ell\delta r}$ | | -0.00046 | |
| $C_{n\delta r}$ | | -0.0028 | |

*4.6. Aircraft Mission Performance Estimation*

Flight theory [16] was used to estimate the performance and tabulated as below.

**Table 9. Estimated Mission Performance**

| **Mission performance Parameters** | **Mission One** | **Mission Two** | **Mission Three** |
|---|---|---|---|
| Gross Weight (lb) | 3 | 4 | 6 |
| Takeoff Distance (ft) | 7.5 | 13.33 | 29 |
| Stall Velocity (ft/sec) | 13.7 | 16.84 | 25 |
| Cruise Velocity (ft/sec) | 45 | 34 | 30 |
| Number of Laps | 4 | - | - |
| Total Lap Time (minutes) | - | - | 5.5 |

## 5. PROPOSED DETAIL DESIGN

At this design stage, detail dimension of the aircraft, system integration and optimization and overall assembly of the aircraft was decided. Priority was given to some specific features while initiating the progression, which are Simple design. Light structure, Swift manufacturability.

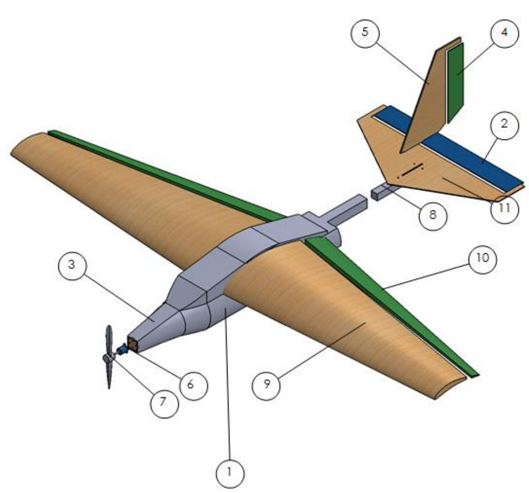



**Fig 13- Proposed Detail Design Drawing**

1. Fuselage
2. Elevator
3. Nose
4. Rudder
5. Vertical stabilizer
6. Motor
7. Propeller
8. Tail-boom
9. Left wing
10. Flaperon
11. Horizontal stabilizer

**Table 10. Aircraft Dimensional Parameters**

| | | | |
|---|---|---|---|
| **Wing** | | | |
| Airfoil | | E423 | |
| Area | | 7.988 ft2 | |
| Span | | 6.92 ft | |
| Root Chord | | 19.78 in | |
| Tip Chord | | 7.91 in | |
| Aspect Ratio | | 6 | |
| Taper Ratio | | 0.4 | |
| $\Lambda_{1/4}$ | | $0^o$ | |
| **Flaperon** | | | |
| Span | | 6.92 ft | |
| % of Chord | | 20 | |
| $\delta_a$ | | $\pm 25^o$ | |
| **Horizontal Stabilizer** | | **Vertical Stabilizer** | |
| Area | 252.5 $in^2$ | Area | 114.2 $in^2$ |
| Span | 27.7 in | Span | 13.85 in |
| Root Chord | 13 in | Root Chord | 11.8 in |
| Tip Chord | 5.2 in | Tip Chord | 4.7in |
| **Elevator** | | **Rudder** | |
| Span | 27.7 in | Span | 13.85 in |
| % of Chord | 30 | % of Chord | 40 |
| $\delta_e$ | $\pm 25^o$ | $\delta_r$ | $\pm 25^o$ |
| Fuselage | | | |
| Length | | 37.42 in | |
| Width | | 7 in | |
| Height | | 7.6 in | |

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## 6. CONCLUSION

Raymer's "Component Buildup Method" was used to estimate the parasite drag which is actually based on semi-empirical theory and therefore the precision is limited. Both XFOIL and Javafoil admit their limitations to some extent to predict the foil characteristics accurately. Advance CFD analysis could give more precise estimations. During performance analysis propulsion data (i.e. thrust) was obtained from Javaprop and later it was found not relevant to experimental value. Stability and control derivatives were derived from the theory of Etkin's "Dynamics of Flight: Stability and Control". Use of advance software (e.g. AVL) should provide a better understanding of the stability and control performance. Performance estimation also involves the limitation, due to the rough estimation of weight. Generally, a better empty and gross weight estimation are done during detail design, which allows a better estimation of performance. Having all the limitations in mind the authors still believe that the proposed preliminary design should be considered as one of the best solution which can be confidently passed to the detail design phase.

## REFERENCES


[1] Raymer,D.P (2006), Aircraft Design: A Conceptual Approach (4TH edition), Washington, DC, AIAA, Inc.

[2] Chris Heintz," ANATOMY OF A STOL AIRCRAFT: Designing a Modern Short Take-Off and Landing Aircraft" ZENITH AIRCRAFT COMPANY, Mexico Airport, Mexico, Missouri.

[3] AIAA Design/Build/Fly Competition – 2012/13 Rules", 31 October, 2012, http://www.aiaadbf.org/2013_files/2013_rules.htm .

[4] Wikipedia" http://en.wikipedia.org/wiki/Strike_fighter" .

[5] UIUC Airfoil co-ordinate Database

http://www.ae.illinois.edu/m-selig/ads/coord_database.html .

[6] MichaelS. Selig, James J. Guglielmo, Andy P. Broeren and Philippe Giguere ,"Summary of Low-Speed Airfoil Data ", SoarTech Publications ,Virginia Beach, Virginia.

[7] Michael S. Selig and James J. Guglielmo, "High-Lift Low Reynolds Number Airfoil Design ", JOURNAL OF AIRCRAFT Vol. 34, No. 1, January- February 1997.

[8] Airfoil Investigate Database http://www.worldofkrauss.com

[9] Java foil

[10] XFLR5

[11] Airfoil Investigation Database (AID)," http://www.airfoildb.com/foils/1280 ".

[12] Hoerner,s. ,"Fluid Dynamic Drag", Published by Author,1958.

[13] Roskam,J. "Methods for Estimating Drag Polar of Subsonic Airplanes", Published by Author, 1971.

[14] Roskam,J. ,"Airplane Design", Roskam Aviation and Engineering Corp. Ottawa, KS, 1985.

[15] Bernard Etkin," Dynamic of Flight: Stability and Control."

[16] Anderson J.D (2005), "Introduction to Flight", Tata Mcgraw Hill.