Prototype Unmanned Aerial Sprayer for Plant Protection in Agricultural and Horticultural Crops

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Abstract. *Aerial application of pesticides has the potential to reduce the amount of pesticides required as chemicals are applied where needed. A prototype Unmanned Aerial Sprayer with a payload of 20 kg; a spraying rate of 6 liters per minute; a spraying swathe of 3 meters, coverage rate of 2 to 4 meters per second and 10 minutes of flight time was built using state of the art technologies. The project is a joint development by University of Agricultural Sciences, Dharwad, KLE Technological University, Hubballi and SkyKrafts Aerospace Pvt. Ltd. The technology for the prototype was divided into electronic, software and mechanical components. Hexacopter configuration with six propellers was chosen, as it provides a good compromise between the stability of an Octocopter and longer flight times of a Quadcopter.*

The airframe of the sprayer was designed from ground up using modern industrial design methodologies. Carbon fiber was a natural choice for the structural frame along with aerospace grade 6061 aluminum. The design was simulated in several iterations and test models were created using Hylam sheets. Electronics and software were derived from px4 and pixhawk, both of which are stable open source flight controller projects. This allowed us to rapidly prototype the sprayer at the same time giving us the freedom to reprogram the flight controller for spraying applications. The weight of the sprayer is 50 kg including a payload of 20 kg. The sprayer can generate a total thrust of 104 kg, providing a Thrust to Weight Ratio (TWR) of a little over two. The energy sub-system calculated for multiple current and voltage ratings of Lithium Polymer (LiPo) batteries and suitable off the shelf battery modules were used. The system is modular; functional components such as motors, propellers, autopilot, spraying system or batteries can be replaced with a different one with little effect on the other components or the sprayer itself. The spraying system consists of a DC powered pump with a six downward facing nozzle on two spray booms, three on each side; each nozzle can be adjusted to control the spraying rate.

Keywords. *Precision agriculture, UAV, Ariel Sprayer, Crop duster, Spraying drone, Hexacopter, Multirotor, Flight time, Pay Load, Thrust, Airframes, Autopilot, Pesticides and Spraying rate.*

1. INTRODUCTION

UAV is an Unmanned Aerial Vehicle, which is flown by a remote control or can be programmed for autonomous flight. Commercial UAVs finds applications in agriculture, infrastructure, emergencies, photo-videography, logistics services and many more areas. Precision agricultural UAVs are used in farming to optimize and improve yield in crop. UAV's with image processing technology are used for crop yield estimation, field mapping and topography applications. Precision agriculture aims at optimizing the yield based on observation, measurement and response to variations in crops [1]. The UAVs until recently were mainly used as measurement and observation tools for concept of precision agriculture. The technological advancement in UAVs have made it possible to lift larger payloads, thus enabling lifting pesticides and insecticides over the fields and apply the same.

In India, large scale mechanized farming did not take off due to fragmented land holdings, manual labor are still employed in large numbers for cultivation. Manual agricultural activity includes spraying, de weeding, sowing and harvesting. The problem is exacerbated due to large-scale migration from rural areas to cities. India has the second largest cultivable land or arable land [2], and largest irrigated crop area in world. For better crop protection and high yield year after year, Indian farmers are manually spraying large quantities of potentially harmful chemicals and in last 4 years 272 farmers died[3] due to pesticides in Maharashtra, India.

The solution to the problem of manual labor needs, health hazards and land fragmentation can be addressed by using unmanned aerial spraying technology. Apart from hobbyists, manufacturers started making agricultural drones as early as 2010's [4] with spraying capacities between 5 and 10 liters. Dà-Jiāng Innovations or DJI; an established drone company, had developed DJI AGRAS MG-1 and MG-1S, which is a Multi-rotor with 10-liter payload, 1.7 liters per min spray rate and 10-15 minute of flight time. However, the very-low volume application rate of 10-liter payload is not compatible with Indian spraying practices where high volume spraying practices are well established. This factor motivated us to develop a larger payload spraying drone with low volume spraying rate for effective use of agriculture drones for small to large land mass (up-to 20 hectares) with reduced number of flights and changes over times.

The objective of this paper is to present design and development of a novel Prototype Unmanned Aerial Sprayer for plant protection and precision agriculture, which is discussed in the further sections.

2. DESIGN GOALS AND PARTS SELECTION

The design goals are principal objectives, which the proposed project aims to achieve. Major steps to derive parameters needed for prototype development such as payload, weight, flight time, type of UAV and selection of important parts are discussed in the below sections.

2.1. PAYLOAD ESTIMATION

The payload is an important component, around which the whole prototype is designed. The volume application rate (VAR) is the quantity of formulation applied per hectare. The information provided in table 2.1, classifies the five different classes for volumes of spraying in liters per hectare (l/ha) for field and tree/bush crops [5].

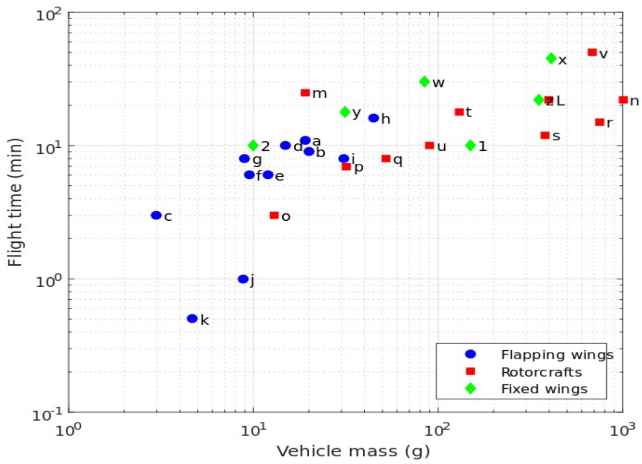
Table No. 2.1 Tabulation of categorized volume application rates for pesticide spraying in liters/hectares for field and tree/bush crops.

	Field Crops in liters/hectare	Tree and Bush Crops in liters/hectare
High Volume (HV)	more than 600	more than 1000
Medium Volume (MV)	300-600	500-1000
Low Volume (LV)	50-300	200-500
Very Low Volume (VLV)	5-50	50-200
Ultra Low Volume (ULV)	less than 5	less than 50

A UAV with payload of 20-liter was feasible to develop for agriculture applications. To meet out this requirement, the pump having 5-6 liters per minute spray rate was selected which will incorporate rapid dispersion. Having 20-liter payload to cover large land holdings significantly reduces number of flights and changeover times. Moreover, findings in survey reveal that 20-liter payload is an effective and efficient alternative to a 10-liter payload sprayer available in the market.

2.2. FLIGHT TIME PREDICTION

With reference of literature survey covering large payload UAV flight data and commercial drone flight times shown in Fig 2.1. [6], an average of 10-13 minute flight time with full payload is essential for prototype.



a. Nano Hummingbird
b. DelFly Explorer
c. DelFly Micro
d. H2 Bird
e. MicroBat
f. Bionic Bird
g. Avitron V2.0
h. 36cm Ornithopter
i. 28cm Ornithopter
j. 15cm Ornithopter
k. 10cm Ornithopter
L. Parrot Bebop drone
m. PD-100 Black Hornet PRS
n. DJI Phantom 2
o. Seiko-Epson uFR-II
p. Ladybird V2
q. Mini X6
r. 350.QX2
s. AR.Drone 2.0
t. QR Y100
u. QR W100S
v. eBee
w. Black Widow
x. Wasp III
y. Univ. Florida MAV
z. H301S
1. Diamond 600 EP
2. EPFL MC2

Fig 2.1. The graphical representation of flight time's vs vehicle mass of surveyed UAV in the current market.

2.3. UNMANNED AERIAL VEHICLE MODEL SELECTION

After thorough consideration, Hexacopter configuration was chosen. Hexacopter has six motors and propellers as shown in Fig 2.2, it provides a good compromise between the stability of an Octocopter and the long flight times of a Quadcopter. Px4 and Pixhawk flight controller systems were suitable for this model because both these flight controllers are stable open source projects, this allowed us to rapidly prototype the aerial sprayer at the same time giving us freedom to reprogram the flight controller to spraying applications.

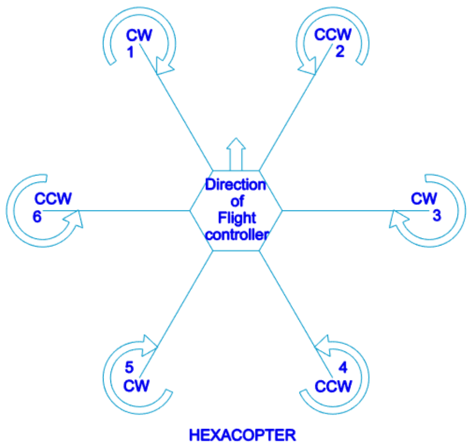


Fig 2.2. Hexa-copter frame with motors and propellers configuration with direction of motion (source https://oscarliang.com/types-of-multicopter)

2.3.1. ALTERNATIVE CONSIDERATIONS

Other technologies such as hydrocarbon fuel based UAVs and fixed wing electric planes were considered for proposed project. The Hexacopter configuration is chosen due to the versatility of vertical take-off and landing as well as the degree of freedom of movements [7].

2.4. DESIGN OBJECTIVES

In view of the above discussions, taking into account the assumptions stated therein, the design objectives of the proposed prototype are as follows:

- To lift and operate with 20 liter liquid payload.
- To spray at 6 liters per minute.
- To fly for 10-15 minute with fully charged batteries.

2.5. TAKEOFF WEIGHT CALCULATION

The takeoff weight of the UAV is the overall gross weight, which includes payload weight, battery weight, structural weight including all the electrical harnesses and electronic systems. Due to lack of data on weight and thrust parameters in large size drone, the calculation was worked backwards from payload weight and flight time.

The calculation is:

The payload weight of 20 kg and flight time of 10 to 13 minutes were fixed values for the calculation. In association with output values, the gross weight was gathered by numerical methods of assuming a final weight and finding the other variables. The important findings were battery weight, which ultimately gave the value of takeoff weight, the calculations are as follows:

The known values:

Payload weight (PW) = 20 kg

Flight time (FT) = 10-13 minute

Thrust to weight ratio (TWR) = 2 for efficient flight of 10-13 minute and 2.5 for agile and acrobatic flight

The unknown values:

Battery weight (BW)

Airframe structural weight (AW)

Gross takeoff weight (TW) = PW + BW + AW (1)

Thrust = TW * TWR (2)

The solution derived is by iterative process of assuming the RHS value and finding the unknowns.

The assumptions are as follows:

Assumed Gross takeoff weight (TW) = 50 kg

Assumed TWR = 2 and 2.5 for two different cases.

Thrust (i) and Thrust (ii) = 100 kg and 125 kg respectively.

Above-mentioned thrust equation provides power consumption for ideal cases. For 100 kg thrust with best-case scenario of a 5 grams per watt power efficiency the battery weight (BW) will be 10 kg.

With Battery weight (BW) substituted in equation number (1) provides, the estimated airframe structural weight (AW) of 20 kg.

The gross take-off weight (TW) of 50 kg, which is derived in view of the above-discussed iterative scheme, has been considered for motor and propeller selection.

Obtained specifications for prototype aerial sprayer are as follows:

a) Gross takeoff weight is 50 kg.
b) Battery weight is 10 kg
c) Airframe structural weight is 20 kg
d) Thrust of 100-125 kg.

2.6. PROPULSION PARTS SELECTION

The propulsion system consists of motors, propellers and electronic speed controllers (ESC). For thrust of 100 kg, the required motors, propellers and ESC selection are discussed in below sections.

2.6.1. MOTORS

T-Motor's P80 Brushless DC (BLDC) motors are used in this project, which matches the thrust required for proposed prototype Ariel sprayer. These motors are having 120 revolutions per volt (KV) and generates 104 kg thrust for Hexacopter configuration.

2.6.2. ESC SELECTION

The T-Motor P80 BLDC motors draws maximum continuous current of 70 Amps, the recommended ESC to drive current of 70A, for selected motor is T-Motor Flame 80.

2.6.3. PROPELLER SELECTION

T-Motor carbon fiber reinforced composite propeller of 30-inch disk diameter and 10.5-inch mean pitch, is compatible with T-Motor P80 BLDC motor, as it generates the required thrust of 100 kg with Hexacopter configuration.

2.7. BATTERY SELECTION

In view of selected motors and ESC's, the power required is calculated according to the weight and flight time. The calculation is as follows:

T-Motor P80 maximum continuous current required: 70 Amperes

The maximum current drawn for Hexacopter configuration: 70 amperes * 6 motors = 420 amperes.

Maximum power required for vertical takeoff of proposed prototype (VA): 192 amperes (T-Motor P80 draws 32 amperes for 70% thrust, this thrust is sufficient for proposed application).

Volts per Lithium polymer cell (LI): 4.0 Volts

Voltage required for individual T-Motor Flame 80 ESC (V): 48 Volts

Battery calculation:

Assumed Flight time for arriving at battery capacity (FT) = 10 minutes and 13 minutes

Number of Li-Polymer cells required = V/LI = 48/4.0 = 12 cells.

First Case: Battery capacity (BC) = (FT (in minutes) * VA) / 60 = (10 minutes * 192) / 60 = 34 Ampere-hour (2)

Second Case: BC = (13 * 192) / 60 = 41.6 Ampere-hour (3)

New Calculation includes two scenarios with different battery capacity, the batteries selected based on payload and TWR ratio:

(a) 32-Ampere-hour at 48 Volt. (4)

(b) 44-Ampere-hour at 48 Volt. (5)

Comparing values of (2)-(3) and (4)-(5) the flight times are projected by substituting the (2)-(3) and (4)-(5) in First Case and second case equation respectively. The tabulated values of different flight times accordingly to the payload weights at two identified scenarios in table 2.2.

The flight time equation is:

Flight time (FT) = (BC * 60) / load required (in amperage) (6)

Table No. 2.2. Tabulation of calculated by substituting battery capacities in equation (6), determines flight times based on T-motor loads available and two identified battery scenarios.

Battery capacity in Ampere-hour and voltage in volts	Payload weight in Kg	Flight time in minutes
32 Ampere-hour and 48 Volts	20 kg (full load)	5-5.5 minutes
44 Ampere-hour and 48 Volts	20 kg (full load)	7-8 minutes
32 Ampere-hour and 48 Volts	No load	10-12 minutes
44 Ampere-hour and 48 Volts	No load	15-17 minutes

It can be observed from the table 2.2., as the payload diminishes while applying the chemicals there is a substantial gain in flight. At a spraying rate of 6 liters per minute, a flight time of 10 minutes can achieve a spray volume of 60 liters over a sizable land parcel. Bundling COTS batteries by connecting them in series and parallel to make desirable battery packs of different capacities was considered.

3. PROTOTYPE UNMANNED AERIAL SPRAYER DEVELOPMENT

In view of above discussed objectives and required parts selection, the development steps and procedures consisting of mechanical design, electrical design and fabrication are discussed in the following sections.

3.1. DEVELOPMENT SCHEMES

The technology for the prototype was divided into electronics, software and mechanical components, with corresponding goals and milestones. The prototype had to be developed from ground up with indigenous techniques and materials and was inspired by “Make in India” initiative; all the fabrication steps were divided among the following disciplines:

- Mechanical Fabrication: The fabrication involves structural design, analysis, simulating stress strain and other aspects.
- Electronic Fabrication: This involves wiring harness and power distribution, signals and battery selection.
- Software Installation: This involves the autopilot installation, programming, configuration and calibration.

3.2. MECHANICAL FABRICATION

The mechanical part design and assembly was done using PTC Creo parametric software. Autodesk Simulation Mechanical software was used for FEM analysis of the parts constructed in proposed prototype.

The mechanical structural design was divided into two parts as follows:

a) Payload design: designing of pesticide container and material selection for the container.
b) Airframe design: designing of structural components for final assembly of prototype.

3.2.1. PAYLOAD SELECTION

The 20-liter plastic container was selected after detailed research and study on many available options. The selected container is made of High Density Poly Ethylene (HDPE); as it is considerably tough and economical in available plastics, which is also compatible with most of the chemicals used in pesticides. The HDPE container is having wide inlet for rapid and easy filling of liquid and small outlet for hose attachment. The container is sourced from a reputed manufacturer, and is verified for possible cracks and punctures by impact and stress tests.

3.2.2. AIRFRAME DESIGN

The most critical part of development was airframe design of proposed prototype; this enabled us to consider the safety factor while selecting airframe members. This involved, drone central core design, design of arms for motors, design of hinges to incorporate folding mechanism in order to accommodate transportation, designing motor mount and designing landing gear. The whole airframe (refer Fig 3.1.) was developed with different aerospace materials, namely carbon fiber twill laminates, aerospace grade aluminum 6061-T6 and alloy stainless steel SAE 304 grade Steel.

Fig.3.1. CAD Assembly of complete prototype with 20-liter payload.

Central Core: The central core is made-up of two hexagonal carbon fiber twill woven plates, separated by brass spacers. The central core houses all the electronics with battery, which is designed to withstand an impact of up to 120 kgs. The central core is a regular hexagonal shape with extreme dimensions: 500mm width, 514mm length and 60mm height including and weighed at 4 kg.

Foldable Arms: The six carbon fiber arms that are diverging normal to each flat face of hexagon with length of 540mm and 32mm outer diameter and supported by foldable hinge machined of Aluminum 6061-T6 with a folding angle of up to 60 degree. The folding is accommodated to reduce space for storing and transporting the UAV, which is by unscrewing a single aluminum screw. The weight of foldable arm including the aluminum hinge and motor mount is 1 kg.

Landing Gear: The Landing gear design, focused on center of gravity of complete assembly. The material used is alloy stainless steel SAE 304 grade tube. The landing gears is designed to mount in aluminum 6061-T6 machined holder mounted to the bottom of central core base plate. The orientation of landing gear was tilted of absorb landing shocks to the center of the airframe where it is most rigid. The weight landing gear including the aluminum holder is 4 kg.

Payload Mounting Design to Central Core: The payload was initially designed for mounting on railings, but because of complex part requirement and number of connecting parts, it was changed to tube cage design. The payload cage is designed with stainless steel SAE 304 grade hollow cylindrical tubes matching the profile of liquid container. The design limited steel cage weight to 2 kg with the fasteners.

3.3. MACHINING AND ASSEMBLY

The detailed designs and drawing are the blue prints for fabricating the real-time prototype. Hylam sheet was selected for dummy assembly (please refer Fig .3.2. (c)) in place of carbon fiber laminates. The CNC operations and other machining activities were carried out on Hylam board and aluminum 6061-T6 please refer Fig.3.2. (a) materials for required profile and shape.

Fig. 3.2. (a) Picture of cnc machining operation on designed part.

Fig. 3.2. (b) The cage assembly for HDPE Payload.

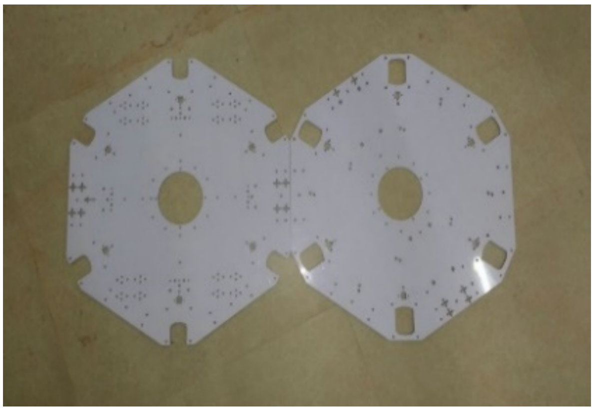


Fig. 3.2.(c) Hylam sheet cutout of central core.

Assembly of dummy model as shown in Fig 3.3. was done to understand the fittings and mountings using all real time components excluding the carbon fiber central core.

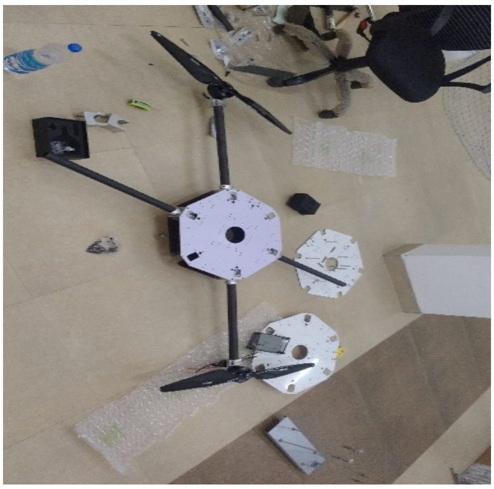


Fig 3.3. In house Assembly of dummy prototype for mount verification.

Fig 3.4. The final assembly of all the real time components.

Fig 3.5. Folded prototype for storage and transportation.

3.4. AUTOPILOT

The autopilot firmware for Hexacopter airframe was selected and calibrated for stable flight using radio remote controller. The flight modes such as altitude hold, landing speed, ascending speed were also designated to the radio remote controller. The configuration of alternate motors in Hexacopter was reversed to cancel out the rolling moment caused by propeller and carry inflow of thrust.

3.5. ELECTRICAL HARNESS

A proper electrical harness is required to handle and transmit the power from source to load. This constitutes, Power Distribution Board, Wire circuitry and connectors.

3.5.1. POWER DISTRIBUTION BOARD

The power distribution boards equally distributes the source current of maximum 1000 amperes, required for Hexacopter motor configuration.

3.5.2. WIRE CIRCUITRY

High conductance silicone wire were selected for high current transmission and for flexibility of wire.

3.5.3. ELECTRICAL CONNECTORS

Application specific Anti-Spark connectors were selected to transmit the high current and importantly to avoid sparks of high current discharge, while connecting and disconnecting.

4. FIELD TRIAL RESULTS AND DISCUSSIONS

The field trials included initial flight checks, spraying operation and final demonstration, all of which is discussed in the following sections.

4.1. INITIAL TRIALS

The initial prototype test was conducted, to identify and rectify any errors. The maiden flight was conducted at Skykrafts Aerospace's private facility and for faculty safety reasons the prototype base was tied to weight as shown in figures. Due to imbalance and improper autopilot parameters, the test failed and two propellers broke after the crash as seen in Fig 4.1.

Fig 4.1. Crash site of prototype unmanned aerial sprayer, with broken propellers.

The propellers were then developed indigenously at Reinforced Plastic Industry located in Bangalore, for continuing the tests. The broken propellers were replaced with indigenized propellers as shown in Fig 4.2. These propellers were placed in alternative positions along with the T-Motor propellers.

Fig 4.2. The indigenized carbon fiber propellers developed at Reinforced Plastic Industry.

4.2. FIRST FULL FLIGHT AND SPRAY OPERATION

Further test flights were done with indigenized propellers, sprayer boom and pump switch trigger. After fine-tuning the autopilot parameters, further tests were carried out by harnessing all the six arms as shown in Fig 4.3, the first full operation flight was conducted in presence of members of KLE Technological University in open land. The operation included, water filled payload to takeoff, maintain altitude and traverse in preconceived path, trigger the spray, complete the travel cycle and safely land.

Fig 4.3. The sand weights suspended to UAV arms for takeoff calibration.

4.3. FINAL DEMONSTRATION

The final demonstration included multiple operations from takeoff, altitude hold and spray consistently over the distance, return to initial position and land. This activity was done in open field approved by University of Agricultural Science, Dharwad, in the supervision of respected Agricultural scientists, PhD. scholars and Field experts. The final demonstration video of Prototype Unmanned Aerial Sprayer can be viewed from the following YouTube link: https://youtu.be/216OtsbyQio.

4.4. RESULTS

Finally, the Prototype Unmanned Aerial Vehicle successfully developed and demonstrated for 20-liter payload and the flight demonstrations were being carried out in the field, under the supervision of Agricultural scientists from University of Agricultural Sciences, Dharwad and field experts.

4.4.1. COMPARSION WITH OTHER AGRICULTRUAL UAV

The qualitative comparison of prototype sprayer with other agricultural drone manufacturer in the market reveals, the payload capacity of 20-liter being the first in its class. The prototype-unmanned sprayer with 6 liter per minute and 10 minute of flight time covers required volume application rate of 50-300 liters per hectare in fewer flights and with less changeover time, compared to DJI AGRAS MG-1S.

Conclusion

The field trial results indicate that the proposed Prototype Ariel Sprayer has successfully completed spraying operation. The Prototype Ariel Sprayer maintains consistent altitude throughout operation as desired by the investigators from University of Agriculture Sciences, Dharwad, with payload of 20 kg. The Aerial vehicle can be upgraded with autonomous flights and hyper spectral camera video transmission for 3D image processing in future.

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