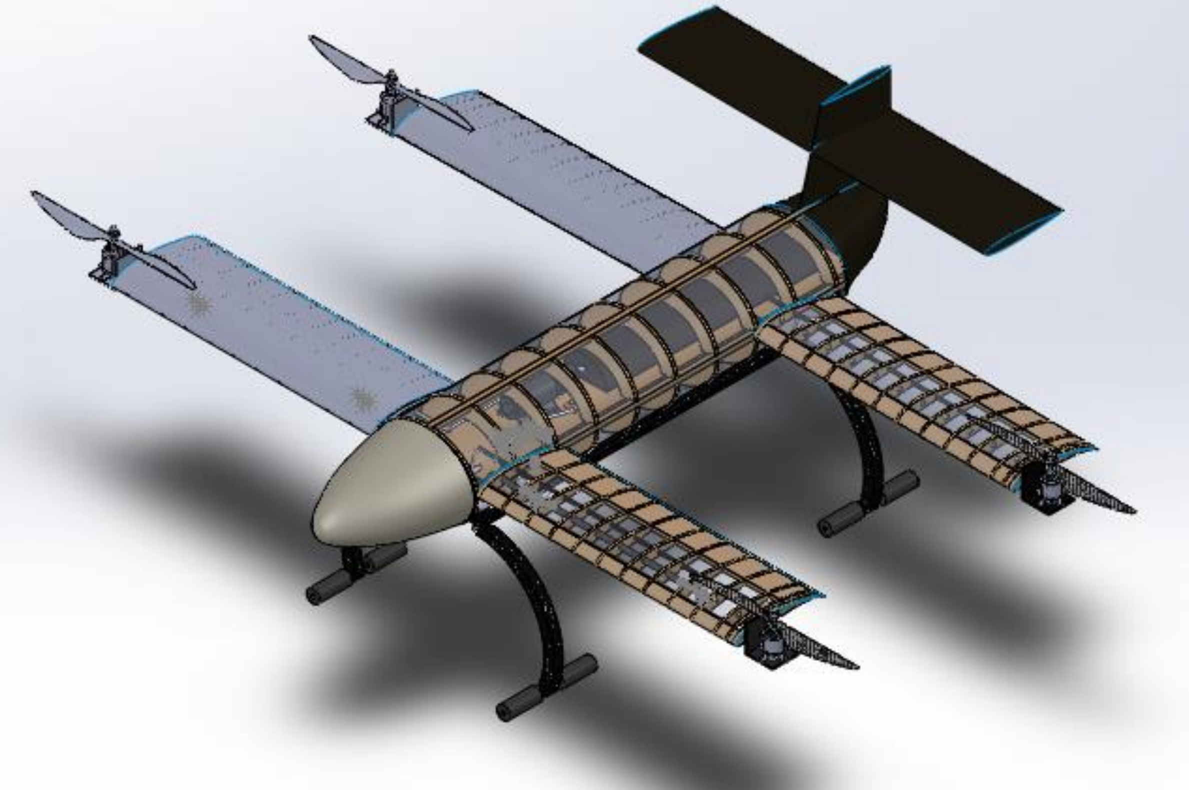

# Unmanned Aerial System (UAS) Challenge Pakistan 2022


National University of Sciences and Technology


Critical Design Report – *The Hive*

**Team Members**

| Name | University | Major | Standing |
|---|---|---|---|
| Sarah Naeem – Team Lead | NUST H-12 | Mechanical Eng. | Sophomore |
| Jawad Akbar | NUST H-12 | Mechanical Eng. | Sophomore |
| Hamza Hussain | NUST H-12 | Mechanical Eng. | Sophomore |
| Syed Muhmmad Hassan Kazmi | NUST H-12 | Mechanical Eng. | Sophomore |
| Ahmed Bin Mushtaq | NUST H-12 | Electrical Eng. | Sophomore |
| Muhammad Hassaan Ghazali | NUST H-12 | Electrical Eng. | Sophomore |
| Ali Khalid | NUST H-12 | Electrical Eng. | Sophomore |
| Muhammad Saad Bin Tariq | NUST H-12 | Geo Informatics Eng. | Sophomore |
| Muhmmad Adeel | FAST NUCES -Isl | Computer Sci. | Sophomore |
| Syed Muaz Ashrafi | NUST -H12 | BS. Economics | Junior |

Kashif

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Sarah

Signature of Compiler – Sarah Naeem
Team Lead – The Hive

# Table of Contents

# List of Figures

# List of Tables

# 1. Summary of CDR Report

## 1.1. Proposed Design

This novel design includes a quad tiltrotor fixed-wing UAV configuration with each rotor attached at the ends of the four wings. With a wingspan of 1.44m and a fuselage length of 1.55m, the UAV has a mass of 4 kg, with a capacity of 3kg for pesticide carriage. The maximum spraying capacity of the drone is 3.5L/min.

With a full payload, it can cruise at 15ms$^{-1}$ consuming only 84 Watts for propulsion. The drone can fly at 30ms$^{-1}$ (max. airspeed for the required mission) with rotors burning only 452 Watts. The UAV can achieve a 55ms$^{-1}$ airspeed (not employed in the current mission) with its 12.5kg maximum thrust.

The spraying mechanism includes two types of nozzles for spraying and misting to maximize spray quality and reduce pesticide consumption per acre. The pump has a BLDC motor for controllable flow and a maximum pressure of 1MPa at 40 Watts power consumption.

Selig S1210 & S1223 are used as front & rear wings airfoils giving the optimum lift-to-weight ratio of wings.

This report provides a thorough analysis and calculation of the drone's mission performance, manufacturability, procurement, and mitigation of all possible safety hazards. This UAV is capable of:

- Stable flight in vertical mode due to widely spaced rotors from the fuselage
- Powerful horizontal flight via thrust from all four rotors positioned horizontally
- Stable transition in flight modes due to variable tilting angles of rotors

Compared to typical fixed-wing and multi-rotor configurations, this configuration produces optimum results as an agriculture UAV for the required mission profile. Comparison with other configurations results in:

- 5.5 to 6 times more power efficient in horizontal cruise than multi-copters. i.e., suitable for spray zones far away from Ground Control Station (suitable for the longest route of 4km in mission)
- Higher precision in spraying than fixed-wing configuration due to capability of hovering, gliding, and staying at transition state while spraying
- More stable hovering and spraying than its parent configuration quad plane

| | |
|---|---|
| **Team Name** | The Hive |
| **Review Items** | Refer below to section 1.2. |
| **Changes since PDR** | |
| **Change** | **Reason** |
| The High wing configuration is replaced with a mid-wing configuration. | Allows for easier to manufacture detachable wings and to reduce lift generation. |
| Aft conventional tail type is replaced with cruciform aft tail configuration. | Greater wake generation would negatively effect vertical stabilizer of conventional tail |
| TMotors MN5008 are replaced with EMAX GT-2826 KV860 | Tmotors are not available locally, and the team changed it to EMAX due to temporary import restrictions |
| 6S Battery is replaced with 4S | EMAX GT-2826 KV860 requires a 4S Battery |
| **Supervisor** | Dr. Kashif Javed – Assistant Professor at SMME |
| **Team Lead** | Sarah Naeem |

*Table 1. Summary chart for CDR*

## 1.2. Payload & Mission summary

The UAV will carry the load at its maximum capacity, i.e., 3kg. It will follow the longest route of 4km towards the spraying zone at a cruise speed of $15ms^{-1}$, ideally consuming 266 seconds and 7.75Wh energy. The UAV will cover the complete spray zone in 118-125 seconds, following its optimal path for the least time consumption, consuming 32Wh energy. UAV will then cruise back to landing at $10.7ms^{-1}$, consuming 47 seconds and 0.65Wh energy. Hence, including 3 seconds of takeoff & 5 seconds of landing, and a transition time of 1.7 seconds, UAV will complete the mission in 441-455 seconds using the optimum energy consumption approach. It is adopted in this mission since time is not an issue and completing the mission before 10 minutes does not end up in bonus points. However, in real-world scenarios in an emergency, this UAV can complete the same mission in <290 seconds with only 28% more power consumption. Details are provided in the Engineering Analysis part.

# 2. Project Management

## 2.1. Progress Review

As the preliminary design review mentioned, the team is subdivided into groups for more accessible communication and effective workload distribution. The previous division has been revised since and is given in table 1.2

| Sr # | Designation/subgroup | Name(s) | Assigned tasks and roles |
|---|---|---|---|
| **3.** | Mechanical design | • Hamza Hussain<br>• Jawad Akbar<br>• Sarah Naeem<br>• Syed Muhammad Hassan Kazmi | • Aerodynamic Analysis<br>• Structural and stress analysis<br>• CAD model<br>• Airframe manufacturing and material selection |
| **4.** | Electrical Circuitry | • Ali Khalid<br>• Muhammad Hassaan Ghazali | • Propulsion system design<br>• Electrical component selection<br>• Battery performance analysis |
| **5.** | Spraying Mechanism | • Muhammad Saad bin Tariq | • Spraying mechanism selection<br>• Selecting suitable pump, nozzles and supporting components<br>• Spray tank design and manufacturing |
| **6.** | Business Model | • Syed Muaz Ashrafi | • Outreach<br>• Industry support and collaboration<br>• Business model |
| **7.** | Control & Computing System | • Ahmed bin Mushtaq<br>• Muhammad Adeel | • Control and computing system design<br>• Selecting supporting hardware |

*Table 2.1.1. Team Division and description*

The workflow in Figure 2.1.2. shows task division from the PDR up to manufacturing and is divided according to the groups mentioned in Table 2.1.1.

A team tracker on the Google Drive Shared folder tracks the progress & timeline of each team till the CDR. Figure. b.b.b shows a part of The Hive Tracker.

All files in the project, including CAD models, reports, simulations, and source codes, are managed on Google Drive & GitHub repository [1] shown in Figures 2.1.3 & 2.1.4, respectively.

Moreover, the team conducted weekly joint team meetings, occasional team meetings with the faculty advisor and regular meetings of different groups to ensure timely completion of work and maintenance of the Project Progress tracker. Communication is done via MS Teams for meetings, WhatsApp groups for regular updates and Emails for notifications & announcements.

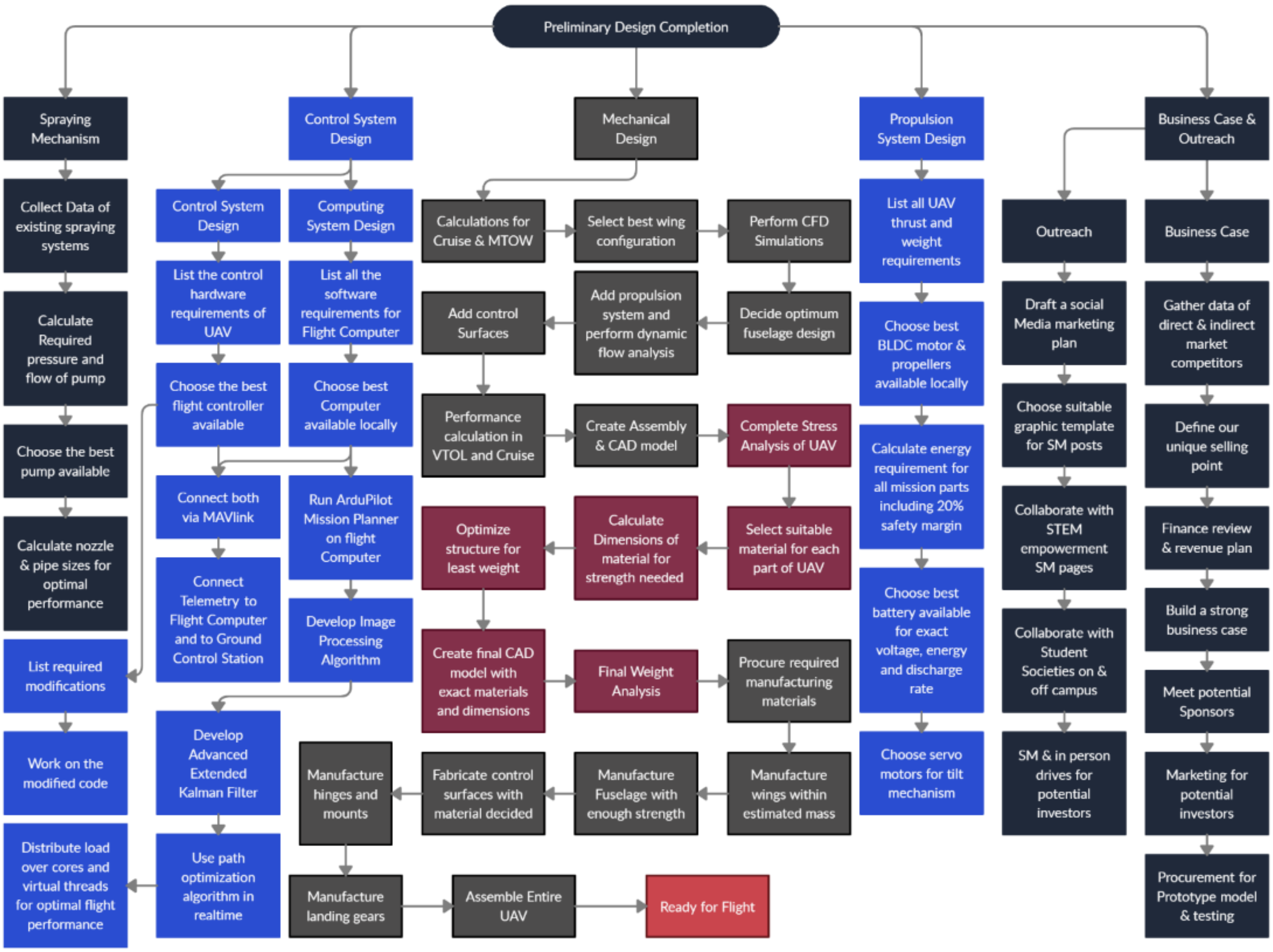


*Figure 2.1.2. Project Workflow after PDR*

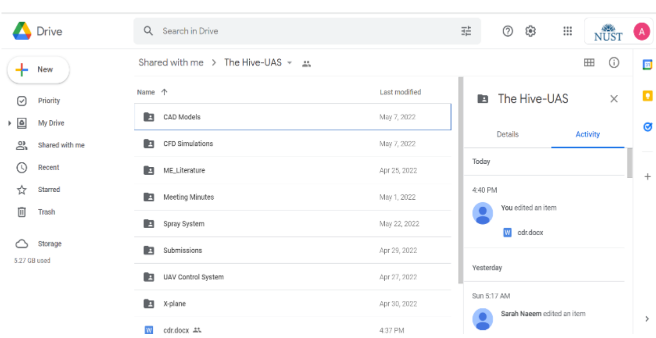


*Figure 2.1.3. Shared Google Drive Folder.* [2]

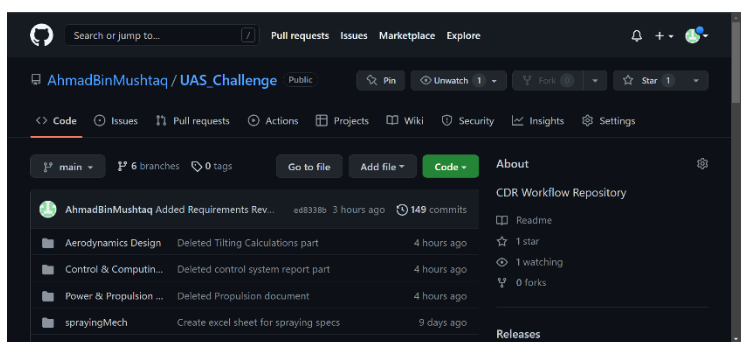


*Figure 2.1.4. Shared Google Drive Folder.* [2]

## 2.2. Summary of Project Resources, Manufacturing and Risks

| Project Part | Human Resource | Other Resources | Procurement | Manufacturing/ Development | Risks | Mitigation |
|---|---|---|---|---|---|---|
| **Spraying Mechanism** | Saad bin Tariq | None | Nozzles, Pump, Pipes and connectors | Optimized spray tank | Leakage, nozzle blockage, unavailable fluid to inflow. | Sump tank, nozzle filters and good connectors. |
| **Flight Control System** | Ahmad bin Mushtaq | ArduPilot source code, Pixhawk 2.4.8 | Open-source software + local available hardware | Fork the ardupilot repo and develop & compile firmware locally | Malfunctioning custom firmware | Continuous trial & error on in real-time flight |
| **Computing System** | Muhammad Adeel | Dronekit-python source code, Pytorch, Numpy | Open source | Fork the repo, develop according to needs and use them | Malfunctioning custom firmware | Continuous trial & error on in real-time flight |
| **Aerodynamic Design** | Jawad Akbar | ANSYS Fluent 2022 | NA | Design revaluation in case of unstable flight | Unfavorable lift/drag generated during flight. | Thorough CFD simulation and performance calculations. |
| **Structure Design & Stress Analysis** | Hamza Hussain Sarah Naeem | ANSYS Workbench | NA | Design revaluation in case of abnormal stress generation | Airframe damage. | Thorough calculations and appropriate manufacturing techniques |
| **CAD model** | Hamza Hussain Muhammad Hassan Kazmi Sarah Naeem | Solidworks 2022 | NA | NA | Improper dimensions used in model leading to errors in manufacturing | Thorough revaluation |
| **Manufacturing** | | CAD model, equipment | Raw material | Airframe, tank, supports | Material damage and injuries | Manufacturing under experienced personnel guidance. |
| **Propulsion System Design** | Muhammad Hassaan Ghazali | None | All hardware components | None | Faulty parts. Part damage & malfunction mid flight | Procurement from well known vendors. Proper connections. |
| **Battery & Power distribution design** | Ali Khalid | None | All components | None | Battery hazards | Employ safe battery practices. |
| **Social Media Outreach & Busin ess Case** | Muaz | Social media accounts. Graphic design software | None | None | Digital backlash. | Practice healthy cyber habits. |

*Table 2. Project resources, manufacturing, and risks*

# 3. Requirement Review

## 3.1. Mission Requirements and Verification

For table 4, the term 'shall' label a mandatory requirement and the term 'should' designates a highly desirable requirement.

| Requirements | Verification |
|---|---|
| A detailed CAD assembly with emphasis on feasibility of design and manufacturing, control capacity and airworthiness. | Detailed CAD assembly created on Solidworks 2022 includes all components and structures employed in the final design. |
| UAS shall have either a fixed wing, rotary wing, or VTOL airframe configuration. | The design is tilt-rotor transition, fixed-wing VTOL aircraft |
| MTOM including payload and UAS shall not exceed 6.9 kg. | In weight analysis, the total mass with full payload is 6.9kg |
| UAS design should cater to rapid assembly/disassembly. | Easy to assemble airframe. |
| The UAS shall navigate waypoints and spray at targeted area in a fully autonomous manner and it should carry out fully autonomous take-off and landing. | Control & Computing System enable complete autonomy during take-off, spray & landing along with some advanced computing features. |
| The payload shall be a minimum of 500 ml. | There is 3L payload |
| The spray tank material should comply with UL 94, V0 flammability standards. It can be detachable or fixed to the UAV. For detachable tanks, re-attachment must be possible within the shortest amount of time. | Fixed spray tank manufactured from Carbon fiber is employed. |
| UAS airframe shall be designed from scratch. | Entire airframe is self-manufactured. |
| Cost for COTS components shall not exceed PKR 250,000. Proposed design solutions should be cost-efficient. | Total cost for COTS items adds up to 146K which is well below the specified limit. |
| Radio Equipment shall comply with PTA directives and licensed for use in Pakistan with a reliable operating range of 1km. Control of the UA and the FTS is 'spread spectrum' complaint to 100mW spread spectrum configuration to IR2030 and CE marked 4. | 433 MHz 500MW Telemetry used with range of 2.5km and spectrum available for personal/household devices |
| UA shall automatically return to landing zone/take-off or activate flight termination after a loss of data link of more than 30 seconds. | Advanced RTL feature in case of disconnected telemetry |
| UA shall automatically terminate flight in case of loss of GPS signal, for more than 3 minutes. | Flight termination feature included in the flight control system |
| 'Return Home' signal shall be capable of activation by safety pilot. | Available in Mission Planner for Ground Control Station |
| A separate GPS data logger shall be fitted on top of the UAV, with clear exposure to the sky allowing real-time GPS information recording from take-off till landing. It shall also provide post-flight evaluation of the 3D trajectory. Placement of tracker should comply with vehicle safety and provide a glitch free flight safety review. | Provision has been left in design for GPS data logger and the control system is also compatible with it. |
| UAS design should plan on a target mission flight path with a distance of 2-4 km, from take-off to landing. | (With ref to battery consumption) |
| UAV to operate further than 500 m up to 1000 m where it may be flown safely and tracked within segregated airspace. | Telemetry used in UAV allows safe communication up to 2.5km range |

| | |
|---|---|
| UAV shall fly at a maximum altitude of 100m. | UAV is designed to cruise at about 30m AGL |
| UAV shall operate from within 10m x 30 m box, oriented at 30 degrees of wind direction. Landing must be within box, may be touchdown or roll out. | UAV shall use advanced computer vision to detect exact landing position and shall land with centimeters precision |
| Ground control station shall display all required information and be visible to operators, flight safety officers and judges. | Using telemetry, flight data logs are sent to ground control station using MAVlink and are displayed in mission planner |
| Should operate in winds of 20 kts gusting up to 25 kts and light rain. Shall be capable of landing and take-off in crosswind components to runway of 5 kts with gusts of 8 kts. | Drone shape designed for minimum air friction caused by wind<br>High Thrust motors used for powerful propulsion against any windspeed below 55kts |
| Maximum airspeed in level flight shall not exceed 60 KIAS. | 35-40 KIAS adequate for completing the mission. Motor thrust will be adjusted accordingly. |
| Design and construction shall employ good design practice and use appropriate materials and components. | All materials and manufacturing methods are finalized after a thorough market analysis. |
| Design shall be supported by satisfactory structural integrity, stability and control, flight and navigation performance and reliability of critical systems. | Balsa airframe with carbon fiber reinforcements for structural integrity. Pixhawk, GPS and image processing for flight control and navigation. |
| Batteries used shall contain bright colors for easy detection in the event of a crash. | Battery pack will be bright colored. |
| At least 25% of upper, lower and each side shall be a bright color to facilitate visibility in air and event of a crash. | The entire external surface will employ surfacing of bright colored sheets. |
| UA shall remain within VLOS of remote pilot and remain below 100m AGL. | UAV path trajectory will make sure that it remains in boundaries |
| UA shall not be flown within 30 m of any person/structure not under the control of the Remote Pilot. During take-off and landing, it shall not be flown within a 10m distance. | UAV will not cruise below 30m in horizontal flight and would follow the exact trajectory where no humans intervene |
| UA shall remain in controlled flight and within the demonstration zone boundary during the entire flight | Safety precautions and settings are all set in flight control system |
| UA appearing uncontrolled or moving into ‘No Fly’ zone shall be subjected to manual override, failure to do so shall activate flight termination. | Safety precautions and settings are all set in flight control system |
| Consideration should be given to environmental impact. | BLDC motors with minimum noise production are used and environmentally friendly practices are employed for manufacturing. |

*Table 3. Requirement Review*

## 3.2. Mission Success Criteria

The mission will be considered a success if the following criteria are met:

I. The UA covers the longest distance path to reach the SZ and navigate all WPs.
II. The UA completes the entire mission within 10 minutes.
III. The UA carries adequate payload to effectively spray entire spray zone.
IV. The UA performs successful flight termination and manual override.
V. The UA performs controlled flight without any damage to itself, property, or people.
VI. No safety violation occurs.

# 4. Design Description

## 4.1. Design Rationale

### 4.1.1. Airframe

A fixed-wing airframe design has opted for our UAV with a double pair of wings placed along the same axis. The wings are positioned midplane to the fuselage with a tilting rotor on each wing. This orientation provides the desired weight, strength, and performance efficiency in our mission objectives.

#### *4.1.1.1. Wings*

Our design includes two rectangular mid-wing pairs, placed one after the other, with a taper ratio of 1 and a dihedral angle of zero. The design follows a primary unswept wing with an aspect ratio of 7.2 (low aspect ratio). A lower aspect ratio allows for easier maneuverability which is one of the core requirements of our mission.[3]

The wingspan of both wings is approximately 1440 mm. The airfoil in the leading pair of wings is S1210[4], oriented at zero degrees. The trailing wings use S1223[5], oriented at five degrees. Each wing section has a chord length of 200 mm. The chosen orientation and dimensions provide us with the ideal amount of lift, cruising speed, and altitudes required for the fly-off mission. A skeletal structure composed of balsa cross-sections and longitudinal spars will provide the main frame of the wings. This frame is reinforced by high-strength and lightweight circular rods running along the entire wingspan. The frame is surfaced to provide a smooth, streamlined surface for good aerodynamic performance.

Each wing will house a 9 g servo and a 20 g servo for the ailerons and tilting rotors. Rubber pipes will also run along its length with the spray nozzle attached at one end and to the pump at the other. Balsa wood cross-sections are placed perpendicular to the longitudinal-lateral plane. These cross-sections will be manufactured to match the airfoil used. Provisions for support rods, servo motors, wiring, and spray system are provided in these cross-sections.

The wings can be detached from the main assembly through simple reinforced connections to allow rapid assembly/disassembly. The details for these connections are discussed extensively in the manufacturing portion.

#### *4.1.1.2. Empennage*

The Empennage refers to the tail section composed of a vertical and horizontal stabilizer. The UAV will ideally cruise at a zero-degree pitching angle at all times. The Sum of moments along all three axes must then always be zero. Due to the presence of 4 tilting rotors with relatively large propeller blades, a wake region will be generated. This wake must not blanket our tail sections, significantly reducing control efficiency. Our Empennage must also be lightweight and provide sufficient Control. For this, a cruciform tail orientation has been opted for. It is a type of aft tail configuration, intermediate between the conventional and T-tail, where the vertical and horizontal tails form a '+'. It combines the benefits of both and reduces several drawbacks of both tail configurations. [8] If aligned properly, a deep stall is avoided while maintaining low wing weight. Section 4.2. further shows calculations for the tailplane area. Control Surfaces are discussed ahead.

#### *4.1.1.3. Fuselage*

For finalizing the fuselage design, a fuselage design requirements verification rubric was employed. Table 2. summarizes the final optimized design.[6]

| Design Requirement | Verification |
|---|---|
| Adequate space to house payload and system hardware. | The mounting plate runs through the entire length of the fuselage with a payload tank mounted between it. Sufficient free space remains after the assembly of all components. |
| Low weight. | A monocoque structure is employed using balsa wood bulkheads and reinforced longitudinal spars. It is covered using heat shrink iron-on model aircraft covering (7.7g/ sq. ft.). |
| It provides a sturdy mounting platform for landing gear. | The landing gear mounts are reinforced at the main mounting plate. |
| Generates the lowest drag possible. | Low wetted and side area with a streamlined nose and symmetric, streamlined contours result in minimum drag. |
| It maintains external symmetry. | It has an elliptic shape, symmetric about the longitudinal axis |
| Airworthiness and compatibility for flight during weather conditions are mentioned in mission requirements. | A sturdy airframe and high-strength iron-on covering are resistant to high winds & gusts and light rain (tensile strength 1,757 kg/sq cm [7]). |
| Manufacturing feasibility | Semi-monocoque structures have better manufacturability than monocoque designs with increased strength than truss assemblies. Locally available material and manufacturing methods are employed for easy access and guidance on equipment handling. |
| Structural Integrity and strength | Truss elements are employed where necessary, reinforced by balsa cross-sections along the longitudinal axis and interlinked support structures allowing loads to be distributed over the entire assembly. |

*Table 4. Fuselage Design requirements and verification*

#### *4.1.1.4. Landing Gear*

The landing gear is essential for safe takeoff and landing and, if designed well, can act as a shock absorber during crash landings. It must be made of appropriate material to avoid shock caused by harsh and crash landing from traveling through the Airframe. For our design, skids are selected as landing gears. These are fixed supports that are attached to the UAVs. These are widely used in VTOLs as there is no need for wheels. The design employs a four-piece landing gear in table-leg orientation. In this type, four rods are connected to the fuselage via hinges. The rods are fastened to one another via a rubber or elastic strip, resembling a table leg. The material chosen is carbon due to its lightweight and high-strength properties. In the event of a crash landing, the rubber material and the hinges provide a damping mechanism; hence, the material breaking chances are low. The landing gear will widen when the UAV lands, but the rubber provides a restoring force to limit this expansion. This action-reaction force pair causes damping and absorbs the shock that the UAV experiences. In case of a crash landing, only the components damaged are repaired or replaced. Unlike most landing gear systems, the entire assembly will not be replaced.

### 4.1.2. Propulsions

Power & Propulsion system of this UAV consists of following:

- 4 EMAX GT-2826 KV860 Brushless Motors
- 14*7'' Carbon Fiber propellers
- Turnigy 5000mAh 4S Li-Po Battery with 40C Discharge Rate
- 20g servos for tilting individual rotors

These components are selected after extensive calculations for optimum performance in fly-off mission. Note: MN5008 mentioned in PDR is replaced by EMAX because it wasn't locally available.

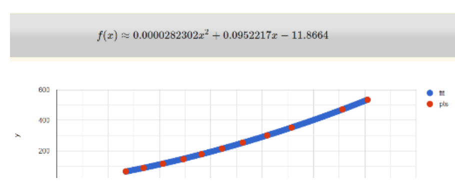


*Figure 1. Power as a function of Thrust*

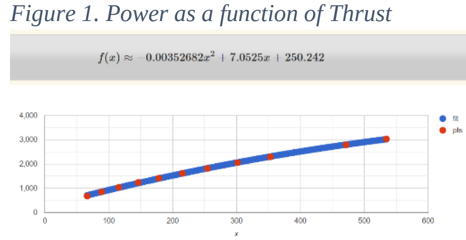


*Figure 2. Thrust as a function of Power*

| Motor | Propeller | Voltage (V) | Current (A) | Power (W) | Thrust (g) | Efficiency (g/W) |
|---|---|---|---|---|---|---|
| EMAX GT2826/05 KV860 | P14*7'' | 15.6 | 7.06 | 110.136 | 795 | 7.218348224 |
| | | 15.43 | 13.8 | 212.934 | 1283 | 6.025341186 |
| | | 15.21 | 24.9 | 378.729 | 2021 | 5.33626947 |
| | | 14.93 | 33.05 | 493.4365 | 2487 | 5.040162209 |
| | | 14.68 | 41 | 601.88 | 2852 | 4.738486077 |

*Figure 3. EMAX GT2826/05 KV860 performance values* 2

Data of all locally available motors is collected into the GitHub repository. The detailed datasheet of EMAX motors is not available online. All the data from the official website and thrust tests in workshops is gathered using finite values for this motor and datasheets available for similar motors; the closest continuous function was plotted against experimental values of thrust & power as shown in Fig. 4 & 5. Below are some power & thrust specifications of the motor used. Thrust for a single motor is written as a function of power using an online function calculator as:

$$thrust = -0.001632532 \cdot power^2 + 5.3238 \cdot power + 250 \qquad --- \ (i)$$

This continuous function gives a precise value for power between 50-850 Watts. Lift & Drag values for the Airframe on different airspeeds were obtained from simulations (detail in aerodynamics section). Again, using finite values, the estimated function was plotted for both lift & drag against airspeed.

$$lift = 0.350317 \cdot v^2 - 0.202576 \ \cdot v \qquad --- (ii)$$

$$drag = 0.0350823 \cdot v^2 + 0.00372739 \cdot v \qquad --- (iii) \qquad \therefore v = airspeed$$

Cruise speed is calculated as: $lift = 0.350317 \cdot v^2 - 0.202576 \ \cdot v = \ total\ mass\ of\ drone$

Using this relation, the ideal cruise speed with a full payload, i.e., 6.9kg (flight towards Spray Zone), comes out to be 14.2ms$^{-1}$, and cruise speed without payload, i.e., 3.9kg (flight back to landing), comes out to be 10.7ms$^{-1}$.

Power consumption is calculated as:

$$drag = \ 0.0350823 \cdot v^2 + 0.00372739 \cdot v = thrust\ of\ propulsion\ system$$

The thrust required for a total payload comes out to be 0.727237 kgf (0.181809 kgf for each motor). Power consumed to require this thrust is calculated by eq. (i) It comes out to be 84.5723W (21.143W per motor). Similarly, the thrust required without payload is 0.421658 kgf, and power consumption is 47.8332W. Calculating energy consumption & time taken for ideal cruise flight of 4km from take-off to spray zone and 500m from spray zone to landing:

$$time = \frac{4000m}{14.2ms^{-1}} + \frac{500m}{10.7ms^{-1}} = 328.42s \ \ (Approx.\ \ 5\tfrac{1}{2}\ minutes)$$

$$energy = 84.5723W \cdot 281.7s + 47.8332W \cdot 46.7s \approx 7.2383\ Wh \qquad (< 10\%\ of\ available\ battery)$$

Ideal time & energy consumption calculations for takeoff, transition, spray zone & landing were done. Calculations are too complicated to be added in CDR. Results are given below.

The battery's energy capacity is 74Wh, about 160% of the total power used in-flight via a 4km route

Calculation for Optimum Energy Consumption

| Part | Time (s) | Average Power Consumed (W) | Total Energy Consumed (Wh) |
|---|---|---|---|
| Take-off | 3 | 2100 | 1.75 |
| Transition to Horizontal Flight | 1.5 | 2560 | 1.066666667 |
| Cruise to SZ | 282 | 85 | 6.658333333 |
| Transition to Vertical Flight | 1.5 | 2560 | 1.066666667 |
| Spray Zone | 210 | 488 | 28.46666667 |
| Transition to Horizontal Flight | 1.5 | 2560 | 1.066666667 |
| Cruise to Landing | 46.7 | 47.8332 | 0.6205029 |
| Transition to Vertical Flight | 1.5 | 2560 | 1.066666667 |
| Landing | 5 | 500 | 0.694444444 |
| | | | |
| | | | |
| Total Mission Time | 552.7 | **Total Energy Consumed** | **42.45661401** |

*Figure 4. The calculation for Optimum Energy Consumption*

Calculation for Optimum Mission Time

| Part | Time (s) | Average Power Consumed (W) | Total Energy Consumed (Wh) |
|---|---|---|---|
| Take-off | 3 | 2100 | 1.75 |
| Transition to Horizontal Flight | 0.8 | 3320 | 0.737777778 |
| Cruise to SZ | 130 | 451 | 16.28611111 |
| Transition to Vertical Flight | 0.8 | 3320 | 0.737777778 |
| Spray Zone | 118 | 950 | 31.13888889 |
| Transition to Horizontal Flight | 0.8 | 3320 | 0.737777778 |
| Cruise to Landing | 16 | 451 | 2.004444444 |
| Transition to Vertical Flight | 0.8 | 3320 | 0.737777778 |
| Landing | 5 | 500 | 0.694444444 |
| | | | |
| | | | |
| **Total Mission Time** | **275.2** | Total Energy Consumed | 54.825 |

*Figure 5. The calculation for Optimum Mission Time*

### 4.1.3. Control Surfaces

Controllability is a crucial characteristic of aircraft design. Control is defined as switching from one trim point to another, where trim refers to the state where the summation of forces along all three axes in an aircraft is zero. Control surfaces are employed to achieve controllability. Our UAV design employs the three primary control surfaces; ailerons, rudder and elevator.

#### *4.1.3.1. Aileron sizing*

Two parameters of the aileron, namely the chord length ($C_A$) and total length along the wing ($b_a/2$) will be considered here. A statistical approach has been employed to find the dimensions of the aileron.

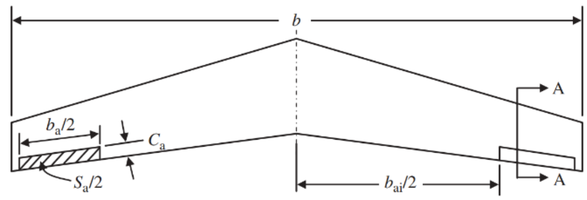


*Figure 4.vertical stabilizer with labeled aileron variables.*[9]

Although many factors influence the chord length of the aileron, one notable consideration is the distance of the rear spar from the trailing edge. The rear spar can serve as a hinge for the aileron, simplifying the design.

In the selected wing airframe, the rear spar is located 0.11 m away from the trailing edge of the wing. The total chord length of the wing is 0.2 m.

$$C = 0.2\ m$$

As per the placement of the rear spar:

$C_A = 0.11\ m$ [10]

$$C_A/C = 0.55$$

Now by:

$$\frac{b_A}{b} = \frac{C_A}{C} \qquad \therefore \quad b = 0.61 \times 2 = 1.22$$

For either side: $b_A/2 = 0.3355\ m$ [10]

To avoid flow separation, maximum aileron deflection $\delta_A$ (positive and negative) will be set at 20 degrees.

*Elevator design:*

The values for surface area and chord length ratios have been selected from the following table for the Cessna 182 due to its smaller size and similar tail geometry to the one selected for the UAV.

| No. | Aircraft | Type | $m_{TO}$ (kg) | $S_E/S_h$ | $C_E/C_h$ | $\delta_{Emax}$ (deg) | |
|---|---|---|---|---|---|---|---|
| | | | | | | Down | Up |
| 1 | Cessna 182 | Light GA | 1 406 | 0.38 | 0.44 | 22 | 25 |

*Figure 5. Extract from elevator characteristics for common aircrafts.* [9]

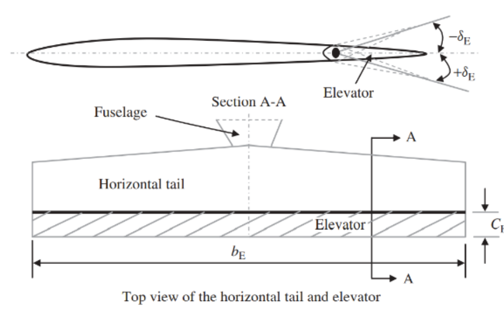


*Figure 6. Horizontal tail and elevator* [9]

The length of the elevator has been taken equal to the chord length of the horizontal stabilizer, that is:

$$b_E = 0.18\ m \quad Chord\ length\ of\ stablizer\ C_h = 0.18\ m\ => \ C_E = 0.44 \times 0.18$$

$C_E = 0.079\, m \qquad \therefore C_E/C_h = 0.44$

#### *4.1.3.2. Rudder sizing*

Rudder sizing follows a similar approach. A rectangular rudder has been selected for the design. In the design,
$b_v = 0.188\, m \quad b_R = 0.188\, m$[10]

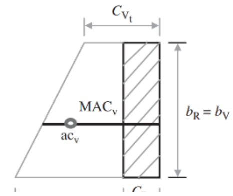


*Figure 7. Vertical Tail and Rudder [9]*

| No. | Aircraft | Type | $m_{TO}$ (kg) | $S_R/S_V$ | $C_R/C_V$ | $\delta_{Rmax}$ (deg) | Max cross-wind speed (knot) |
|---|---|---|---|---|---|---|---|
| 1 | Cessna 182 | Light GA | 1 406 | 0.38 | 0.42 | ±24 | – |

*Figure 8. Extract from Characteristics of Rudder for several aircrafts [9]*

Now,
$\frac{C_R}{C_V} = 0.42, \qquad C_V = 0.18\, m \qquad => \qquad C_R = 0.18 \times 0.42 = 0.0756\, m$ [10]

### 4.1.8. Spraying Mechanism

#### *4.1.8.1. Spray Nozzle*

Four nozzles will be used at either end of the wings. Nozzles extrude from the wing for easy cleaning and will be connected using 5mm rubber pipes. In addition, connectors will be used for easy and secure connection of the pipes since the wings are detachable; hence, 4 connectors in each wing will ensure no leakage. The pump and the tank will be placed in the fuselage for efficient weight distribution. The nozzle chosen can operate in spray mode and mist mode, providing efficient coverage for the spray zone.

| | | | |
|---|---|---|---|
| Nozzle Material | Copper | Spray Distance | 1 meter (can be varied) |
| Spray Flow | 0.2-0.7 ltr/min | **Pipe Diameter** | 5 mm |

*Table 5. Spray Nozzle specifications.*

#### *4.1.8.2. Micro Diaphragm Pump*

A brushless pump is chosen for this mission. The performance details for this model are listed in Table 5. Lightweight and high quality were the main selection criteria for the pump.
Caution: Pump should be used in dry condition, cannot submerge into water.

| | | | |
|---|---|---|---|
| Voltage | 12 V | Current | 3 A |
| Flow | 5ltrs/min | **Power** | 60 W |
| Pressure | 100 Psi | **Connector Size** | Fits 6-10 mm inner diameter pipe. |

*Table 6. Pump specifications*

## 4.2. Aerodynamic Analysis

### 4.2.1. Airfoil Analysis

I Initially, airfoils generating high lift and low Reynolds numbers were short-listed to cope with the mission and efficiency constraints. After an iterative process of combining two airfoils, the best possible combination was selected. The lift curve was obtained using Xfoil. With an upstream airfoil S1210 at 0 pitch, a downstream airfoil S1223 at 5 pitch, a chord length of 200mm for both airfoils and 0.49m between the wings gave a net lift coefficient of 2.43 for Reynold's number of 1.5-2 $\times 10^5$.

Forces - Direction Vector

| Zone | Coefficients Pressure | Viscous | Total |
|---|---|---|---|
| airfoil1 | 1.0322571 | 0.0010769496 | 1.033334 |
| airfoil2 | 1.3976985 | 0.001127866 | 1.3988263 |
| Net | 2.4299555 | 0.0022048156 | 2.4321604 |

*Figure 10. CFD lift force values.*

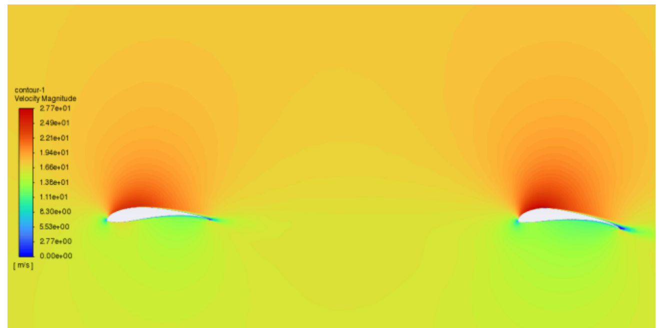


*Figure 9. Velocity contour from CFD Analysis for chosen airfoil configuration.*

### 4.2.2. Wing And Fuselage Analysis

With a maximum required force of 6.9kg during level flight the wing area was calculated using

$$A = \frac{2F_l}{\rho V^2 C_l}$$

The shape of the fuselage was kept elliptical to encourage laminar flow over the surface and wing edges, treating it as a streamline body during horizontal cruise. Also, considering it as a blunt body during VTOL

Forces - Direction Vector (0 1 0)

| Zone | Forces [N] Pressure | Viscous | Total |
|---|---|---|---|
| plane | 86.56639 | -0.062369219 | 86.504021 |
| Net | 86.56639 | -0.062369219 | 86.504021 |

Forces - Direction Vector (1 0 0)

| Zone | Forces [N] Pressure | Viscous | Total |
|---|---|---|---|
| plane | 7.472392 | 1.5657713 | 9.0381633 |
| Net | 7.472392 | 1.5657713 | 9.0381633 |

and transition state, the elliptical shape reduces pressure drag during vertical flight at much lower velocity

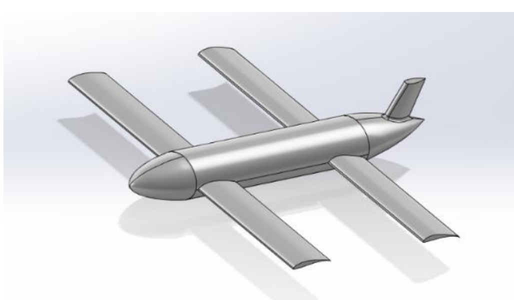

*Figure 14. CFD for forces along y-axis (lift).*

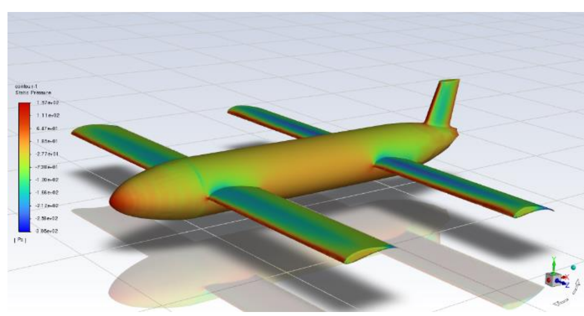

*Figure 12.Pressure contour from CFD simulation of test model.*

than cruise velocity. The nose was kept relatively long to make it sleek and streamline for reduced drag having 254mm length. The fuselage, nose and tail were kept symmetrical about the X and Z axis to avoid any lift generation. The following CAD model was generated for simulation. Simulation was carried out in Ansys® Fluent. The K-Omega turbulence model was opted and a tetrahedral mesh with average mesh size of 50mm and 5mm at fluid and surface zones respectively. [11]

### 4.2.3. Tail Analysis

The Volume Ratio model is used to compute the tail area. The tail should be sized to generate enough counter torque for adequate stabilization. Reasonable amendments were made to incorporate our design parameters and variation.

$$C_{HT} = \frac{S_{HT} * L_{HT}}{S_W * c_{MAC}}; \;\; C_{VT} = \frac{S_{VT} * l_{VT}}{S_W * b}$$

The values for the volume ratio of horizontal and vertical stabilizers were obtained from the tabulated data in Empennage Statistics and Sizing Methods for Dorsal Fins [8]. The Raymer and Roskam models were used for horizontal and vertical tails, respectively.

The results are concluded that the vertical tail sweeps from 200mm to 160mm chord having a mean chord length of 180mm meters and a height of 188mm. The horizontal tail has a 180mm chord and 820mm span. The horizontal tail is situated midway onto the vertical stabilizer to heighten it and prevent turbulent air from the propeller from disturbing its laminar flow. The aerodynamic center is situated 23.5" from the nose tip.

## 4.3. Structural Analysis

**Bending Moment of wings:**

$$Centre\ of\ mass\ along\ x = 46.2\ mm$$

$$Total\ weight\ of\ UAV = 6.9kg \times 9.8\frac{m}{s^2} = 67.7N$$

$$Previously\ calculated\ lift\ force = 74\ N$$

$$rear\ wing\ weight = W_{wing,rear} = 160.45g = 0.16045kg$$

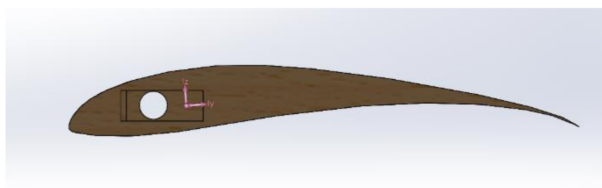

Figure 15. Airfoil Section from wing CAD model.

$$front\ wing\ weight = W_{wing,front} = 153.96g = 0.15396kg$$

Assuming that each wing produces 1/4th of the total lift (L). Then the balance of vertical forces for the wings imply:

**Front: (For lift=weight of UAV)**

$$V = \frac{L}{4} - W_{wing,front}$$

$$V = \left(\frac{67.7}{4}\right) - (0.15396 \times 9.8)$$

$$V = 25.54\ N$$

Corresponding bending moment for center of mass at 0.0462 m:

$$W = 0.0462 \times 25.54$$

$$W = 1.18\ Nm$$

**(For calculated lift)**

$$V = \frac{L}{4} - W_{wing,front}$$

$$V = 17\ N$$

Corresponding bending moment for center of mass at 0.0462 m:

$$W = 0.0462 \times 17 = 0.785\ Nm$$

**Rear: (For lift=weight of UAV)**

$$V = \frac{L}{4} - W_{wing,rear}$$

$$V = 15.35\ N$$

Corresponding bending moment for center of mass at 0.0462 m:

$$W = 0.0462 \times 15.35 = 0.71\ Nm$$

**(For calculated lift)**

$$V = \frac{L}{4} - W_{wing,rear}$$

$$V = 16.93\ N$$

Corresponding bending moment for center of mass at 0.0462 m:

$$W = 0.0462 \times 16.93 = 0.78\ Nm$$

## 4.4. Performance & Dynamic Analysis

### 4.4.1. Vertical Flight

#### *4.4.1.1. Assumptions*

- The UAV experiences negligible friction (drag) in the vertical direction

#### *4.4.1.2. Mathematical Model*

For vertical flight, the model is the simplest since drag is neglected. The real-life values will be significantly different, but since only takeoff and landing is vertical, there would be a negligible effect on overall mission time and energy consumption.

Summing all force vectors on UAV, $ma = vertical\ thrust - weight \quad => a = \frac{thrust - weight}{mass\ of\ UAV}$

Acceleration can be written as a power function using the estimated function (thrust as a function of power). Distance traveled can be expressed as a function of total energy consumed, integrating it twice w.r.t time. Optimizing the total energy, we find out that 10.5kgf total thrust for the UAV gives optimum energy consumption for 30m takeoff

| | Time | velocity | distance | Energy Consumed |
|---|---|---|---|---|
| 3209 | 3.207 | 18.67497 | 29.963985 | 2.079783203 |
| 3210 | 3.208 | 18.68079 | 29.982668 | 2.080431514 |
| 3211 | 3.209 | 18.68661 | 30.001358 | 2.081079826 |
| 3212 | 3.21 | 18.69243 | 30.020053 | 2.081728137 |

*Table 7. Vertical Flight Energy consumption*

### 4.4.2. Horizontal Flight

For horizontal flight, calculations are simple too. Since the UAV is cruising at constant airspeed and altitude, all vertical components are of no concern; for horizontal components, $drag = thrust$.

Since lift can be expressed as a function of velocity using Fluent Simulations, velocity from $lift = weight$ comes out to be 14.2ms$^{-1}$. From this cruise speed, drag can be calculated; hence, the required thrust is calculated using that drag. Since power can be written as a close function of thrust for EMAX GT-2826/5, power consumed can be calculated for the horizontal cruise. Using this methodology, power consumed during the cruise becomes 84 Watts.

*Table 8. Horizontal Flight performance.*

| 1 | Speed | Vertical Thrust (kgf) | Horizontal Thrust (kgf) | Total Thrust (kgf) | Thrust per motor (kgf) | Power per Motor (W) | Total Power (W) | Cruise Efficiency |
|---|---|---|---|---|---|---|---|---|
| 142 | 14 | 0.183054286 | 0.706970843 | 0.730285317 | 0.182571329 | 21.23690757 | 84.94763027 | 1.516921969 |
| 143 | 14.1 | 0.08467335 | 0.71706819 | 0.722050113 | 0.180512528 | 20.98355051 | 83.93420202 | 1.488195071 |
| 144 | 14.2 | 0 | 0.727237134 | 0.727237134 | 0.181809283 | 21.14309294 | 84.57237177 | 1.488950207 |
| 145 | 14.3 | 0 | 0.737477674 | 0.737477674 | 0.184369418 | 21.45844022 | 85.83376088 | 1.500590225 |

### 4.4.3. Rotors Transition State

#### *4.4.3.1. Conventions*

- Tilt angle in horizontal flight is set as 0° and in vertical flight as 90°.

#### *4.4.3.2. Mathematical Model*

For simplicity, we assume that thrust magnitude during the transition phase remains constant and only the tilt angle changes. The thrust provided by rotors is divided into vertical and horizontal components depending on the instantaneous tilt angle.

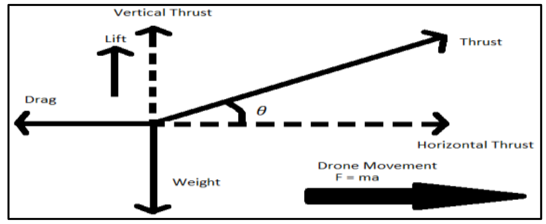


*Table 9. Vector Diagram for Transition state forces.*

$$Vetical\ Thrust = Weight - lift = Thrust\ \cdot sin\theta$$

$$=> \theta = sin^{-1}\left(\frac{Weight - lift}{Thrust}\right) - - - (i)$$

$$Horizontal\ Thrust - drag = ma \qquad => a = \frac{Thrust \cdot cos\theta - drag}{mass\ of\ UAV} - - - (ii)$$

Acceleration of UAV is represented as function of tilt angle & drag force. Tilt angle is a function of lift in (i). Fluent simulations show that drag & lift can be written as function of horizontal velocity as:

$$drag = 0.350317v^2 - 0.202576v\ - - - (iii) \quad lift = 0.0350823v^2 + 0.00372739v - - - (iv)$$

Hence, using (i) and (iv), θ can be written as function of velocity.

$$\theta = sin^{-1}\left(\frac{Weight - 0.0350823v^2 + 0.00372739v}{Thrust}\right) - - - (v)$$

Using (ii), (iii) & (v), acceleration is written as function of velocity. Hence, equation becomes:

$$a = \frac{Thrust \cdot \cos\left(sin^{-1}\left(\frac{Weight - 0.0350823v^2 + 0.00372739v}{Thrust}\right)\right) - drag}{mass\ of\ UAV} - - - (vi)$$

Velocity & Speed are given as: $v = \int_{t_0}^{t} a\,dt - - - (vii)$ $\qquad distance\ s = \int_{t_0}^{t} v\,dt - - - (viii)$

The flight controller does not continuously control tilting but controls discretely, i.e., changing every clock cycle, which changes the tilt angle every micro-second according to the equations above.

The easiest and most accurate way to calculate the complete spectrum of tilt angle, horizontal & vertical speed, lift, and drag is to distribute the time domain into discrete parts of microseconds (Δt) and then, from t = 0s & v = 0ms$^{-1}$, start calculating lift, drag and acceleration. Use $v_{i+1} = v_i + a_i\Delta t - - - (ix)$ & $s_i = v_i\Delta t + \frac{1}{2}a_i\Delta t^2$ to calculate distance and next interval velocity.

Calculations for the transition region are made in an excel sheet using this approach, keeping Δt = 20µs.

| | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Time | Velocity | Lift | Drag | Vertical Thrust | Horizontal Thrust | Transition Angle | Acceleration | Total Distance |
| 46294 | 0.92584 | 14.18464596 | 67.61178 | 7.111577 | 0.008223723 | 117.5999997 | 0.004006672 | 17.04347822 | 6.300361917 |
| 46295 | 0.92586 | 14.18498683 | 67.61509 | 7.111918 | 0.004905089 | 117.5999999 | 0.002389803 | 17.04347825 | 6.300645621 |
| 46296 | 0.92588 | 14.1853277 | 67.61841 | 7.112258 | 0.001586373 | 117.6 | 0.000772895 | 17.04347826 | 6.300929331 |
| 46297 | 0.9259 | 14.18566857 | 67.62173 | 7.112599 | -0.001732424 | 117.6 | -0.000844052 | 17.04347826 | 6.301213047 |
| 46298 | 0.92592 | 14.18600944 | 67.62505 | 7.112939 | -0.005051302 | 117.5999999 | -0.00246104 | 17.04347825 | 6.301496771 |
| 46299 | 0.92594 | 14.18635031 | 67.62837 | 7.11328 | -0.008370262 | 117.5999997 | -0.004078067 | 17.04347822 | 6.301780501 |
| 46300 | 0.92596 | 14.18669118 | 67.63169 | 7.11362 | -0.011689303 | 117.5999994 | -0.005695134 | 17.04347818 | 6.302064239 |

*Table 10. Transition state performance values.*

During the transition from 90° to 0°, the time taken is 925ms and the distance covered is 6.3m.

Note: This calculation assumes that drone acceleration is the bottleneck, not the tilting servo speed because the tilting servo used in this UAV has a higher angular velocity than the transition state.

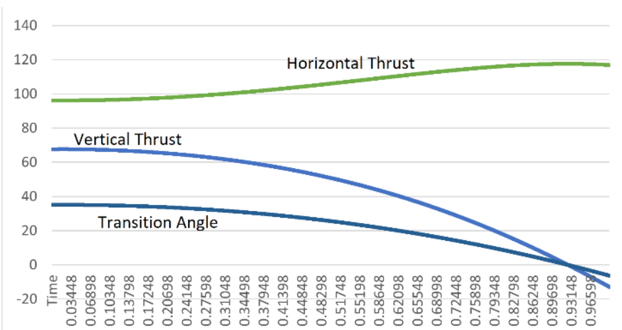


*Figure 17. Thrust variation over time.*

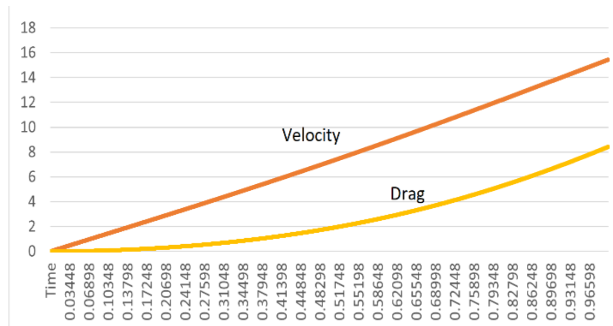


*Figure 16. Drag and velocity variation over time.*

## 4.5. Weight Analysis

Weight analysis showed that the combined weight of the UAV and all its components minus the payload is approximately 3.9 kg, leaving behind a 3 kg capacity for payload, which is the ideal amount of fluid required for effective spraying of the entire spray zone. The weight analysis is given in the table below.

| COMPONENT | QUANTITY | WEIGHT (individual) | Total Weight (grams) |
|---|---|---|---|
| EMAX GT2826/04 1090KV | 4 | 175g | 700 |
| Turnigy 5000mah 14.8V (4S) 40C Lipo Battery | 1 | 550g | 550 |
| Mini Brushless Water Pump | 1 | 350g | 350 |
| Pixhawk 2.4.8 Flight Controller | 1 | 38g | 38 |
| GPS Module | 1 | 23g | 23 |
| Pixhawk Radio Telemetry | 1 | 19g | 19 |
| Raspberry Pi | 1 | 50g | 50 |
| Camera | 1 | 3g | 3 |
| APC 12x6EP | 2 | 27g | 54 |
| APC 12x6E | 2 | 27g | 54 |
| Airframe | 1 | 2100g | 2100 |
| | | | |
| | | | |
| Total weight | | | 3941 |

*Table 11. Weight Breakdown*

## 4.6. Control System and Flight Controller

The Control & Computing System hardware consists of:

| | |
|---|---|
| Flight Control System | **1.** Pixhawk 2.4.8 (ARM Cortex M4, 6-axis gyroscope + accelerometer, barometer, compass, failsafe co-processor)<br>**2.** NEO-M8N GPS Module (Accuracy of 2m & 18 Hz update rate) |
| Flight Computing System | 1. Raspberry Pi Model 4 B (4GB RAM)<br>2. Raspberry Pi Night Vision Camera (5MP, 1080p) |
| Telemetry | 1. 433 MHz 500mW radio telemetry (2.5km range |

*Table 12. Control System Components*

The hardware for the control system is selected after a detailed analysis of all available options in terms of cost (time & money), reliability, and mission limitations. Control and Computing systems, both are put inside the UAV for two reasons:

- **Complete autonomy of UAV:** UAV is independent of any ground control station and can complete spraying missions outside the telemetry range with great precision.
- **Advanced Computing & Artificial Intelligence:** Using HD image processing, machine learning, advanced model-prediction algorithms & artificial intelligence on a powerful quad-core Raspberry Pi, the onboard computing system makes this UAV the first of its type, which outperforms any manual or autonomous agriculture drone in the market.

The controller and Computer are present on different adjacent boards inside UAV. The schematic below shows the rough idea of electrical connections (not the original electrical schematic, just a rough schematic for better understanding).

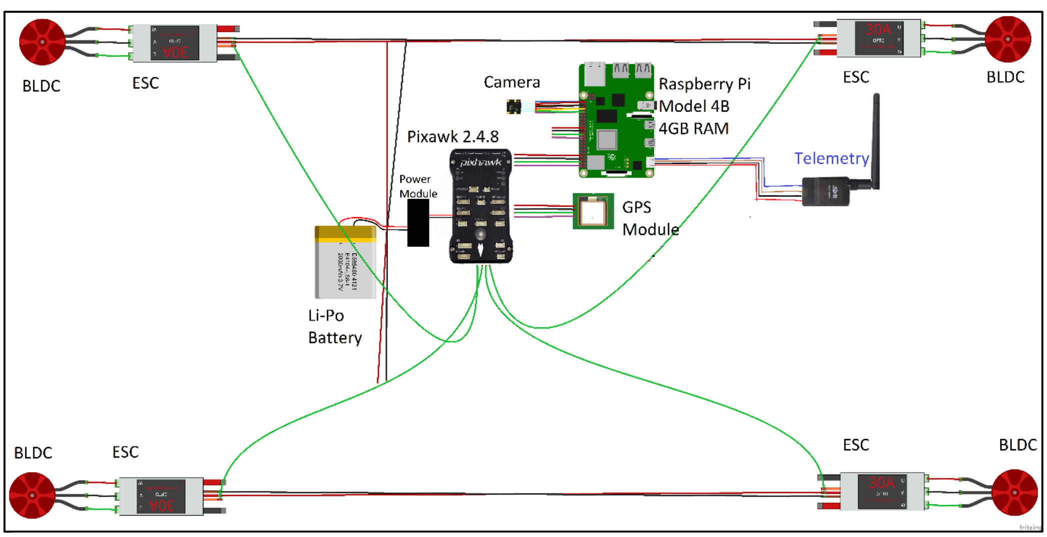


*Figure 18. Control System Schematic*

The most optimum approach would be to embed the flight controller (ARM Cortex-M4 + 32-bit failsafe co-processor), all control sensors (MPU6000, ST micro gyroscope + magnetometer), flight computer (ARM Cortex-A72, SRAM, DRAM), and all peripherals on a single PCB. It would significantly reduce the wiring across all avionics. The main issue in this approach is the fabrication of this all-in-one PCB. It is estimated to be minimal of 6-layer PCB with <150µm scale, which is not available in Pakistan.

Moreover, designing all connections, power optimization, signal latency & area optimization require more time and effort. Depending on the time & resources available, this does not seem impossible to achieve soon.

### 4.4.1. Flight Controller Software

Pixhawk runs modified ArduPilot firmware for quad tiltrotor UAVs with four rotors tilting. Modifications in the firmware provide optimum performance with our UAV's aerodynamic specifications. Modifications include:

- Vertical to Horizontal or Horizontal to Vertical Flight Transition with variable tilt-angle (enabling both time & energy optimization according to requirements)
- Drone stabilization by controlling four tilting servos on independent PIDs (for optimum stability)
- Shifting Telemetry to Flight Computer to enhance the performance of control loops in-flight Computer since there is only one core in Pixhawk (ARM Cortex-M4)

### 4.4.2. Image Processing:

The Raspberry Pi Night Vision Camera enables the drone to capture high-quality images during the day and at night. It would allow real-time computer vision in the UAV. We use Open-CV written in C++ for faster image processing.

In addition to Open-CV, the drone uses with YOLO (You only look once) algorithm for real-time object detection using Machine Learning. It would allow the drone to be fully autonomous since it would be able to recognize objects in the images of the camera and make movements according to the landscape.

### 4.4.3. Path Optimization:

The drone should take the shortest path to complete its task optimally. The drone ensures this with the most efficient path optimization algorithms. The drone would use the Traveling salesman problem algorithm to find the shortest Hamiltonian path.

Now the drone has the shortest path(a), but the drone (in fixed-wing mode) cannot completely follow the path generated by the previous algorithm. It occurs due to the speed of the drone and the maximum turn angle of the drone. For the final optimized path, the drone would use the Band-Turn mechanism. It would help the drone achieve the image's path (b). Thus, the drone would use this path to consume the minimum energy needed.

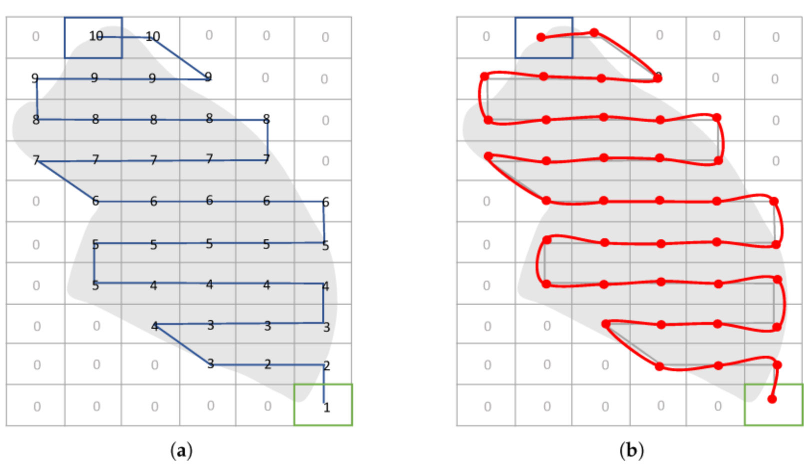


*Figure 19. Path Optimization*

## 4.5. CAD Model

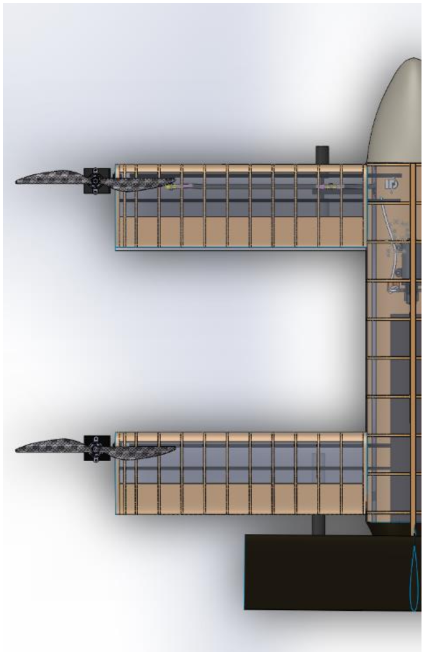

Figure 21. CAD model Top half view.

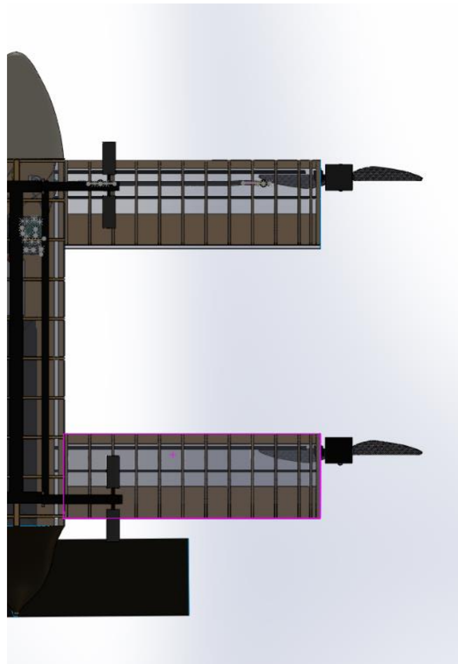

Figure 20. CAD model bottom view.

The CAD model was created on Solid works 2022 and is subject to change based on the issues we may face in the design. Additionally, the material used in this model may not align with our actual chosen material due to unavailable libraries whoever, the closest fit as been chosen. This caused an inaccurate mass analysis of the model.

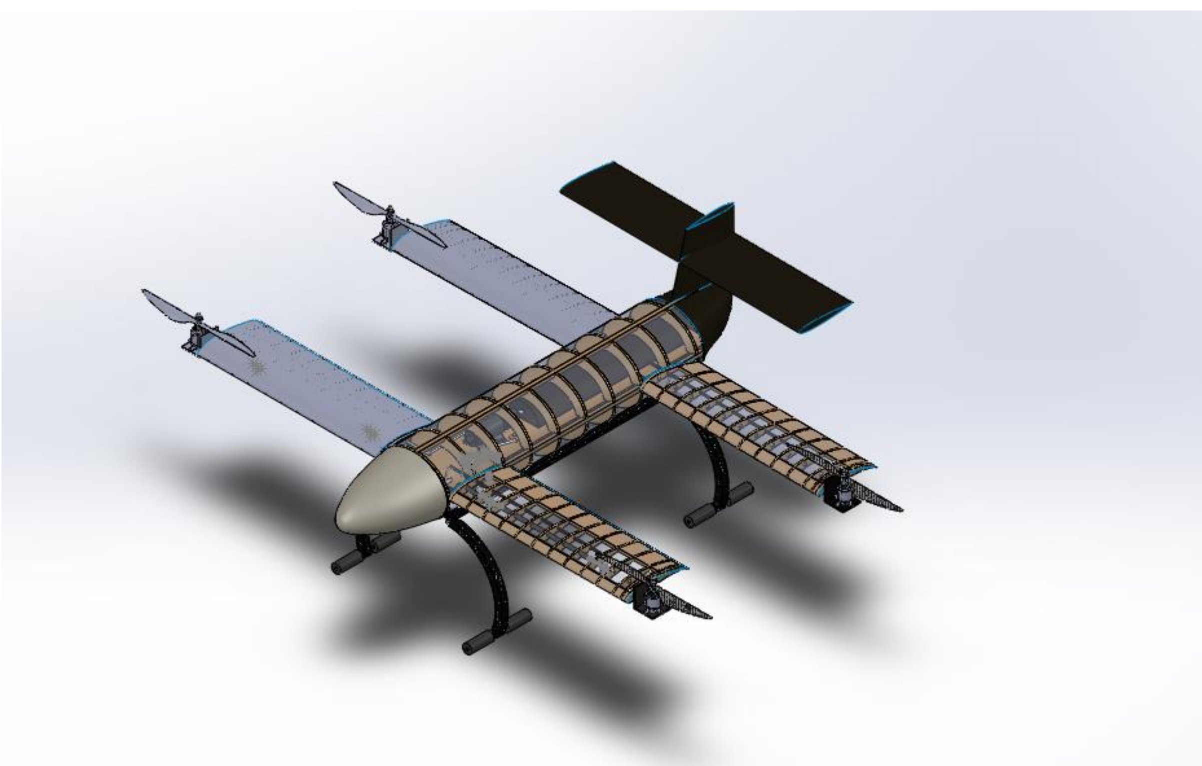

Figure 22. Isometric view of model.

# 5. Safety Case

All the possible security threats & risks either related to drone hardware or its control system are carefully listed along with the worst-case scenarios for each. These risks are addressed during the design, components selection, software selection, and code modification. Moreover, all the possible security protocols shall be ensured in test flights to minimize casualties.

Out of all these threats & risks, major ones are listed in CDR along with their severity and how we minimized them or aimed to during test flights and final fly-off.

| Probability | Severity | Risk | Mitigation |
|---|---|---|---|
| Improbable | Marginal | Pixhawk Processor Failure | - Failsafe 32-bit co-processor |
| Remote | Minor | Control loop glitch | - Frequent test-flights with deep analysis of flight data log |
| Improbable | Major | Losing connection between flight controller & flight computer | - RTL or safe landing depending on GPS connection, distance from launch and remaining battery |
| Remote | Marginal | Motor Failure | - Use state-of-the-art BLDC motors |
| Occasional | Major | Propeller Failure | - Use Carbon Fiber Propellers |
| Remote | Major | Battery Failure | - Small Failsafe battery for RTL or immediate Landing |
| Improbable | Major | Pesticides Tank Leakage | - Carbon fiber as manufacture material, waterproof sheet on electrical components |
| Improbable | Minor | Pesticide not available to pump inflow | - Sump in tank to ensure steady supply to pump |
| Probable | Minor | Nozzle Blockage | - Filter in pump inlet |
| Improbable | Minor | Leakage from pipes | - Good quality connectors & Thermal resistant pipes |
| Remote | Minor | Aircraft Stalling | - Proper airfoil/angle of attack selection.<br>- Reasonable deflection of control surfaces when operated.<br>- Maintaining cruise speed greater than stalling velocity. |
| Remote | Marginal | Crash Landing | - Manual override system in place in case of emergency landing.<br>- Proper landing gear installed to bear impact.<br>- Proper material selection. |
| Occasional | Minor | Unstable flight due to uneven weight distribution | - Proper component sizing.<br>- Properly assembled airframe.<br>- Drag reduction via optimization of aircraft geometry. |
| Occasional | Minor | Damage to Surfacing Material | - Selection of appropriate material meeting tensile strength requirement. |

| | | | |
|---|---|---|---|
| | | | - Provision of clearance from ground in case of impact via landing gear.<br>- Selection of easily replaceable materials in case of minor damage. |
| Remote | Minor | Damage to airframe in case of impact/collapse of airframe due to load on mount plate | - Selection of appropriate material for airframe possessing suitable mechanical properties.<br>- Structural reinforcement of airframe.<br>- Proper mounting of components on plate and uniform load distribution across mounting plate. |
| Occasional | Major | Propeller damage during transition phase | - Adequately secure fixture of propeller on shaft.<br>- Selection of appropriate time for transition to avoid unnecessary drag/abrupt flow separation across the propeller blade. |
| Occasional | Marginal | Li-Po Battery may catch fire | - Charge on cement surface, Store in nonflammable container, do not charge unattended to avoid overcharging. |
| Occasional | Minor | Li-Po Battery may swell | - Immediately stop charging, store in fireproof container, wait for it go back to normal size, may have to replace battery. |
| Remote | Major | Battery Short Circuit | - Vigilant wiring and connections of battery for fly-off and charging. |

*Table 13. Possible risks and their mitigation.*

## 5.1. Safety Steps in Control & Computing System Design:

Since the drone is most vulnerable to any bugs or glitches in software, safer software is a higher priority than performance-optimized software for our Control & Computing System team. In this regard, the modifications in the control loop will be used in test flights after being checked by the faculty advisor and will be used in fly-off after multiple test flights without any glitch or unwanted output.

## 5.2. Safety Steps in Propulsion Design:

A safer propulsion system implies a safer flight. Motors & Propellers used in the drone are the highest quality ones available in the market to ensure the safest propulsion system possible. However, to ensure the safety of the electrical motors, it is crucial to take the following precautions:

- Constant troubleshooting to establish whether the features in the motors are working properly
- Do not leave a short-circuited battery for long because it would eventually explode.
- Do not power the motors beyond their voltage capacity.
- Never leave a motor to operate unattended.

## 5.3. Safety Steps in Spray System Design:

Pipes of good quality are used to ensure that there is no leakage of flowing pesticides. The high-quality pump is used to minimize failure probability. The spray tank is designed to minimize leakages in case of a crash.

# 6. Manufacturing & Support

## 6.1. Airframe

The wing airframe will be constructed using balsa wood sections of 5mm width and 10mm width on the ends, which will provide adequate reinforcement and a platform for accurate surfacing. These sections will be laser cut, and holes are measuring 8mm,6mm and 10mm (dia) will be provisioned in them. Carbon fiber support rods of 8mm and 6mm dia will be inserted along the wingspan for effective stress distribution. These will protrude out of the fuselage-end of the wing to provide a platform for insertion into the fuselage, making the wings re-attachable. The spray system pipe will be inserted through the 10mm hole. For further reinforcement and ease of surfacing, the wing's leading edge will be covered entirely with balsa wood sections glued to each other. Similarly, the trailing edge will be solid balsa wood.

Sheeting will be employed to surface the wings. Vinyl wraps will be the material of choice. Provisions for spray system nozzles and aileron servos will be ensured prior to the sheeting to prevent damage to the surface and unnecessary material use.

## 6.2. Spray Tank

The tank to store liquid will be manufactured using a negative mold made of latex rubber. The negative mold is enclosed by a plaster mother mold or retaining mold made with fiberglass to ensure that the rubber will maintain its shape during casting. The carbon fiber with a thickness of 0.46mm will be used as the material to make the tank using the wet lay-up technique. However, the overall tank thickness will be around 0.6 mm as the resin will be applied on both sides.

Wet lay-up involves cutting and laying the fiber into the mold before applying the resin with a brush, roller, or sprayer. This workflow is the least expensive and has the fewest needs to manufacture carbon fiber parts, but it also demands the most expertise to produce high-quality parts.

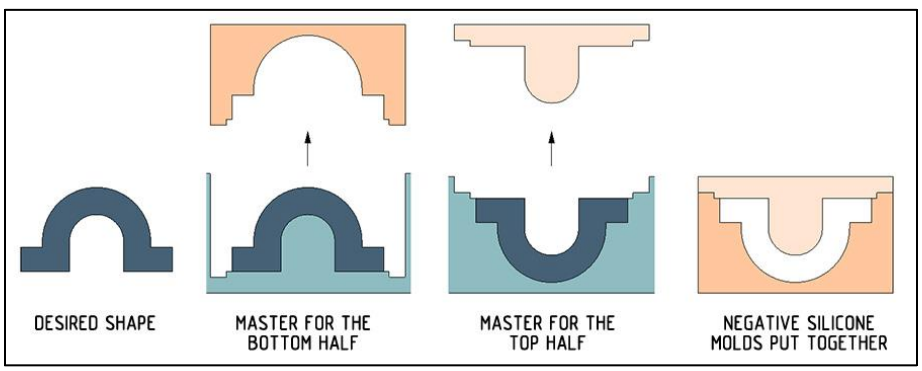


*Figure 24. Manufacturing process for spray tank.* [12]

**SPECIFICATIONS**

| | |
|---|---|
| WIDTH | 12" (30 cm) |
| COLOR | Black |
| MATERIAL | Carbon Fiber |
| WEAVE | 2 x 2 Twill |
| WEIGHT | 220g/sq. meter |
| THICKNESS | 0.46 mm |
| TOW | 3K (3,000 filaments) |

*Figure 23. Selected Carbon Fiber specifications.*

Desired shape in our case is the water/pesticide tank. That tank will initially be made from high density polyethene as it easy to shape it according to the design specifications. For making the master mold the polyethene tank will be covered by thin layer of cling plastic wrap with thickness of 0.02 mm. This is done to prevent any chemical reaction between polyethene and the latex rubber. In addition to that, a releasing agent is used to separate the mold from the object.[13]

In general, carbon fibers have low densities, high thermal and chemical stabilities in the absence of oxidizing agents, and great creep resistance. Furthermore, the strength provided by carbon fiber is very high. Hence, in a situation of a crash the tank will not rupture, protecting the electrical components from the liquid.

## 6.3. Storage and Handling

The carrying case for the drone, which measures 65 inches long by 12 inches wide by 18 inches high, is designed to be compact for convenient handling, as it has detachable wings. High density polyethene foam is used in the case to secure the fuselage and wings inside a box made of hard board waterproofed with nylon covering. Waterproofed zips are attached at the edges for easy access to the drone. Color-coded connectors are utilized for quick and easy drone assembly.

## 6.4. Innovation

A high-resolution multispectral camera that can be mounted to a drone can be used to gather information on the crop's growth, health, and potential yield. Additionally, machine learning can be utilised to change the flight path of the drone after highlighting, in real time the areas that need to be sprayed with fertilizer utilizing the spectral response of the fertilized crop.

# 7. Qualification Test Plan

Table 13 provides an overview of the qualification test plan for the proposed UAV design.

| Sr no. | Objective | Method | Success criteria | Test Results |
|---|---|---|---|---|
| **1.** | MTOW of 6.9 kg. | Weighted analysis. Weighing scales-fully loaded aircraft with weighted dummy tracker. | MTOW < 6.9kg | NA |
| **2.** | Navigation of way points | Test runs with GPS data logger and inspection of flight trajectory | All waypoints in range of 10 meters of trajectory | NA |
| **3.** | Assembly/Disassembly | Wings capable of detaching | Takes <=5 minutes | NA |
| **4.** | Environment-Friendly propulsion system | Electrical Propulsion System | Doesn't burn any hydrocarbons | NA |
| **5.** | Minimum payload of 500 ml. | All analysis and calculations performed with a 3L payload margin. | For effective mission completion the UAV should carry 2.2-3L of payload | NA |
| **6.** | Fully Autonomous Flight | Raspberry Pi microcontroller and Pixhawk flight controller | Performs take-off, landing, navigation of WP and spraying mission with full autonomy. | NA |
| **7.** | Flight Termination System | Use of backup battery, GPS and flight automation. | Ending the UAV's flight in a controlled manner. | NA |
| **8.** | Cost for COTS components | Detailed cost list accommodating shipment cost and 10% provision for price hike. Opting for locally available products. | Less than PKR 250,000 | NA |
| **9.** | Airworthiness, control capacity and manufacturability of CAD model | Design was discussed with local manufacturers to determine its manufacturability and control | Only the materials available should be used to make the CAD model. | NA |
| **10.** | Tracking System | Use of 3D trajectory for in-flight tracking for accurate results. | Provides both real-time and post-flight evaluation in 3D trajectory | NA |
| **11.** | Landing | Combining shock absorbers and a wide base. | UAS stops within the specified 10 m x 30 m box. | NA |
| **12.** | Ground Control Station | Shifting telemetry to Flight Computer for efficiency. | Relaying between the UAV and ground station always. | NA |
| **13.** | Weather limitations | Innovative use of ailerons and elevators to prevent stalling under adverse weather conditions. | Operates in 20kts winds, gusting to 25 kts and light rain. Successful take-off and landing in crosswind component of 5 kts (to runway) with 8 kts gusts. | NA |
| **14.** | Fuel/battery combination | The mathematical models to compute battery requirement | The battery should power all motors and servos. | NA |
| **15.** | Low environmental Impact. | Use of brushless motors and electrical power to reduce sound and pollution. | Low pollution, fuel efficient, low noise, non-hazardous. | NA |

*Table 14. Qualification Test Plan.*

## 8.0. Cost Analysis

The parts were selected by meticulously cross-checking different vendors according to our weight and thrust requirements; we selected a battery and motor for our UAV. For our flight computer, we used a raspberry pi and Pixhawk microcontroller. We had to select components that were compatible with it, such as a camera, GPS module and a telemetry system.

Our materials are sourced locally from well-known and trusted vendors. Our three leading vendors were:

- Full throttle
- Arctic Hobbies &
- Electrobes

We ensured that the total cost of our COTS materials remained well below the limit given in the competition rules.

| Item | Material No. | Full Description | Quantity | Price | Name | Price Per Part | Vendor |
|---|---|---|---|---|---|---|---|
| 1 | Turningy | 5000mah 14.8V 40C Lipo | | 11150 | Battery | | Full Throttle Hobbies |
| 2 | Rasberry pi Model 4B | 4gb 1.5GHz | 1 | 35 000 | MicroController | | Electrobe |
| | Rasberry Pi Night Vision Camera | 1080p 30fps | 1 | 3 500 | Night Vision Camera | | Electrobe |
| | Pixhawk Radio Telemetry | 433 Hz | 1 | 49800 | Telemetry | | Electrobe |
| | NEO-M8N GPS Module | max altitude 18000m | 1 | | GPS Module | | Electrobe |
| | Pixhawk 2.4.8 | 168MHz. Includes Gyro and Acceleromete | 1 | | Flight Controller | | Full Throttle Hobbies |
| | Pixhawk Power Module | Max Volt:18 Max Current 60A | 1 | | Power Module | | Full Throttle Hobbies |
| | Brushless Water Pump | Max flow rate:3.5L/min | 1 | 1600 | Water Pump | | Daraz |
| | OLYCAT 10 pcs | Flow rate: 80 - 145 ml/min | 10 | 566 | Nozzles | 57 | Daraz |
| | EMAX 2826 | | 4 | 23200 | Motor | 5800 | Arttech Hobbies |
| | Hobby wing | | 4 | 19200 | Speed Controller | 4800 | Arttech Hobbies |
| | APC 12x6E | Propeller | 2 | 2500 | | 1250 | Arttech Hobbies |
| | APC 12x6EP | Propeller | 2 | 29000 | | 14500 | Arttech Hobbies |
| | CF Rod 12x 10mm | | 4 | 9000 | | 2250 | Arttech Hobbies |
| | SG-90 Tower Pro Server Motor | | 4 | 300 | | 1200 | |
| | | | Total Price | 146316 | | | |

*Table 15. Cost Analysis*

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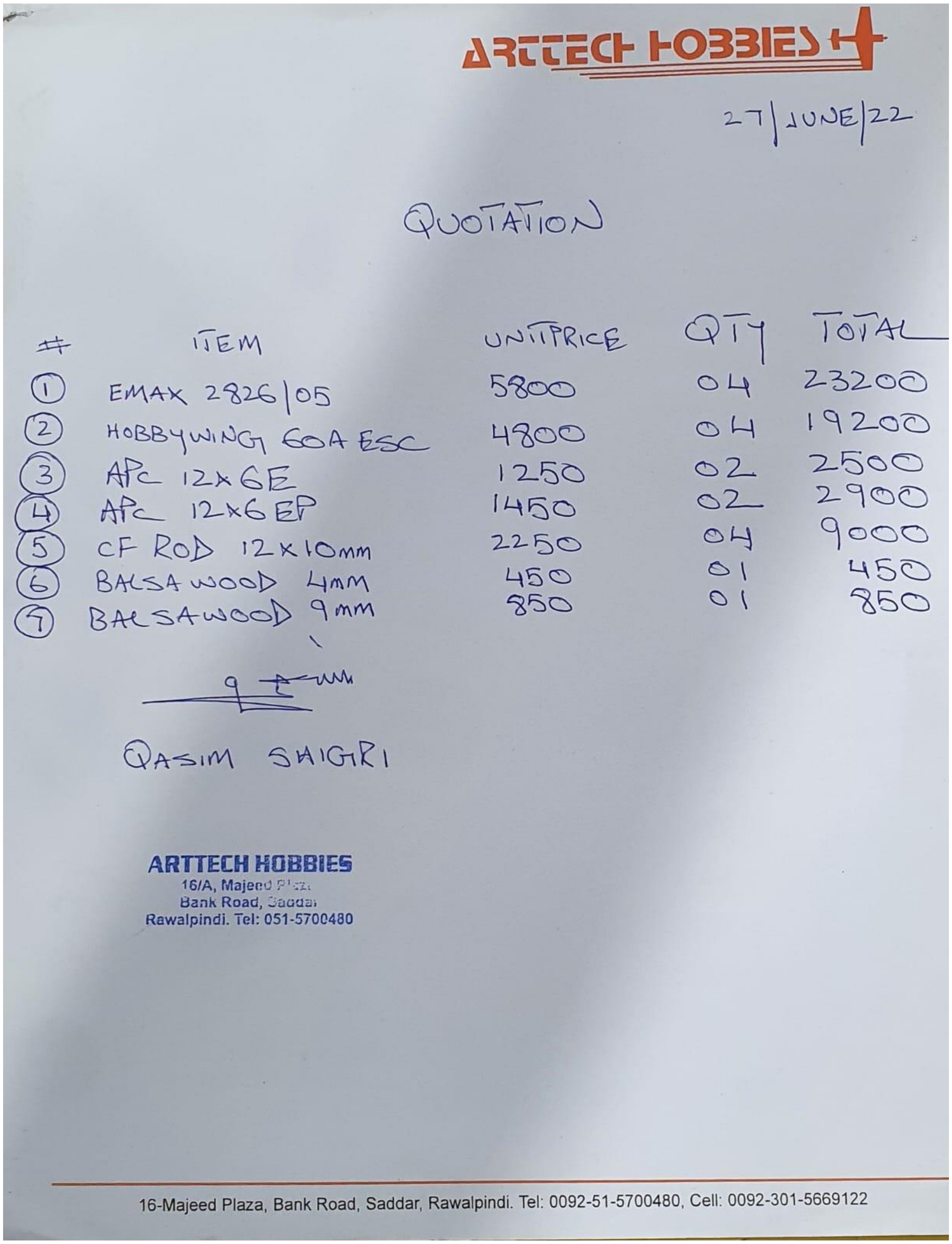
# Appendix

## A.1. Cost Quotations



ARTTECH HOBBIES

27/JUNE/22

QUOTATION

| # | ITEM | UNIT PRICE | QTY | TOTAL |
|---|---|---|---|---|
| 1 | EMAX 2826/05 | 5800 | 04 | 23200 |
| 2 | HOBBYWING 60A ESC | 4800 | 04 | 19200 |
| 3 | APC 12x6E | 1250 | 02 | 2500 |
| 4 | APC 12x6 EP | 1450 | 02 | 2900 |
| 5 | CF ROD 12x10mm | 2250 | 04 | 9000 |
| 6 | BALSA WOOD 4mm | 450 | 01 | 450 |
| 7 | BALSAWOOD 9mm | 850 | 01 | 850 |

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