KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

COLLEGE OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

A REPORT ENTITLED

DESIGN, FABRICATION AND TEST OF AN UNMANNED REMOTE CONTROLLED AGRICULTURAL HEXACOPTER.

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DECLARATION

This report, entitled "Design, Construction and Test of an Unmanned Remote Controlled Agriculture Hexacopter", is declared as our authentic work, borne of our own ingenuity, skill and work and was carried out at the Kwame Nkrumah University of Science and Technology (KNUST) as a basic requirement for the award of a BSc. Aerospace Engineering under the wonderful tutelage of **Mr. Peter Oppong Tawiah** in the **2018/2019** academic year.

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ABSTRACT

Herein lies a step-by-step account of the design, fabrication and test of a working remotely controlled electric hexacopter capable of performing aerial spraying of liquid agro chemicals. The scope of the entire piece is captured in five chapters.

After several improvements of designing aerial vehicles in KNUST, this group was tasked with the mammoth task of designing a 'new' breed of hexacopters capable of carrying large payloads of agro chemicals and spraying onto medium sized farms as required. More specifically, the finished product was required to be lightweight yet strong enough to allow aerial spraying.

Due to the inexistence of previous KNUST Aerospace Engineering works in the field of agriculture, the agriculture aspect of the project was basically done from scratch. Through careful analysis and thorough research on works from outside the university, five ingenious concepts were developed and assessed. The engineering technique of a decision matrix was used in arriving at the final concept.

A light-weight, geometrically suitable frame was chosen. The design emphasized functionality as well as aesthetics. As such, efforts were made to ensure that all wiring and exposed elements were tucked in neatly. The spraying mechanism employed, made use of the geometry of the frame. For instance, tubes carrying the spraying fluid were passed directly under arms with all cables and wires passing through the holes of frames to avoid them hanging around the structure.

In the end, the finished product was characterized with the ability to carry a payload of 2kg on a light structure in flight for aerial spraying.

ACKNOWLEDGEMENT

It is impossible to convey in cold print our utmost gratitude to the Almighty Himself; to our dear project supervisor, Mr. P.O. Tawiah for his great guidance; and to our committed lab technician, Mr. Ernest Adomako for the myriads of experiences he shared with us. Also, we are grateful to all members of previous unmanned aerial vehicle project groups from KNUST. Their illustrious works made our journey much easier and clearer. Last but not least, we deeply appreciate our very own of the class of 2019 (Aerospace Engineering). Their tremendous efforts, contributions and criticisms have all culminated to this great piece of academic work.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: - INTRODUCTION

A hexacopter (hex) is a type of multi-rotor aerial vehicle that has six motors (propellers) capable of lifting itself and maintaining hover. Unlike a fixed wing aircraft, a hex generates both thrust and lift using the same set of motors and propellers.

Hexacopter power plants are mostly arranged in alternating fashion. This is deliberately down to cancel out all forms of undesired counter-torque generated by the rotating propellers.

Forward and sideway movements are achieved by differential thrust application. Reducing the speed on certain parts of the hex causes the vehicle to move in that direction. Upward and downward motion are the result of increasing and decreasing thrusts respectively.

1.1 HEXACOPTER

The components for all drones are the same. What differs is the number of motors used to generate thrust and the battery capacity. The premier advantage of the hexacopter over quadcopter and tricopter is its ability to remain in flight upon losing one or two motors. Nonetheless, yaw control will be lost and it is the safest bet to go for.

The motors used for a hexacopter should be of the exact same size and weight, with same specifications. The typical type of motor on every drone including hexacopter is an outrunner motor. The motors must fit with the ESCs and the battery as well.

1.2 PROBLEM STATEMENT

Four years down the line, final year Aerospace Engineering students of KNUST have sought to optimize drone design and construction for aerial photography amidst numerous challenges encountered year after year in the quest to achieve this. This group however seeks to tackle another practical application of the drone technology aside aerial photography and real-time imaging which have been done by our predecessors. We desire to design and build an unmanned remote controlled agricultural hexacopter.

These drones inspect large farms of over 10,000 hectares in a few hours, which is beyond human capabilities. These agricultural drones are less costly, versatile and offer a wide range of services related to farm imagery, crop status, irrigation needs and pest attacks on farms. They can be used for seeding and this offers a great deal of time savings to farmers as compared to the traditional methods. Along with ground robots (e.g., GPS-guided autonomous planters, sprayers, weeders and combiners) and regular satellite guidance, they could offer total automation of farm production procedures.

The farmer will then not have to go through the drudgery of spraying these farms. Farmers as a result of this are exposed to a lot of health hazards while mechanically spraying all by themselves. The traditional crop spraying is quite inefficient and tedious as it takes relatively long time to spray very large areas and is not even precise as it leaves some parts of the crops completely unsprayed or better still less sprayed than the others. Traditional sprayers such as the field sprayers are quite difficult to operate in sloppy or hilly terrain and may also destroy a lot of crops during the spraying.

However, drones can also be designed to carry pesticide as payload and then spray it more efficiently. These drones can spray 50-100 acres per day that is about 30 times more than traditional spraying methods. Drone spraying is not influenced by terrain and crop height. This method of spraying also protects the farmer from harmful animals. All these advantages of drone spraying over the traditional make it more efficient, reliable, and safe.

It is against this backdrop that even though our predecessors have made great strides in building drones for aerial photography we seek to design, build and test a drone for agricultural purposes.

1.3 OBJECTIVE

The objective of this project is to design, build and test a remotely controlled unmanned electric hexacopter capable of performing aerial spraying of agrochemicals onto medium-sized vegetable farms and nurseries.

1.4 SPECIFIC OBJECTIVES

- To design and build a light-weight (7 kg) yet strong remotely controlled electric hexacopter.
- To design a hexacopter that can carry about 2 litres of agro-chemicals and spray onto vegetable fields.
- To construct a three minutes endurance machine with stability necessary to ensure good spraying results.

1.5 METHODOLOGY OVERVIEW

- Literature Review - Journals, articles and books related to hexacopters and/or crop spraying perused. Also, previous reports would be critically analyzed.

- Design, concept generation and evaluation - Several conceptual designs will be produced. Based on a strict evaluation criterion, the design would be carefully studied and innovative features would be incorporated into a final design.
- Simulation - The chosen design for aerial spraying agricultural hexacopter would be digitally designed and simulated to analyze its performance under all conditions.
- Construction and testing - Avionics, electric motors, tank and spray nozzles would be installed on a constructed frame. The constructed device would undergo a ground test, test flight and spraying tests.

1.6 STRUCTURE OF THE REPORT

Chapter 1 is the introductory chapter, it encompasses a brief description of a hexacopter with a historical review of its development; project background, problem statement, objectives and a general overview of the methodology.

Chapter 2 gives the literature review of the study. It entails the analysis of previous research and findings done by research institutions and companies.

Chapter 3 tackles the methodology which covers the various conceptual designs, evaluations and material selection of the hexacopter.

Chapter 4 focuses on the detailed design and calculations of the hexacopter with results and discussions on the findings made in addition to the various ground and flight tests that were carried out to test the functionality of vehicle.

Chapter 5 deals with conclusion and recommendations for the project. It entails various challenges that were encountered in the process and achievements made.

CHAPTER 2 – LITERATURE REVIEW

In this chapter, an overview of previous research works on the hexacopter is captured. The various configurations, parts and accessories of a hexacopter is also discussed. Furthermore, the agricultural applications pertaining to this project is captured. Hexacopter dynamics has also been briefly tackled in here.

HISTORY OF MULTIROTOR AIRCRAFT

The multi copter airplane as we see today is an improvement and refinement of a historical work that began several decades ago. Motivated by the success of the Wright brothers flight in 1903, there have been attempts to vertically lift off and land. Attempts therefore was made to build quadrotors. The building of the quadrotor helicopter commenced with the design and construction of the Breguet-Richet Gyroplane No.1 (1907). This was the first rotary wing aircraft to lift itself off the ground, although only in tethered flight at an altitude of a few feet. The design proved to be very unstable and hence impractical.

Going forward, Etienne Oehmichen also experimented with rotorcraft designs in the 1920s and came up with the Oehmichen No.2. Among the six designs he tried, his quadcopter No.2 had four rotors and eight propellers, all driven by a single engine. (Anderson)

DRONES AND THEIR USAGE IN AGRICULTURE

However, behind the scenes, the military has also made attempts of getting unmanned aerial vehicle(UAV) into the air. First efficient use of drones was seen during military conflicts starting from early 20th century. For a long stretch of time, say a few decades, their usage was confined and stayed within the preserves of military engineering groups. Drones were initially developed to counter the enemy Zeppelins in World

War I. It seems, earliest drone to be used in military warfare was developed in 1916. During the period between World Wars I and II, there were several modifications and improvements to drone technology. (Nicole, 2015)

During recent decades, UAVs engaged in warfare named Global Hawk. Predator and so forth are noteworthy for this. These are high altitude drones of long flight endurance. They cover long distance in a day to seek the targets (Tetrault, 2014). However, it seems, until past decade, most of the drones used in surveillance and military zones were fixed-wing type.

However, in recent times this drone technology has been made available to the general public. The proliferation of drones especially the rotor copters can be attributed to the technological advancements in electronics which has made it very easier to control multirotor UAVs.

Further the use of drones for aerial photogrammetry, studying weather pattern and even agricultural usage has contributed to the recent development and proliferation of multirotor UAVs like the quadcopter and the hexacopter.

For centuries improvement in farming and other agricultural work has mainly been attributed to scientific research and technological advancement. It is therefore of no surprise that drones found their way in to the agricultural sector. (Krishna,2018).

The need to perform tasks such as crop scouting, gathering accurate data about crop health, supplying fertilizers and water, spraying plant protection chemicals and so forth have necessitated the introduction of Drones in agriculture. Similar needs like these was what inspired the Japanese Agricultural Department to contract Yamaha Motor Company (Japan) to build a crop-dusting drone. Therefore, in 1983, the company launched the now popular RMAX copter drone. First commercial use of Yamaha's R50 had begun by 1987. At present, RMAX is a popular agricultural drone in the farms of Far East. It is used to spray pesticides to rice crop.

Agricultural drones made of low-cost wood and cameras attached to them have been in vogue, since past 5 years in Latin American nations such as Peru. They provide excellent high-resolution imagery of crops such as potato and wheat (Cisneros, 2013).

It is against this backdrop of making UAVs very useful in farming that we seek to design and build a hexacopter for agricultural spraying.

2.1 VARIOUS HEXACOPTER CONFIGURATION

The hexacopter has 6 motors apart on a symmetric frame, with three sets of CW and CCW propellers. There are various hexacopter configurations one can choose from;

1. The Y6 configuration
2. The Hexa X configuration
3. The Hexa + configuration**2.2 Y6 CONFIGURATION**

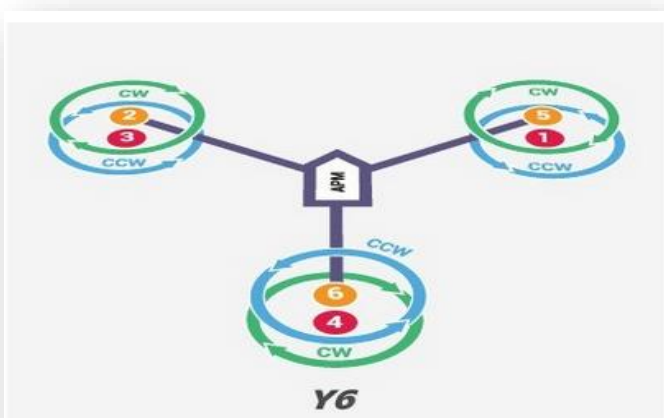

Figure 1: Y6 Configuration Diagram

The Y6 has 6 motors in a Y shape frame. It has 2 motors per arm, one above one below. It uses both CW and CCW propellers on the same arm.

Figure 2: Y6 Configuration

2.3 HEXA 'X' CONFIGURATION

An hexa X configuration has 6 motors that are mounted on 6 arms of the frame, with three set of CW and CCW propellers. It shares similar characteristics with the Y6 except for its disadvantages. In the Hexa 'X' configuration two pairs of arms each form the front and aft of the copter.

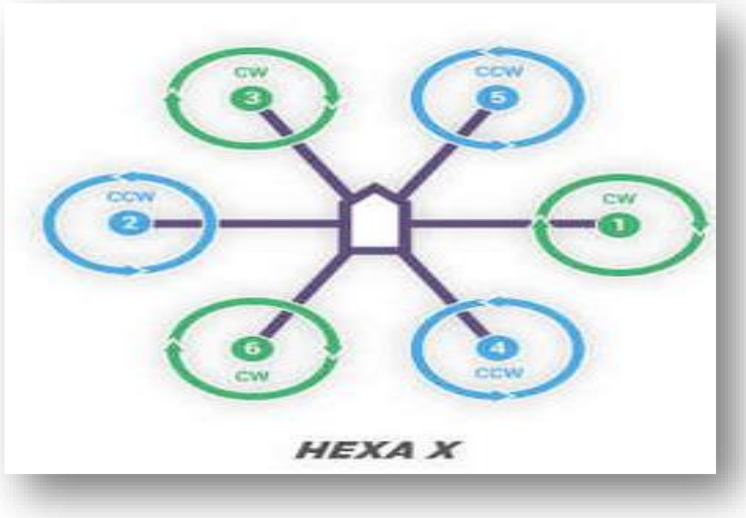

Figure 3: Hexa X Configuration Diagram

2.4 HEXA '+' CONFIGURATION

Just like the hexa X, the hexa + has 6 motors. A motor is mounted on each of the 6 arms of the frame. It has three (3) sets of CW and CCW propellers. However, unlike the Hexa'x' only a single arm is considered as the forward and aft of the copter.

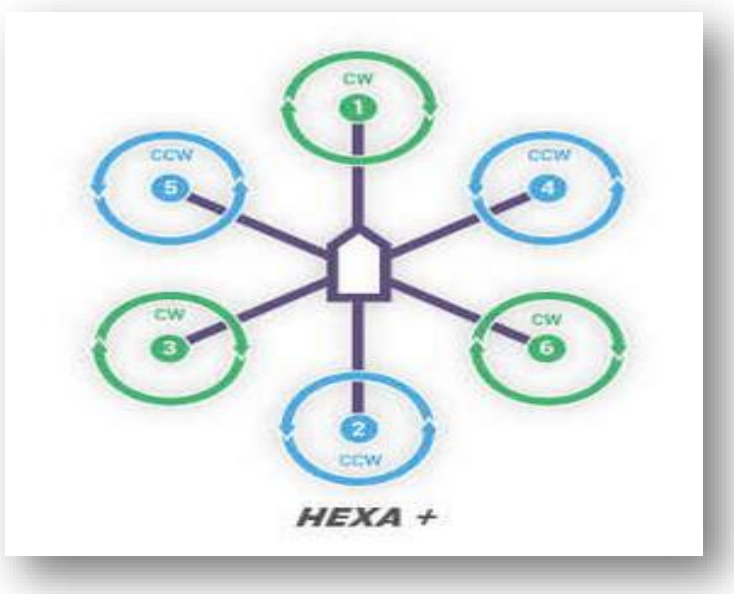

Figure 4:Hexa + Configuration Diagram

2.5 DIFFERENCE BETWEEN ‘X’ AND ‘+’ CONFIGURATION

- For X configuration, pitch and roll will be varied using two motors while the ‘+’ configuration moment will be varied using one motor.
- The X is more stable than the +.

2.6 PARTS OF A HEXACOPTER

A hexacopter (hex) is generally a six-rotor aerial vehicle. In many ways, it can be regarded as an elegant yet effective upgrade of a quadcopter (four rotors). Among all the accessories that a hex may come with, it essentially consists of seven main parts: the frame, power source, motors, propellers, a flight controller, electronic speed controllers (ESC), power distribution module and a radio controller. Other components such as a spraying sub-system (in the case of this project) and an FPV (First Person View) set may be added to allow the vehicle to perform some specific task or tasks.

2.6.1 Frame:

The frame may be regarded as the chassis of the hexacopter. All external and internal forces (applied and transmitted) are ultimately borne by the frame. Hence in simple terms, the frame must be strong enough to withstand all forces encountered during the service-life of the hex but must ironically be light enough to be able to be lifted by the available power plant.

Choice of the frame depends on the use of the hex and what flight performance one desires. Frame designs vary based on the configuration, available material and required dimensions. Some maverick designs, contrary to the more generic six-limb hex configuration, like the Y6 configuration have for instance been tested and applied;

Figure 5:Hexa X design

Figure 6:A Y6 Design

Materials:

Material selection is based on a number of sometimes conflicting requirements. Chief among them are cost, material density, vibration absorption and strength. Materials range from fully natural sources to composites. A few are discussed below.

Wood:

The use of wood in the air-vehicle manufacture predates the invention of the UAV (Unmanned Aerial Vehicle) itself. In classic UAV manufacturing, balsa is chiefly used. Balsa wood is relatively cheap and can be machined into desired shapes without the use of complex machinery. Still in the wood domain, another strong candidate for the job is bamboo. It is common knowledge that bamboo can support enormous loads (that is why it is used during building construction). The main difficulty with its use is in getting it in desired shapes and sizes since whole bamboos are mostly hollow.

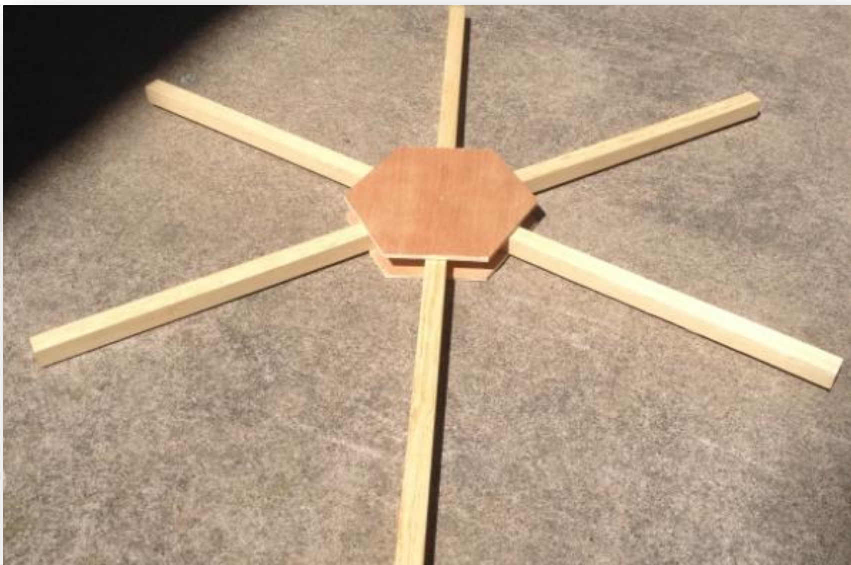

Figure 7:Wooden Hexacopter Frame

Aluminium:

Aluminium is renowned worldwide for being the first in solving the engineering paradox of light yet strong. While this is fantastic in aeroplane manufacturing, it is generally no extraordinary feet as aluminium is regarded as relatively heavy in the drone world. The availability of its well-known machining techniques is a plus. Though heavy, a thin (meets stress requirements), well casted single aluminium frame structure eventually inures to great weight savings for the entire drone.

Figure 8:Aluminium Frame

Fibreglass:

It is a composite covering material made of glass fibres in resins. Compared to wood and aluminium, it is stronger and lighter but flexes when exposed to bending forces. It is also not opaque to radio waves nor readily available on the Ghanaian market.

Figure 9:Fibre glass

Carbon Fibre:

Regarded as the most technologically advanced material of the day in the drone world, carbon fibre is superior to wood, aluminium and glass fibre in many regards. It is so far the lightest and strongest material and additionally does not flex under bending forces. Its major drawback, however, is its opaqueness to radio waves. This may make remotely controlling the hexacopter difficult especially when the vehicle is far from a control station.

Figure 10:Carbon Fibre

Below is a table comparing the materials with respect to the Ghanaian market.

Table 1:Material Selection

Material	Density $10^3 Kg/m^3$	Cost per unit length	Vibration Absorption	Availability	Strength
Wood	0.16	MODERATE	HIGH	HIGHLY AVAILABLE	GOOD
Aluminium	2.71	RELATIVELY HIGH	POOR	AVAILABLE	BETTER
Fibreglass	1.9	HIGH	MODERATE	UNAVAILABLE	HIGH
Carbon Fibre	1.7	VERY HIGH	MODERATE	UNAVAILABLE	VERY HIGH

2.6.2 Motors:

Motors form the power plant of the hexacopter. Most drones are electrically powered and hence electric motors will be analysed. Generally, there exist two varieties: brushless motors and brushed motors. The latter is almost never used in drone design since its power requirements are significantly large.

The torque required to produce the necessary lift can only be produced by huge sized motors and may even require some gearing system of a sort. Brushless motors, on the other hand, offer fantastic abilities as they do not have any carbon brushes within them. Commutation of terminals is done electronically and hence, offers better speed and torque characteristics. Power requirements are also relatively low with prolonged motor life as well.

The kind of motor to use is fundamentally linked with the total weight of the aerial vehicle. In drone design synthesis, knowing the total weight beforehand is usually difficult. What is usually done is to get a rough estimate and use the information to size your motors. As a rule of thumb, the motors should collectively produce at least two times the net weight of the remotely controlled aircraft. The motor may be top-mounted or bottom-mounted on the frame.

Figure 11: Motor

2.6.3 Batteries:

For an electrically controlled drone, batteries provide the power that drives the motors. An ideal battery would be one that is lightweight but can sustain a prolonged flight time. The most common battery in use is the Lithium Polymer(LiPo) cell. LiPo batteries are characterized based on the battery Discharge Rate, Capacity and Number of Cells.

Capacity:

This refers to the power that the battery can deliver. For a constant voltage source like LiPo Batteries, power is usually quoted in milli-amp-hour(mAh). A larger mAh value means more flight but generally implies more weight since they are generally heavier.

Discharge Rate:

As the name implies, it characterizes the rate at which a battery can release its power. Batteries with low discharge rate tend to have a shorter life since motors try to draw more power than can be supplied and hence the battery dies out soon. If one is lucky, the batteries may not get damaged but the performance of the hexacopter will be ridiculously slow and this may cause crashing.

Voltage:

Higher voltage batteries tend to have a higher power. However, since voltage count is directly related to the number of cells, a trade-off between weight and voltage must be made.

Figure 12: Battery Voltage

2.6.4 Propeller:

They are generally the set of rotary wings aboard the UAV. They convert the rotary mechanical energy of the motors to useful thrust. This is done by rapidly spinning the propellers at high RPMs. This causes large amounts of air to be pushed down and by Newton's third law, the entire drone lifts off. Propellers are classified by their pitch and diameter. Pitch is defined as the travel distance of one single prop rotation.

Generally, propellers with higher pitch mean slower rotation but will increase the vehicle speed which also uses more power. A higher pitched propeller moves a greater amount of air, which may create turbulence especially when close to ground. Lower pitched props, on the other hand, generate more torque with more acceleration whiles taking up less current. The greater the pitch, the higher the thrust and necessary motor output and the higher the power drawn from the battery.

Through experience, multi-rotor designers tend to use propellers whose pitch is less than 6 inches. Again, a good propeller-motor (with respect to its power rating) combination, if not achieved, can result in serious inefficiencies. What this means is that putting, for instance, a very low pitch propeller on a very fast motor can cause the propeller to be overspun (when trying to accelerate upwards), hence, generating not enough thrust to sustain the manoeuvre. This may end up crashing the entire hexacopter.

Figure 13:Propellers

2.7 Flight Controller:

Signals received by the receiver from the transmitter are fed into a flight controller. Generally, it is a software-hardware package, with input/output (I/O) pins that allow manoeuvring.

It is almost impossible for a human to control the rotational speeds of three or more motors simultaneously with enough precision to balance the craft in the air. The importance of flight controllers is established here. A flight controller is a circuit that processes signals and feeds motors and other circuitry with the appropriate voltages and currents.

The majority of flight controllers also employ sensors to supplement their calculations. These range from simple gyroscopes for orientation to barometers for automatically holding altitudes. GPS can also be used for auto-pilot or fail-safe purposes.

Figure 14:Flight Controller

2.7.1 Remote Control Transmitter:

For all practical purposes, Hexacopter are not tethered to command station via cables. Instead, a wireless system is deployed to enable distant control of the UAV. While many systems exist, control is normally achieved using radio waves.

An alternative could have been the use of infrared light (as in television set control) but it is limited because it requires a line of sight in other to work. This is evidently a major drawback in drone use.

The Transmitter sends Pulse Modulated Waves(PMW) via the radio signals to an onboard receiver to be decoded and implemented. Various Transmitters come with various functions in terms of the number of channels (control inputs), the proportionality of movement of control sticks, etc.

Figure 15:Transmitter

2.7.2 Electronic Speed Controller (ESC)

Hexacopter control and manoeuvring is chiefly achieved through differential thrust application. That is, one motor is made to move faster than the other and so forth. This implies individual motors will have to receive different amounts of power at different times. This work is done by the Electronic Speed Controller. It converts PMW signals from the transmitter and flight controller to voltages and delivers it to the motors. In the event alternating current (A.C) motors are used, the ESC also converts the D.C power from the battery to A.C.

In addition to that, Some ESCs encompass a Battery Eliminator Circuit(BEC) to provide 5 V power to the on-board electronics.

Figure 16:ESC

2.8 Landing Gear:

It is the structure upon which all components rest. It is the main load bearing member of the hex during landing and so if not properly designed, may fail the entire structure during heavy landing or crashes. Some multi-rotor designs even do not possess a landing gear as they carry no special equipment on board. Of the variety that landing gears have, there exist a number of options: struts, floats and skids.

Figure 17:Landing gear

NOZZLE

The provision of the correct nozzle for the job enables safer and more efficient spraying. Appropriate nozzles for the intended task should be supplied with the equipment. A minimum of one nozzle type suitable for herbicide application and one for fungicide/insecticide application shall be supplied with the equipment.

Deflector nozzle (also called impact, flood or anvil nozzles) are used for single nozzle application of soil applied herbicides.

Flat fans are best for spraying products onto flat surfaces: for foliar applications, the application of herbicides to soil and insecticides onto walls for control of stored product pests.

Hollow cone nozzles are used for general spraying of foliage and give good coverage of the outer parts of a canopy (used to apply insecticides and fungicides).

Solid cone nozzles are used for spot and band spraying.

Adjustable multipurpose nozzles are not recommended for crop protection use. Spray quality is difficult to reproduce and this type of nozzle encourages operators to adjust and touch nozzles contaminated with pesticide.

HIGH PRESSURE AND DRIFT

One of the primary sources of operator hazard from hand-carried portable sprayers relates to high pressure (over 4 bar) which can produce fine droplets which are prone to drift and inhalation. High pressures can also increase hazard due to component failure leading to a major leakage of spray liquid. Therefore, a key criterion in appropriate sprayer design is the provision of systems of pressure control, within the sprayer, and at the nozzle.

This guide specifies the functional requirements for sprayers and the pressure limits recommended to minimize this potential hazard without compromising spraying efficiency.

2.9 HEXACOPTER DYNAMICS

The hexacopter is a UAV that belongs to the family of multirotor. The hexacopter model is a rigid body with a symmetrical structure. This multirotor has six arms located from the center towards the vertices of a hexagon. Each arm has a propeller at the end, which is driven by an electric motor. The controlling board and battery are mounted at the center of the virtual hexagon. Because the model of the hexacopter is symmetrical, the center of gravity of the hexacopter is at the center of the hexagon. Of the six propellers, a pair of three propellers spin in one direction while the other three spin in the opposite direction. The blade on every propeller have a fixed pitch.

2.9.1 Basic Movements

The movements of the hexacopter are controlled by the angular speed of the propellers. Each propeller produces a thrust individually by pushing the air downwards. Various upward thrusts are used to give motion to model, as the source of the thrust is outside the center of gravity. In addition, with the upward thrust, reaction torque is also produced opposite to the rotation direction of the rotor. A pair of three rotors spinning in the same direction provide a resultant torque which is equal and in opposite direction of the pair of other three rotors; overall, the torque is zero when they all are spinning at same angular speed. The basic four movements of any flying objects as:

2.9.1.1 Maneuverability

The angular speed of every propeller is mapped in a particular way to generate control signals for these basic movements. In other words, the control signal of these basic movements collectively decide the angular speed of a particular rotor. The roll and pitch angle of the hexacopter results in the motion or movements along the ground, which counts for the linear movement of the hexacopter. The little pitch angle to the hexacopter provides a forward or backward movement to keep the overall thrust the same.

2.9.1.2 Throttle

The throttle is the main control of the hexacopter to provide the motion in vertical direction. The thrust generated by the propellers collectively results in all hexacopter maneuvers. All the blades have fixed pitch, so on the same angular speed they produce the thrust upwards which counter the force of gravity acting on the model. With the increase in angular speed the thrust will also increase. The certain constant threshold thrust is required to compensate the total weight of the hexacopter. With further increase or decrease in angular speed, this will generate upwards or downwards motion in vertical direction.

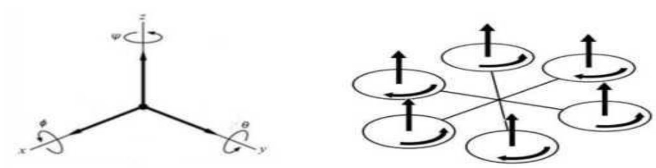

Figure 18: Thrust is shown by arrows upwards

2.9.1.3 Roll

The rotation of the hexacopter on X-axis as the center of rotation axis is called roll. The angular speeds of the propellers are controlled separately. The thrust produced by the three right side propellers is increased and the thrust produced by the three left side propellers is decreased to generate the rolling effect. The increase in thrust is the same as the decrease in the thrust so that the total thrust of the hexacopter remains the same.

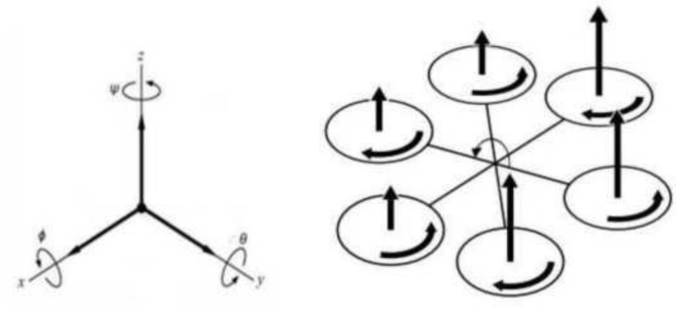

Figure 19: Right side thrust is increased and left side thrust is decreased to counter clockwise direction

2.9.1.4 Pitch

The rotation of the hexacopter on Y-axis as the center of rotation axis is called pitch. As it is generating roll, pitch is also generated by changing the angular speeds of the propellers. The two propellers are on Y-axis, so a change in their thrust will not have any effect in generating pitch. The thrust of consecutive two propellers on one side of the Y-axis is increased and thrust of the other two is decreased by the same proportion. The change in the thrust of different parts of the hexacopter will generate the pitch.

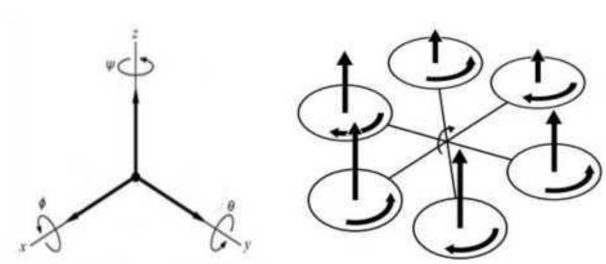

Figure 20: Two propellers generates more thrust while opposite two are generating less thrust to produce clockwise pitch.

2.9.1.5 Yaw

The rotation of the hexacopter on Z-axis as the center of rotation axis is called yaw. The Z-axis is the same as the vertical axis passing through the center of the virtual hexagon. In order to generate the clockwise rotation of the whole body, the thrust generated by propellers rotating clockwise will be increased and the thrust generated by propellers rotating in counter-clockwise motion will be decreased in the same proportion.

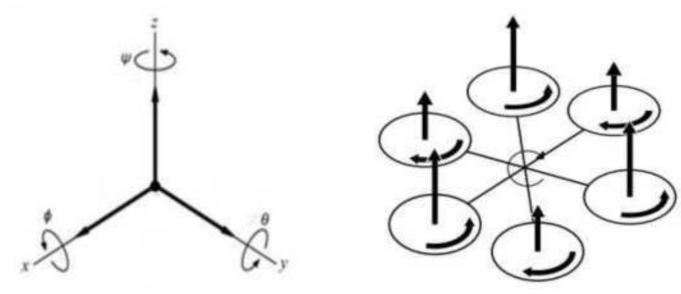

Figure 21: Thrust is increased and decreased for propellers rotating clockwise and counter-clockwise to produce Yaw

2.10 MODELING

Body Fixed Frame

The hexacopter model has 6-degree of freedom (DOF), so in order to track its motion a body-fixed frame is required. The body-fixed frame is the fixed frame with its origin at the hexacopter’s center of gravity. The body-fixed frame is compared with inertial frame to calculate the change of the basic movements (throttle, yaw, pitch, roll). The inertial frame is the frame with its origin on the surface of earth.

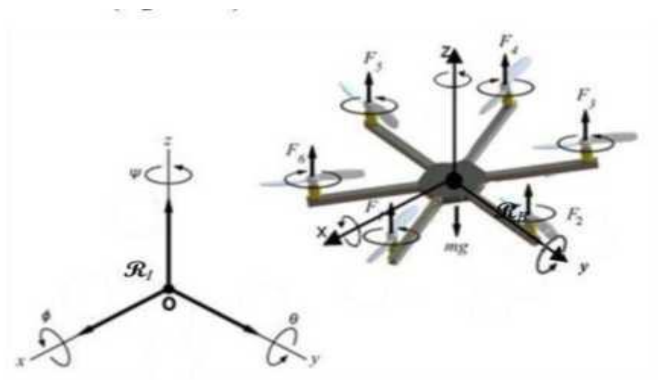

Figure 22: Inertial frame and Hexacopter with body fixed frame

2.10.1 KINEMATICS

The inertial frame is denoted as RI and the body fixed frame on the hexacopter body is denoted as RB. The three Euler angles, namely yaw angle ^, pitch angle ***6,*** roll angle 0 are used to describe the orientation of the hexacopter [6]. Together all three angles form the vector ***rj = [<p 0 <p].*** The range of angles 2 ' 2) and for ***<p*** is ***(—n,n).*** The hexacopter performs the change in three Euler angles with the assumption that the origin is same before and after all the changes. The body-fixed frame is transformed

DYNAMIC MODEL OF THE HEXAROTOR

The mathematical model of the hexacopter has to describe its attitude according to the well-known geometry of this UAV. More specifically, this aerial vehicle basically consists of six propellers located orthogonally along the body frame. There are three movements that describe all possible combinations of attitude: Roll (rotation around the X axis) is obtained when the balance of rotors 1, 2 and 3 (or 6, 5 and 4) is changed (speed increases or decreases). By changing the angle, lateral acceleration is obtained; pitch movement (rotation around the Y axis) is obtained when the balance of the speed of the rotors 1 and 6 (or 3 and 4) is changed. The angle change results in a longitudinal acceleration; yaw (rotation about the Z axis) is obtained by a simultaneous change of speed of the motors (1, 3, 5) or (2, 4, 6).

2.10.2 HEXACOPTER KINEMATICS

This subsection describes the dynamical models of the Six Rotor. The schematic structure of the hexacopter and the rotational directions of the propellers are illustrated in Figure 22. In order to describe the hexacopter motion only two reference systems are necessary: earth inertial frame and body- fixed frame (R_B -frame).

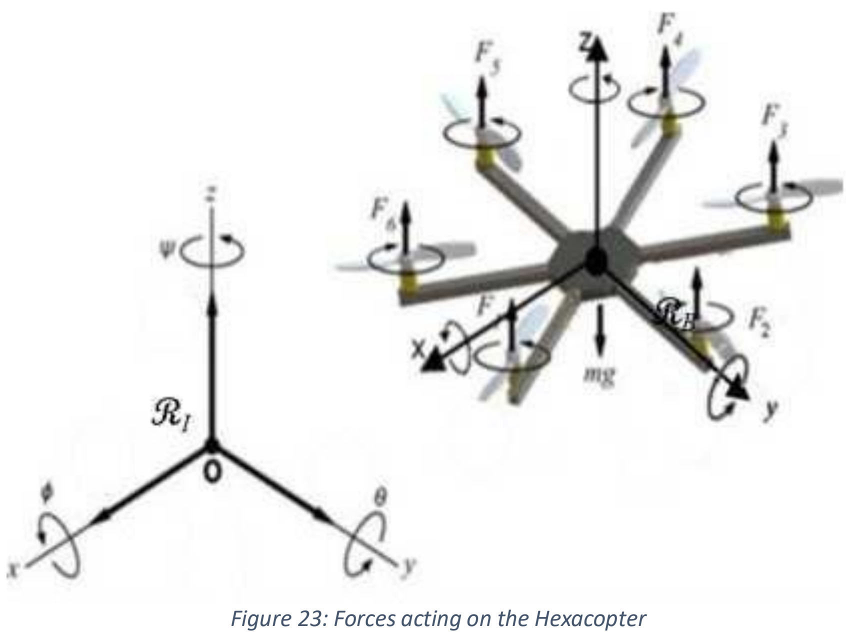

Figure 23: Forces acting on the Hexacopter

The orientation of the hexacopter is given by the three Euler angles, namely yaw angle y, pitch angle 0 and roll angle ^ that together form the vector n = [^, 0, y]^T. (4> and 0 ***e***] - ^ ^ [; y ***e***]-n ,n [ ) The position of the vehicle in the inertial frame is given by the vector E, = [x, y, z *]*^{T}.

2.10.2 CONTROL OF HEXAROTOR

In this section, a control strategy is based on two loops (inner loop and outer loop). The inner loop contains four control laws: roll command ($), pitch command (9), yaw control (y) and controlling altitude Z. The outer loop includes two control laws positions (X, y). The outer control loop generates a desired for roll movement (9_d) and pitch ($\$_d$) through the correction block. This block corrects the rotation of roll and pitch depending on the desired yaw (y_d). The figure below shows the control strategy we adopted.

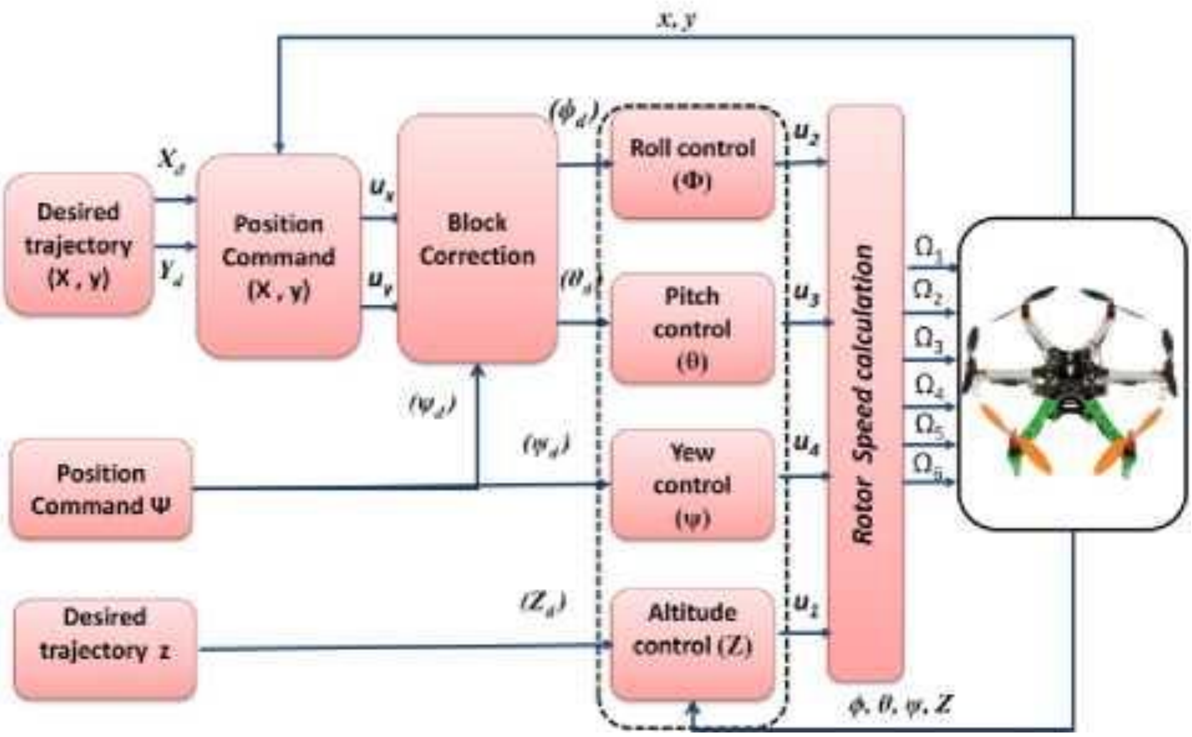

Figure 24: Block diagram of PID

CHAPTER 3 – METHODOLOGY

This chapter entails specific processes used in the conceptual design of this project. Six concepts were developed using Solid Edge ST9 (Solid Works) software and were evaluated using Design Decision Matrix Method. To obtain the best possible design, five different concepts were generated using varying frameworks which includes both quantitative and qualitative methods to get the best stable concept capable of withstanding loads during flight. Furthermore, several simulation and physical tests were conducted on the frame to check for strength and stiffness.

3.1 DESIGN CONCEPTS

3.1.1 CONCEPT 1

Concept 1 as pictured below consists of a two thin frame hub situated above and below the frames which holds it in place for structural strength and stiffness. Its configuration is a plus (+) with six (6) arms whereby each arm at angle of 60˚ from each other which can be detached. It employs aluminium as down hub plate and combination of Perspex and Aluminium as top hub plate and a rubbery base footing as shock absorber. On top of the upper plate hub includes a rectangular transparent protective shield covering the on-board computers and sensors. This feature would protect the components during fall or crashing and allow the hexacopter to fly in rainy weather.

The spraying mechanism is made up of a thin light metallic rod below the pump which holds the nozzles in place for even spray distribution during flight. Furthermore, the spray tank is situated in the centre for stability of the hexacopter during flight and on ground.

Figure 25:Concept 1

Advantages

- Thin Aluminium hub plates which adds structural strength and rigidity to the hexacopter.
- Adjustable pump to set the flow rate of the chemical to prevent nozzle damage.
- Slots on the frames allowing for easy arm replacement.
- A rectangular transparent protective shield covering the on-board computers and sensors prevents damage of the components during landing and rain.
- Spray rod situated below pump to prevent uneven spray distribution by downwash of the propellers during flight.

Disadvantage

- No propeller guards to protect the propellers from damage during crush.

3.1.2 CONCEPT 2

Concept 2 is a H-configuration hexacopter. It employs two thin plate central hubs with two frames perpendicular to the third frame. It is made of four pieces landing arms (made of light composite hollow materials to reduce the overall weight of the hexacopter) connected to the hub. This concept is best suited for aerial photography and video recording. In between the two hubs is a compartment for the battery to prevent sun rays from direct contact with battery. The arms of the frames have been braced to the platform to increase strength and stability of the hexacopter.

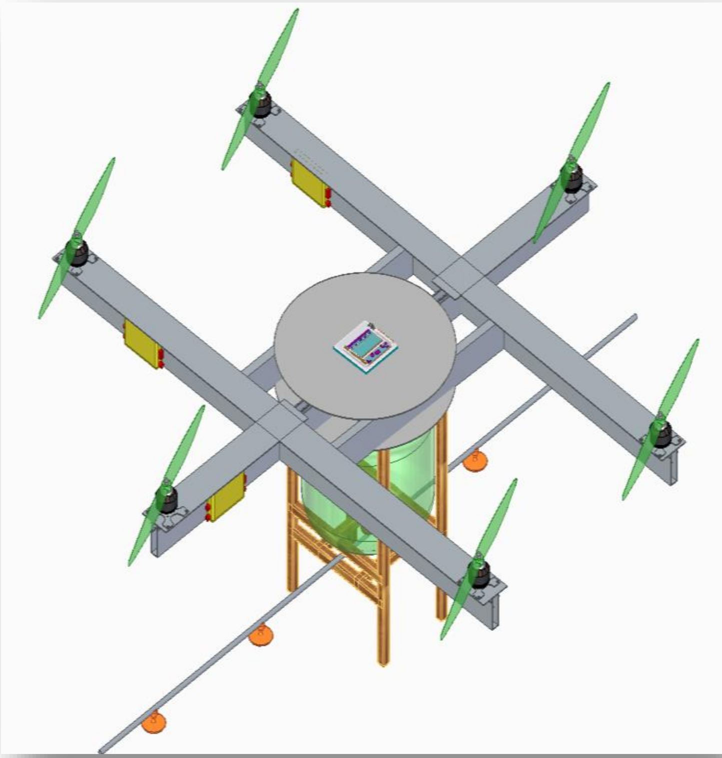

Figure 26:Concept 2.

Advantages

- The configuration is very simple and easy to design and construct.
- It also offers a larger platform space to accommodate electronics.

Disadvantages

- Instability can arise when the tank is not positioned properly.
- It is a complex design with a lot of errors.
- It lacks propeller guard for protection of the propellers during crush.
- It does not have a rectangular transparent protective shield to cover the on-board computers and sensors during landing and rain.

3.1.3 CONCEPT 3

Concept 3 is a Y-configuration hexacopter. It consists of the hub and arms. Each pair of arms is rigidly connected and separated at an angle of 120˚ from each other. It entails a tri-landing gear each mounted per arm. The electronic components are protected by a transparent rectangular protective shield.

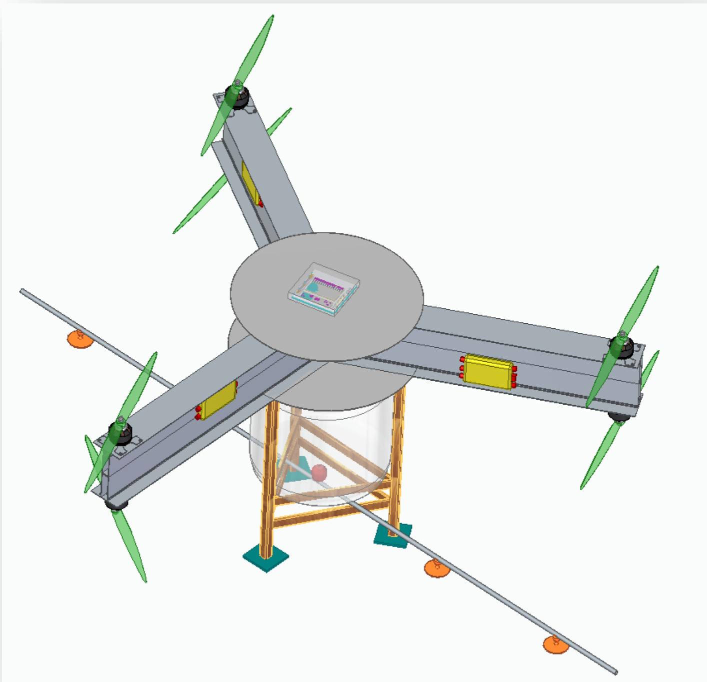

Figure 27:Concept 3

Advantages

- A rectangular transparent protective shield covering the on-board computers and sensors prevents damage of the components during landing and rain.
- High manoeuvrability during flight.

Disadvantages.

- Complicated design which needs high precision work.
- No propeller guards to protect propellers from damage during crush
- Difficulty during landing due to the landing configuration.

- Instability is high due to high manoeuvrability.

3.1.4 CONCEPT 4

This is similar to concept 1 above due to frame configuration. But it is incorporated with protective guard and a different spraying mechanism. Instead of a long cylindrical thin rod for nozzles positioning, the nozzles are situated just below the motor to eliminate the rod thereby reducing weight.

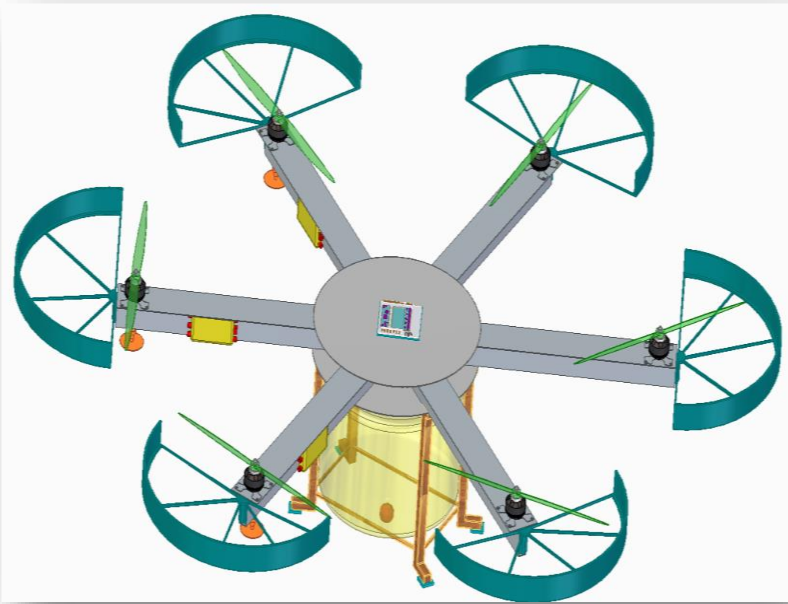

Figure 28:Concept 4

This is shown below

Advantages

- Propeller guards to protect propellers from damage during crush

Disadvantages

- Non-adjustable pump which can destroy the nozzle due to high pressure.
- Since the nozzles are located just below the motor, there could be uneven spray distribution due to the downwash air from the propeller during operation.
- It does not have a transparent protective shield to cover the on-board computers and sensors.
- No high pressure pump to boost the liquid since it is working against gravity.

3.1.5 CONCEPT 5

Concept 5 is also similar to concept 3 in terms of frame alignment. It has propeller guards on each arm. The nozzles are located below the lower arm at a specified distance from the propeller. Each nozzle can be controlled electronically.

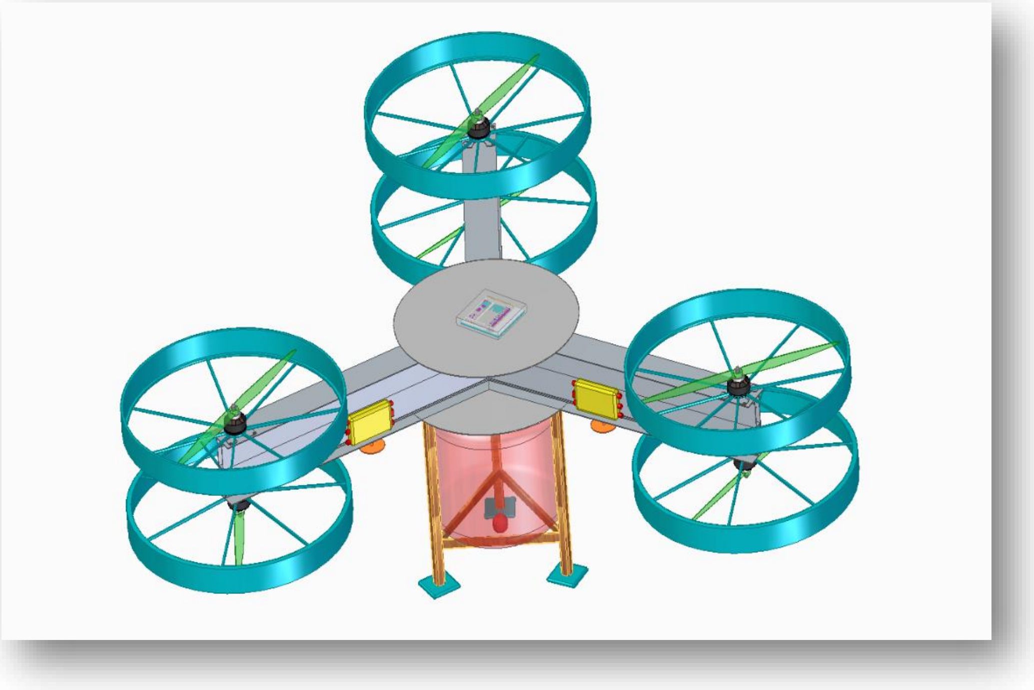

Figure 29:Concept 5

Advantages

- Nozzles can be controlled electronically
- Has propeller shield to prevent damage to propeller during crush.
- Nozzles located a specific distance from the propeller to reduce uneven spray distribution during operation.

Disadvantages

- High pressure pump is needed to boost the liquid since it is working against gravity.
- Complicated design which needs high precision work.
- Instability is high due to high manoeuvrability.

3.1.6 CONCEPT 6

Concept 6 is made up of a stand-alone body which includes electronic components and spraying tank embedded in it. It has capsules which the frames and landing gear can be attached and detached. Also, the tank can be removed from the main body for servicing. All the electronic components are protected by a rectangular transparent protective shield.

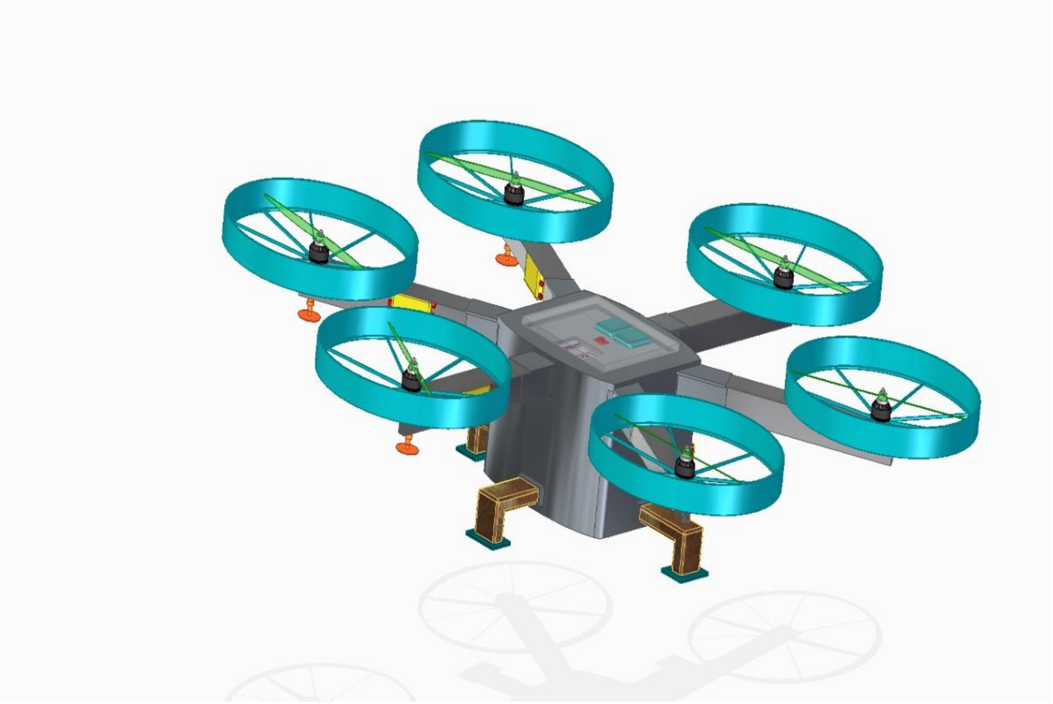

Figure 30: Concept 6

Advantages

- Easy storage after flight since arms and landing gear are detachable.
- Protective shield to prevent damage to electronic components by rain and other particles.

Disadvantages

- Very complicated to manufacture.
- Uneven spray distribution due to spraying tank interference.
- Strength and stiffness of arm is poor.

STRESS ANALYSIS

TEST RIG CONSTRUCTION

To verify whether the motor-propeller combination generates the required thrust, a simple setup for determining the approximate amount of thrust developed by each motor-propeller combination was put together.

This setup is basically akin to a see-saw. On one end was the motor-propeller-combination and on the other, was a weight hanger from which weights were hung in increments of hundred grams.

The motor was set to spin at full throttle on one side and weights were placed on the weight hanger on the other side of the test rig until the entire platform balanced. The weight accumulated on the other end is approximately the maximum amount of weight one motor-propeller combination can lift.

The test rig is shown in the figure below:

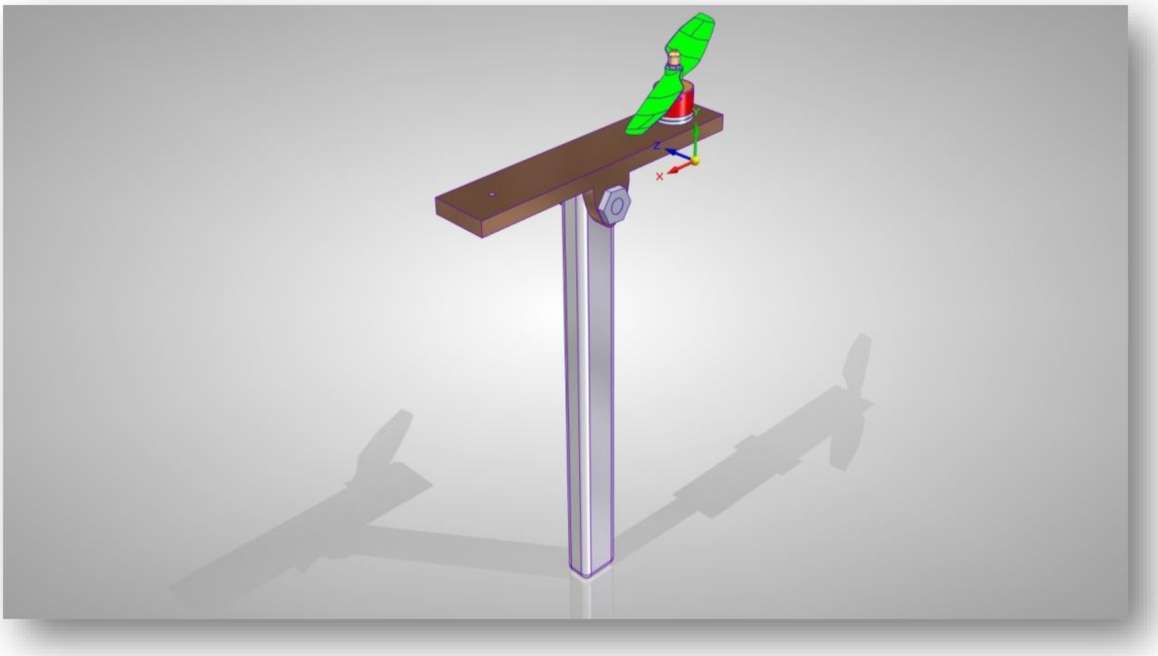

Figure 31: Thrust Test Rig

Experiment to determine the deflection of beam

Stress analysis requires the establishment of stress and strain rate fields that result from the imposed forces and shape changes in specific material. The goal of stress analysis is to design structures that can withstand a specified load using a minimum amount of material. That is, it tries to find a balance between strength and amount of material,

The motors placed on the ends of each arm exert an upward force (thrust) on the arm with the arm consequently acting as a cantilever beam. Based on this behaviour, it was imperative that the maximum deflection of the beam be determined. To do this the three-point flexural test was performed on the test specimen.

The three-point flexural test provides values for the modulus of elasticity in bending $E_{f,}$ flexural stress $\sigma_{f.}$ the main advantage of the three-point flexural test is the ease of the specimen preparation and testing. However, this method has also some disadvantages: the results of the testing method are sensitive to specimen and loading geometry and stain rate.

Testing procedure

The test specimen is placed on two supporting pins a set distance apart which in this case happens to be 450millimeters.

A hydraulic press applies a force at the centre position of the test specimen,

The force is increased continually until the material fails.

The value of the final force corresponds to the maximum yield strength of the specimen.

For rectangular specimen, the calculation of the flexural stress is:

$$\sigma_f = \frac{3FL}{2bd^2} \qquad \textit{Equation 1}$$

Where:

F = Load at the point of failure

L = Specimen length

b = Width of the test beam

d = Depth of thickness of the test beam

$$\sigma_f = \frac{3 \times 400 \times 0.3}{2 \times 0.042 \times 0.005^2} \quad = 228571428.6\text{Nm}^{-2}$$

CHAPTER 4-DETAILED DESIGN

4.1 DESIGN WEIGHTED DECISION MATRIX

Weighted Decision Matrix is a criterion used to weigh or compare the various concepts in terms of manufacturing, maintenance, aesthetic, life span, safety, durability, strength etc. This helps designers to choose most favourite of the various designs before detailed design is enacted.

The various scores were derived by multiplying the weight associated with each criteria and the corresponding value given to the concept. For values for the cost criteria, lower cost equals higher values and higher cost equals lower values. From table 3.5.1 above and comparing the total values of the various concepts, it was concluded that concept 1 was the most suitable design for the project. Other modification was done on the final concept.

Table 2: Decision Matrix Table

Criteria	***Density***		***Load Bearing Ability***		***Vibration Absorption***		***Availability on Market***		***Cost***		***Permeability to Radio Waves***		***Total Concept Value***
Parameter	***Material Properties***		***Material Yield Stress***		***Material Property***		***By checking on Market***		***By checking on Market***		***Material Property***		
Weight	***0.25***		***0.25***		***0.1***		***0.15***		***0.15***		***0.1***		
	Value	***Score***	***Value***	***Score***	***Value***	***Score***	***Value***	***Score***	***Value***	***Score***	***Value***	***Score***	
Wood	***3***	***0.75***	***1***	***0.25***	***4***	***0.4***	***4***	***0.6***	***4***	***0.6***	***3***	***0.3***	***2.30***
Aluminum	***2***	***0.5***	***4***	***1***	***3***	***0.3***	***4***	***0.6***	***3***	***0.45***	***1***	***0.1***	***2.95***
Fiberglass	***4***	***1***	***3***	***0.75***	***3***	***0.2***	***1***	***0.15***	***1***	***0.15***	***1***	***0.1***	***2.35***
Carbon Fiber	***4***	***1***	***3***	***0.75***	***3***	***0.3***	***1***	***0.15***	***1***	***0.15***	***1***	***0.1***	***2.45***

4.2 THE DETAILED DESIGN

4.2.1 WEIGHT AND THRUST ESTIMATION

The mass of the hexacopter includes the mass of the frame, batteries, wiring, electronics, motors, payload and miscellaneous components like dampers, straps and others.

Total mass = (7 kg in all)

$W_{frame} + W_{batteries} + W_{motors} + W_{electronics} + W_{wirings}$ T+ $W_{\mathrm{payload}} + W_{Miscellaneous} = W_{total}$ *Equation 2*

Table 3:Weight Estimation

Part	Estimated weight (mass/kg)
W_{frame}	1.5
$W_{payload}$	2.0
W_{motors}	0.64
$W_{\mathrm{batteries}}$	1.00
$W_{\mathrm{miscellaneous}}$	0.80
$W_{\mathrm{electronics}}$	0.50
W_{wirings}	0.24
W_{total}	6.68

Therefore, the total estimated weight of the hexacopter was approximately 7 kg. With the estimated mass above, the weight exerted by the quadcopter under gravity can be deduced.

Weight = mass x acceleration due to gravity *Equation 3*

Generally, 9.81 ms^{-1} is used as the acceleration due to gravity. The weight is then equal to;

$$\textbf{weight} = 7\ \textbf{kg} \times 9.81ms^{-2}$$

$$\textbf{weight} = 68.67\textbf{N}$$

4.2.3 Electronic Components Selection

Selection of motors

Motors selection takes into consideration the total weight of the aircraft hence the thrust. With various motor-propeller configurations reviewed, the *SunnySky X2814* with *EMP 11*5.5* propeller was selected. This combination produces a thrust of *22.563N* for each motor.

A total of 6 propeller-motor pairs would be employed, hence an expected maximum thrust of *135.378* is expected to lift a mass of *13.8kg.*

$$22.563 * 6 = 135.378N$$

$$Equivalent\ mass\ of\ thrust\ can\ lift = 135.378N / 9.81 = 13.8kg$$

With a thrust to weight ratio of 2:1, the take-off mass becomes 6.9kg.

Since the current requirement per motor is 29.5A a total current is 177A.

Table 4:Propeller Type

2814 KV870					
Propeller Type	Voltage	Current	Thrust(G)	Power(W)	G/W Ratio
EMP11X5.5	14.8V	29.5A	2.3kg	436.6	5.26

Electronic speed controller

An electronic speed controller is selected based on the maximum current pull of the motor. The *Sunny Sky X2814* has a maximum current draw of 29.5A per motor. To ensure the protection of the ESC, a higher current requirement of 40A was selected. This selection was based on the fluctuations in the current draw leading to destruction of the ESC. A higher current for the Electronic Speed Controller guarantees its prolonged lifespan.

Battery selection

The Li-Po battery is the most common battery used in powering R/C aircrafts. The battery made of Lithium Polymer chemistry (hence the name Li-Po) is selected because no other battery provides as much energy while delivering high amounts of current in so small of a package due to it high energy density. This is advantageous in terms of longer flight times, better manoeuvrability, faster flying and ability to recharge.

To select the specific LiPo battery, the voltage required to power the motors was considered. The *Turnigy 10000mAh 4S 30C LiPo Pack was* selected.

Table 5:Motor rating

Minimum Capacity	**5000mAh**
Configuration	**4S1P / 14.8v / 4Cell**
Constant Discharge	**30C**
Peak Discharge (10sec)	**40C**
Pack Weight	**556g**
Pack Size	**144 x 49 x 36mm**
Charge Plug	**JST-XH**
Discharge plug	**5.5mm Bullet-connector**

Wire gauge sizing

For this project, the American wire gauge (AWG) was used. Using the table 5, 18 AWG was selected as the wire size required for the connection between the ESCs and the motors, and between the ESCs and the wiring harness which were both to carry 14.75 A. 8 AWG was selected as the wire size required for the parallel connection between the batteries and for the wiring harness, which was to carry 177 A.

Table 6:Wire Gauge Sizing

8 AWG	**200 amps**
10 AWG	140 amps
12 AWG	90 amps
14 AWG	60 amps
16 AWG	35 amps
18 AWG	20 amps
20 AWG	12 amps
22 AWG	10 amps

Connector selection

Selection of connectors are important because of the various power connections made. Correct selection of connector sizes prevent excessive heat generation hence fires.

Table 7:Connector Selection

Diameter	Maximum Current
2 mm	20 A
3.5 mm	40 A
XT60	60 A
4 mm	70 A
5.5 mm	150 A
8 mm	200 A

In accordance to the table 6, 2 mm bullet connectors rated at 20 A were selected for the motor cables, which would be carrying 14.75 A. To carrying about 177 A of current from the battery, 8 mm bullet connector rated at 200 A was used.

For the motor cables, which would be carrying 17.5 A, 2 mm bullet connectors rated at 20 A were used.

For the cables carrying power from the battery, that is, the battery series connector and the wiring harness, which would be carrying currents of about 140 A, 5.5 mm bullet connector rated at 150 A was used.

FLIGHT CONTROLLER SELECTION

Rather than manually programming a controller from scratch, a plug and play flight controller was selected because the main objective of the project was to design a hexacopter for spraying agrochemicals. The flight controller was mainly selected based on its ability support a hexacopter and provide extra channels for the spraying function of our hexacopter. Based on these two criteria we had to choose between the Ardupilot: APM and Copter Control-3D(CC3D). however, since we were not interested in autonomous flight we finally settled on the CC3D because of its relatively cheaper price and other favourable features including the following:

- MultiRotor controller with auto-level including TriCopters, Quadcopters and HexaCopters
- Weight of 12.6 g with a V4 bootloader pre-installed
- Input Operating voltage of 5 V
- Flybarless Helicopter controller with auto-level
- Fixed Wing UAV controller
- Powerful STM32 32-bit microcontroller running at 90 MIPs with 128 KB Flash and 20 KB RAM
- 3-axis high performance MEMs gyros and 3-axis high performance MEMs accelerometer
- Tiny 36 mm by 36 mm 4-layer PCB for superior electrical noise reduction and flight performance

- Software support for Windows, Mac and Linux
- Direct high speed USB support with no drivers required, a truly plug and play device.
- Spektrum satellite receiver support
- Futaba S-BUS hardware support and PPM
- Innovative Flexi-port technology for superior port flexibility and
- 4 Mbits on-board EEPROM for configuration storage

The CC3D board of the OpenPilot Mini flight controller is an all-in-one stabilization hardware which runs the OpenPilot firmware. It can fly any airframe from fixed wing to an octocopter and is configured and monitored using the OpenPilot GCS (Ground Control Station) software now called the LibrePilot. Because of its plug and play feature, all that can be modified with regards to the control system programming is to tune the sensors for responsiveness, inner and outer loop stabilization and enabling system compensation [pirouette compensation for this system]. But because of the difficulty and inaccuracies arising in gain inconsistencies with manual extremum seeking, the CC3D does the tuning automatically or has default settings based on the type of vehicle selected (in this case, the generic hexacopter). The calibration of the sensors was done automatically with the GCS during the flight controller interfacing setup and the ESC calibration. All that was required was to make sure that the fc had a much levelled position on the hub.

The CC3D external interface layout features the main port; flex port, a 6 channel PWM input for servo and ESC, a 6 channel signal input for the receiver and a data transmission interface

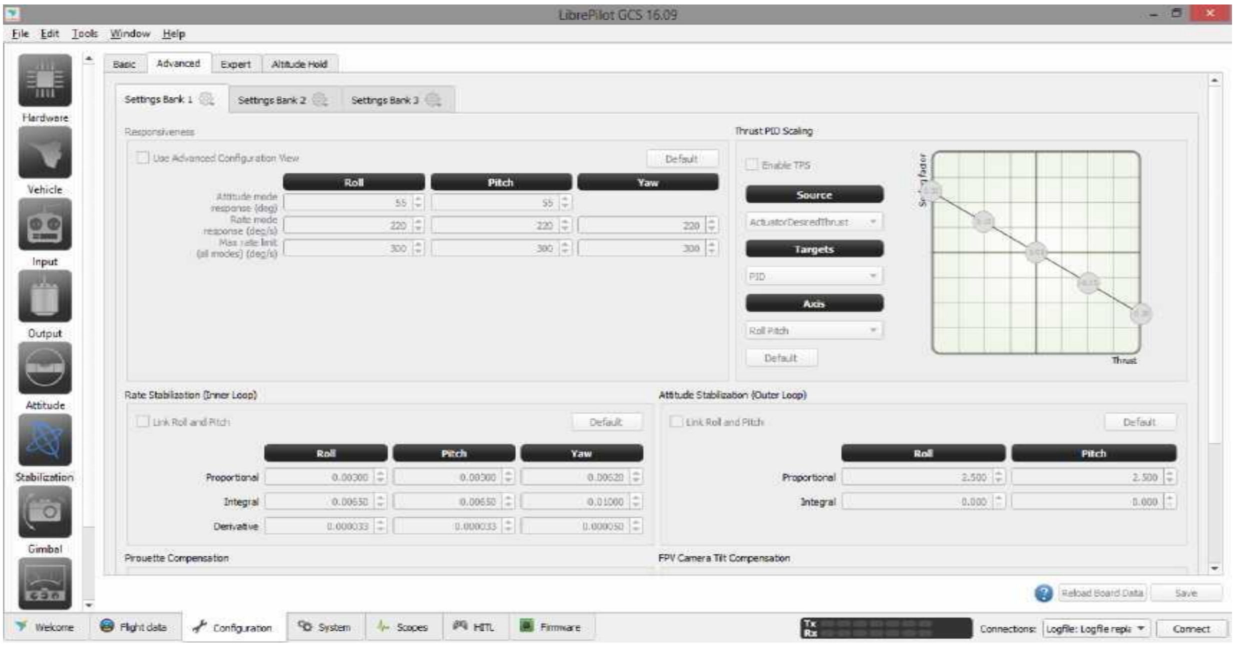

Figure 32: Control System Tuning with the LibrePilot GCS

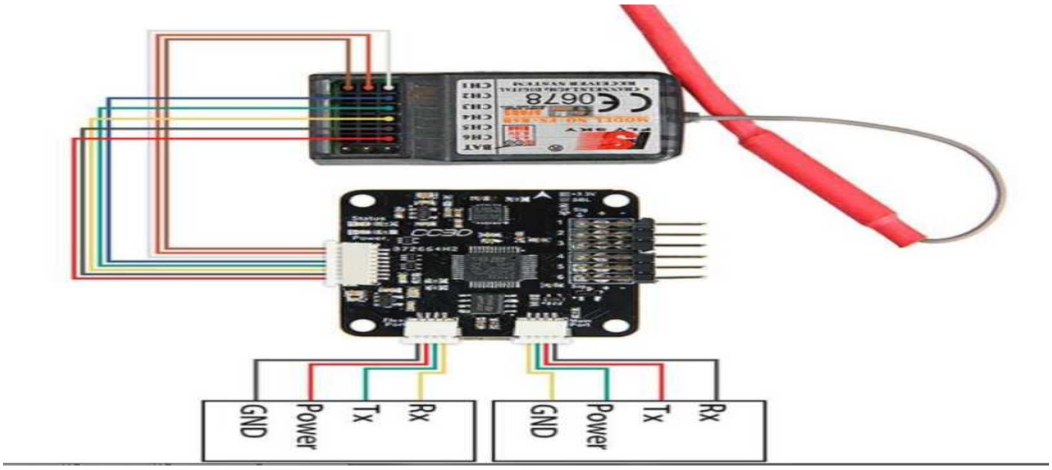

Figure 33:Control System Interface Layout

PERFORMANCE PARAMETERS

4.2.9.1 Endurance (Flight Time)

$$\text{Flight Time} = \frac{\text{Battery Capacity}}{\text{Current Draw}} \qquad \text{Equation 4}$$

For hovering, least current draw is used:

Minimum current draw for the four motors =6 x 27.5=165A

Maximum current draw for the four motors= 6 x 30 $=180$ A

One 10000 mAh Li-Po battery is going to be used.

Therefore $Estimated\ flight\ time\ for\ hovering = \frac{10000mAh}{165A} = 60.606 \times 10^{-3}$h $= 3.63636\ mins$

$Estimated\ flight\ time\ for\ maximum\ performance = \frac{10000mAh}{180A} = 55.556 \times 10^{-3}$h $= 3.33\ mins$

FRAME DESIGN AND SELECTION

Hexacopter Frame Material Selection.

In the design of the hexacopter, a major priority was placed on minimising weight at the end of both design and construction. Hence, the choice of material for the construction of the frame, which is the main body of the hexacopter, became of paramount importance.

There are so many materials which can be used for construction of hexacopter frames. These include bamboo, balsa wood, aluminium, carbon fibre, fibre glass etc. To meet the structural specifications of the frame for the hexacopter, the material chosen had the following properties;

- Stiff and less brittle for stable and smooth flight, avoiding detrimental bends in the sky.
- Light in weight but able to overcome large payload.
- Less or no radio signal interference
- Effective in minimising vibration.

- High strength.

A brief research into various materials which can be used was done to know the best material which possesses the above qualities and do meet the specifications.

Carbon Fibre.

It can be the most suitable material to use for the frames of a hexacopter. It offers really good stiffness and hence provides smooth and stable flight. One disadvantage of it is that, carbon fibre blocks radio signals although there's a way to correct it. Aside that, carbon fibre is relatively expensive and difficult to come by in our part of the world.

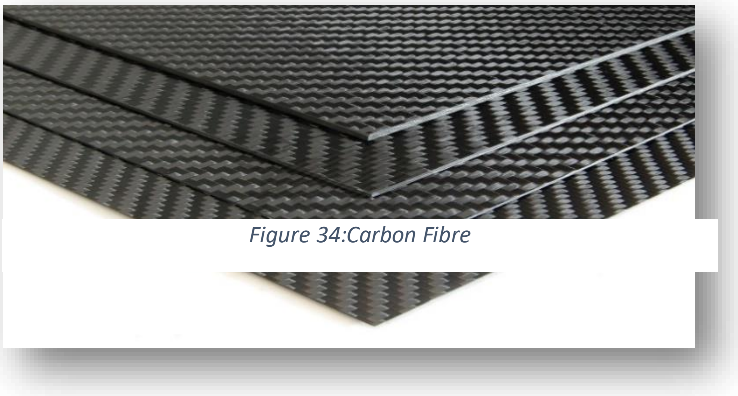

Figure 34:Carbon Fibre

Fibreglass.

Another material considered was thin G-10 fiberglass sheet which is easily machine able. It does not block or interfere with radio signals. In terms of weight and stiffness, it is inferior to carbon fibre. It bends or warps easily and cannot provide the expected stable flight. It also makes nice motor mounts.

Figure 35:Fibre glass

Wood

The wood specie usually used for hexacopter frame construction is Balsa. They are light in weight usually stacked in layers, giving it more strength and rigidity. It is low in density with a density range of 40-340 kgm^{-3}. In the event of crash, wood arms absorb all impact and break saving other components on board and there's high availability. Using balsa wood, it takes more time to prepare the wood for a smooth finish and required arm width. It has less strength as compared to aluminium

Figure 36:Wood

Aluminium.

Aluminium is very lightweight. It can transmit vibration quite well but has great stiffness to help achieve stable flight. Constructing a hexacopter for aerial spraying of water and agrochemicals onto farm crops, we have on board a huge payload. In order to overcome such huge weight and gain maximum lift, very powerful motors are needed.

Aluminium is the best material to go for when using very powerful motors. Aluminium was easy to get, thus high availability and less expensive compared to carbon fibre and fibreglass.

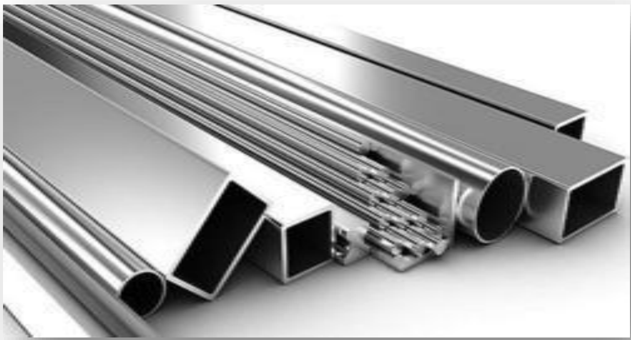

Figure 37:Aluminium

Below is a table comparing the materials with respect to the Ghanaian market.

Table 8: Materials with respect to the Ghanaian market.

Material	Density Kg/m^3	Cost per unit length (GHc)	Vibration Absorption	Availability in Ghana	Strength (MPa)
Wood	0.16	4.09	0.19 – 0.36	HIGHLY AVAILABLE	4.8
Aluminium	2.71	8.50	0.3 -10 ($x10^5$)	AVAILABLE	280
Fiberglass	1.9	60.00	0.08 – 0.38	UNAVAILABLE	1700
Carbon Fiber	1.7	114.00	0.14 – 0.41	UNAVAILABLE	3500

Frame Length

There is no hard rule or definite mathematical and physical equations used in sizing the length of the frame of a Hexacopter. But the principle that is normally followed by Hexacopter hobbyist is that the more stable a drone is expected to be, the longer its frame; and the more manoeuvrable it is aimed to be, the shorter the frame length.

A range of 700 mm to 850 mm is popularly used by drone hobbyists (Jack, 2016) and since this Hexacopter is expected to be stable and manoeuvrable simultaneously, there must be a smart compromise between stability and manoeuvrability. As such, a 800 mm long frames with widths of 46 mm were designed and built to test for optimum performance with due regard to the trade-off.

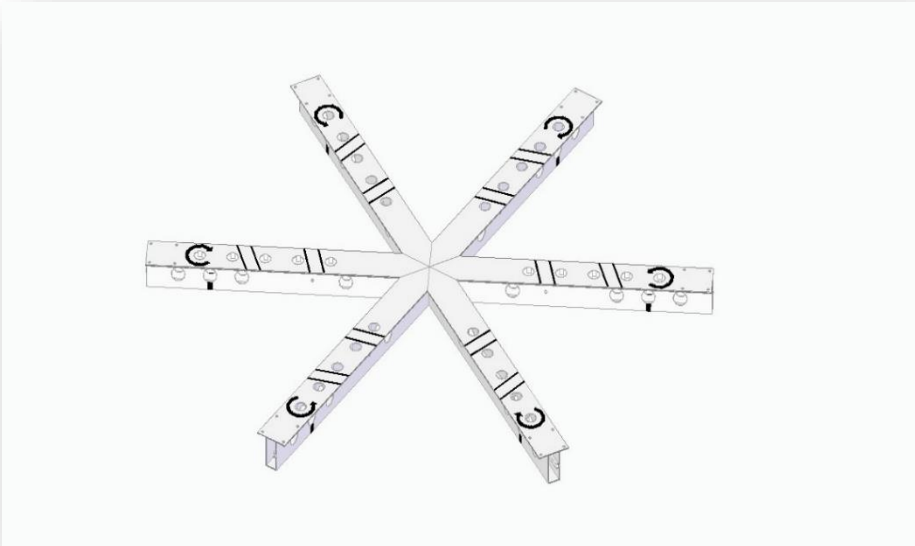

Figure 38: Frame

Theoretical Frame Mass and Centroid

With the strength and density information obtained, the Solid Edge ST9 in conjunction with Ansys software programs were used to theoretically calculate the weights of the individual components and entire assembly. Thus, the weight of the flanges, webs, hub and landing gear were obtained. Consequently, the total weight of the assembly was obtained as 1.965kg which was consistent with the actual measured value with a negligible error. The centroid of the assembly viewed from the top was also obtained as follows:

$X_c$bar = 201.453mm

$Y_c$bar = -195.456mm

$Z_c$bar = -186.564mm

measured from the ST9 software reference axis.

Hub Design and Construction

A rounded hub with diameter 280mm was made out of fibre glass based on location points on the frame mapped out by the inner nails to house the electronic and electrical components of the hub. Perspex was chosen because it is strong and permeable to radio signals. 4 mm diameter holes were made in a rounded pattern in the centre plate to serve as points of attachment of the components.

The hole-to-hole distance was determined (i.e. from the tip of the hub (about 50mm and 180mm). The holes were not made too close to each other and this was done to prevent possible fracture of the glass due to the holes' proximity. The same plate geometry was maintained for the lower hub plate made; one at the top to house the micro controller and receiver, and the other to hold the frame and the tank holder in place.

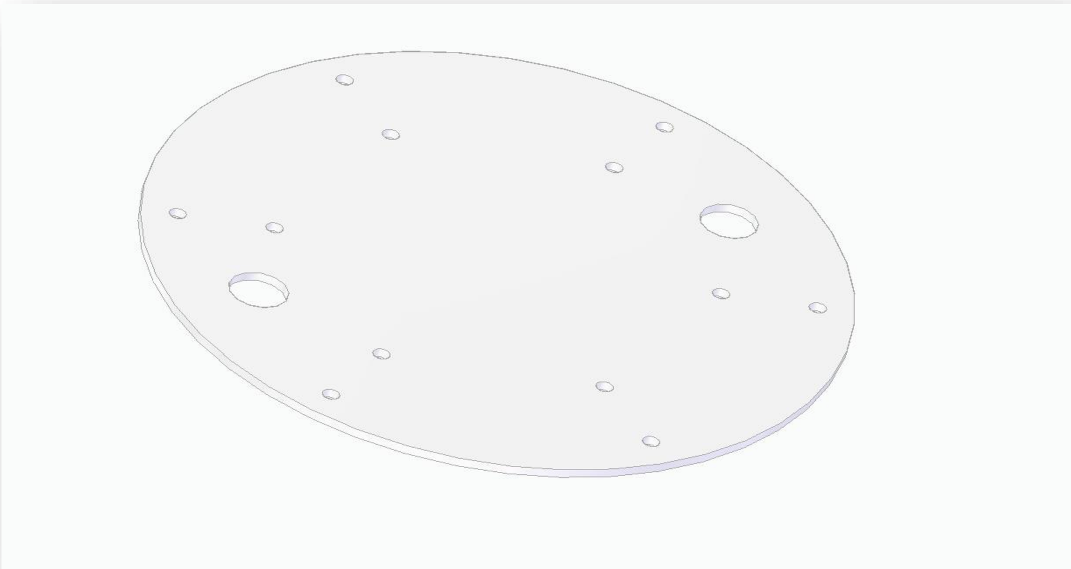

Figure 39: Hub

Landing Gear Design

The chosen hexacopter design concept features a strut design made of square hollow aluminium. A dimension of 264mm x 36mm x 24mm was chosen to compensate for the tank's compartment.

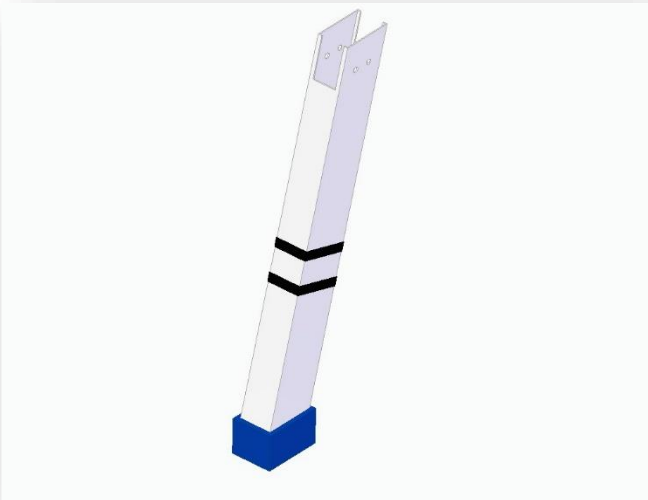

Figure 40: Landing gear

4.2 SPRAYING SYSTEM

4.2.1 Components

This 'agro-hexacopter' is designed to be able to accomplish aerial spraying of agro-chemicals on medium sized farms. The spraying system consists primarily of:

- A Reservoir
- Centre plate/ Hub
- A Pump
- Nozzles
- Connecting Tubes and Inter-Connects

Below is a description of the components and their interconnections and how they function together to deliver the chief function of this special aerial vehicle.

4.2.1 Reservoir:

The reservoir (or tank) is an on-board storage volume which carries the liquid agro-chemical to be sprayed. It is a light-weight plastic structure having a 2-liter capacity volume. It has been chosen to be easily removable so as to allow efficient maintenance practices. Per this design, the reservoir also provides a sitting(space) for the pump (and its intake) hence, eliminating the need for a pump housing and connecting tubes between the pump and the reservoir. Below is a three-dimensional CAD model of the tank

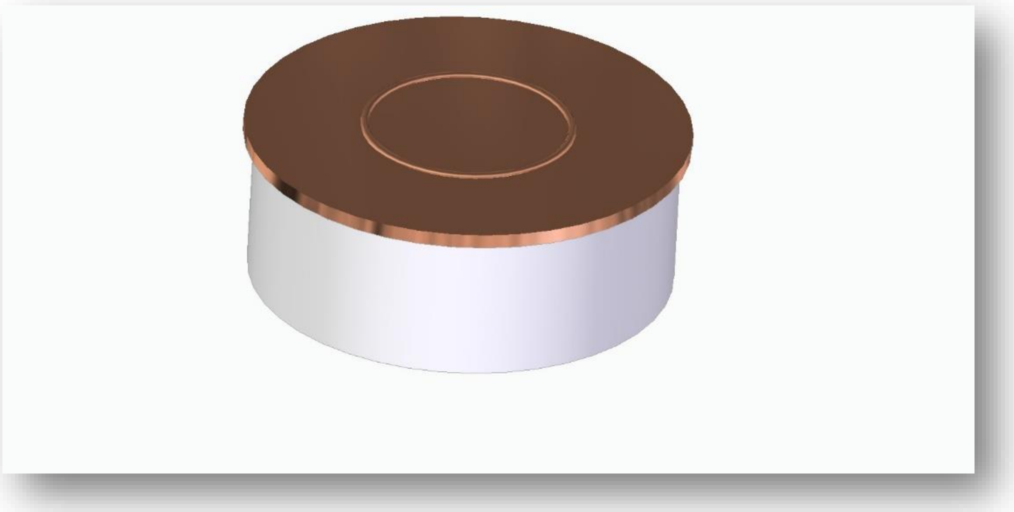

Figure 41:Tank

4.2.2 Pump:

The basic function of the pump is to draw fluid from the tank and force it through the tubes and finally to the nozzle, where the fluid is sprayed onto the farm. In the traditional setting (which is highly inefficient for large scale purposes), the knapsack sprayer provides a mechanical means whereby the farmer pushes a rod up and down continuous the deliver high pressure fluid to the nozzles. Here in this design, an electrical motor is used instead. With specifications of 12V 6A, the pump can deliver 2 lit/min at full capacity.

4.2.3 Nozzles:

Nozzles are arguably the most important part of a sprayer. They determine to a large degree the efficacy obtained from a pesticide, the amount of drift, and the overall satisfaction an applicator receives from an application. With this large selection, choosing the right nozzle can be challenging. The good news is that there isn't a bad nozzle on the market today. The bad news is that there are plenty of opportunities to use a good nozzle improperly. To avoid pitfalls, applicators must carefully determine their application goals, consider the target, the mode of action of the pesticide, the environment, and the sprayer features and capabilities before selecting a nozzle (Thomas M. Wolf, Today's Nozzle Market – Clearing up the Confusion)

Categories of Nozzles:

- Conventional Flat Fan
- Pre-Orifice
- Low-Pressure Air Induced
- High Pressure Air-Induced

For our application in a medium sized farm, a conventional flat fan nozzle is optimum.

Some Other Factors to consider:

1. **Target Type:** Broad-leaf plants can be particularly difficult to wet. This means finer sprays must be applied to the plant in order to be efficient. In flooding applications, coarser spray pattern may be required. The different spray patterns illustrated demonstrate the need for different nozzles for different applications.

2. **Travel Speed**: Moving the nozzle faster or otherwise has its own advantage of improving work rate. However, it has the ability to greatly increase drift. (Drift is occasioned when the target for spraying is partially or completely missed. This can be due to wind. Drifting drastically reduces the expected outcome from spraying and may end up depositing the sprayed chemicals into waterbodies, etc.). Therefore, for higher travel speeds, a nozzle that facilitates flooding must be chosen over one that delivers fine spraying patterns.
3. **Boom Height:** As discussed above, drifting is of great concern when spraying farms. The height at which the nozzle sprays also determines which nozzle to use. For applications where spraying is down close to the target, a fine spray pattern is desired as flooding may cause excess chemicals to be deposited at particular occasions. The reverse is true for high spraying heights.

Figure 42:Types of Nozzles

Flexible Connecting Tubes and Inter-Connects:

They are the means by which the fluid is transported from one component to the other. With an outside diameter of 9mm and an inside diameter of 6mm, the tubes initially increase the velocity of flow (due to the reduced cross-section as compared to the intake) before the fluid finally gets to the nozzle. The interconnects also allow branching of one tube into two when required.

4.3 PERFORMANCE PARAMETERS (FUNCTIONAL REQUIREMENTS)

4.3.1 **Forward Thrust**

The maximum thrust produced by the propellers is a direct result of the amount of thrust produced by the selected motors.

Therefore, the maximum thrust provided by each propeller is 22.563N.

Therefore, the total maximum thrust provided by all 6 propellers is 6 X 22.563 = 135.378N

4.3.2 **Optimum pitch angle for maximum thrust**

For a hexacopter to stay aloft while achieving forward translation in flight, there is an optimum angle (α) at which the hexacopter should be tilted. This ensures hexacopter still maintains balance along with thrust in motion

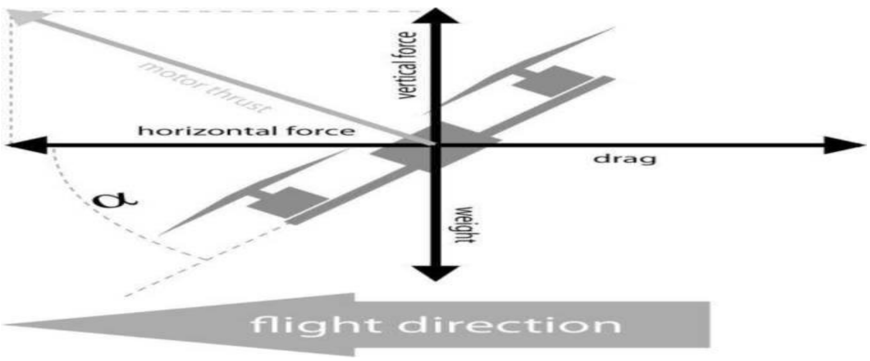

Figure 43: Pitch Angle for maximum trust

Mathematically,

Weight of the hexacopter is:

W_q= cos α T *Equation 5*

Where W_q is the weight of the hexacopter

T is the thrust and a is the pitch angle

The estimated weight of the hexacopter is 7 kg. (7.0x 9.81 = 68.67 N)

$$cos\alpha = \frac{w_q}{T} = \frac{68.67}{135.378} = \ 0.5$$

$$\alpha = \cos^{-1}(0.5) = 60^{\circ}$$

The optimum pitch angle for forward translational motion = 60^o

Resolving forces on the hexacopter, the forward thrust is given by:

F_t = sin a x T *Equation 6*

F_t = sin 60^o x 135.378N = 117.241 = 117.2 N

4.2.9.1 Surface area of the upper surface of the Hexacopter

Surface area of the arms

Length of the arm = 700 mm, the width = 50 mm

A_{arms} = 0.2100 m^2

Surface Area of the hub

Length of hub = 200 mm

A hub = 0.1257 m^2

4.2.9.2 Area of Upper Surface of the Hexacopter

Therefore, the area of the top part of the hexacopter is the sum of the area of arms, hub and motor mounts.

$$A_T = A_{arms} + A_{hub} \quad \text{Equation 7}$$

A_t = 0.2100 + 0.1257 =0.3357 m^2

4.2.9.7 Maximum Forward Velocity

$$F_{thrust} - F_{gravity} - F_{drag} = ma \quad \text{Equation 8}$$

Where m is the mass, a is acceleration and F is force

Furthermore, motor thrust is normally shown as P in gram for selected propeller types therefore it is multiplied by gravity

$$T = p \times g \quad \text{Equation 9}$$

For forward flight;

$$\sqrt{1-(\frac{mg}{T})^2} \times T - \frac{\text{density of air}}{2} C_d \times A_{effec} \times v^2 = ma \quad \text{Equation 10}$$

T is total motor thrust acceleration due to gravity, C_d is drag coefficient; A_{effec} is effective area of quadcopter.

Due to drag, the hexacopter will reach a limit speed without further acceleration.

$$\sqrt{1-(\frac{mg}{T})^2} \times T - \frac{\text{density of air}}{2} C_d \times A_{effec} \times v^2 = ma \quad \text{Equation 10}$$

The factor with the square root suggests that a certain fraction of thrust is needed to keep the hexacopter at constant altitude. The vertical component of the motor thrust must compensate for the gravitational force, mg. When the hexacopter is tilted 90^0 from the horizontal position, it will not generate any lift because the top part will be facing the free stream air head on and as such the lift component of the resultant force will be parallel to the horizontal and hence the hexacopter will stall.

Hence there is an optimum surface area of the top part of the hexacopter that must be exposed to the free stream in order to have maximum speed.

The effective area = S cos α *Equation 11*

Where S= total area of top part= 0.3357m^2

α= forward pitch angle= 60.^{o}

Therefore, effective area= 0.3357cos 60.^{o} = 0.03893 m^2

At maximum velocity, forward thrust F_T is equal to drag

$F_t = \frac{1}{2} p v^2 A_{effec} C_d$ *Equation 12*

at 300m above sea level density of air = 1.225 kg/m

$v = \sqrt{\frac{2F_T}{\rho A_{effec} \times C_d}}$ *(Farrier, 2017)* *Equation 13*

$$v = \sqrt{\frac{2 \times 117.2}{1.225 \times 0.3357 \times C_d}}$$

$$\therefore V_{forward} = \frac{23.87454418}{\sqrt{cd}} ms^{-1}$$

Maximum vertical translational velocity

The net lifting force of a hexacopter is determined by the difference between the upward thrust and the weight of the hexacopter.

$F_e = T - W$ *Equation 14*

F_e = 135.378– 68.67= 66.708 N

At maximum upward velocity, net upward thrust F_e is equal to drag

$F_e = \frac{1}{2} \times \rho v^2 \times A_T C_d$ *Equation 15*

at 300m above sea level density of air =1.225 kg/m

$A_T = 0.3357 m^2$

$v = \sqrt{\frac{2F_e}{\rho A_T \times C_d}}$ *Equation 16*

$v = \sqrt{\frac{2 \times 66.708}{1.225 \times 0.3357 \times C_d}}$

$\therefore V_{upward} = \frac{18.0119}{\sqrt{cd}} ms^{-1}$

4.2.9.8 Range

Theoretically, the maximum range of a hexacopter is unlimited. This is however limited by the hexacopter's hardware

Battery

The preferred battery for quadcopter nowadays is the Lithium polymer battery. Multi-rotors themselves aren't suited for long flight times. For a given distance, it will take the speed and fuel life of the battery, where the speed is heavily dependent on the battery this time. Most hobby grade hexacopters have a battery life of 8 to 10 minutes whereas the best professional versions have at most 30 minutes. The motors drain a lot of life out of the battery because the batteries are not only powering the motors, but also multiple camera gimbal motors, GPS, and lots of other electronics. In a general sense, though, it is correct in that the battery technology - not the cost - is currently the limiting factor.

Transmitter

In the more modern world, RF is used to control UAVs, longer distances are best gained by lower frequencies which usually cost more for equipment; followed by sensitivity of the receiver/antenna, and the output power of the signal. Generally, the basic cheaper setups will use 2.4 GHz and get around 300 meters (~1000 feet).

SPRAYING SYSTEM

The chief role of this hexacopter is to carry out aerial spraying of agro-chemicals. Hence, one of the most important systems aboard the multi rotor is the spraying system. It can be subdivided into:

- Spraying Subsystem.
- Low Level Indicator Subsystem.

SPRAYING SUBSYSTEM

This subsystem consists of:

- Tank and holder design
- Pump
- Nozzle and tubes

Figure 44: Tank and Holders

TANK

A transparent cylindrical plastic tank with a removable lid was chosen. The removable lid ensures regular and easy cleaning of the tank.

The tank has a base diameter of 20cm and a height of 8.5cm, giving a total of three liters (3000 cm^3) of volume. Though the designated payload is to be 2 kg which roughly equates to two litres, the unavailability of the desired tank led to the choosing of a three-litre tank.

TANK HOLDERS

To hold the payload in midair, a thin plate C-section made of aluminum was used.

The sections, six of them, were held to the frame by the same bolt and nut pairs that hold together the frames of the hexacopter. This arrangement ensures that the excess weight that would have arisen (due to an altogether different holder system) was eliminated.

PUMP

The pump is a light weight submersible pump which is capable of delivering a maximum of four litres per minute when fed with a 12V DC supply. The desired flow rate for this application (with respect to the tank capacity) however, is at about 0.5 per minute. Hence, the input voltage supplied to the pump was throttled down through a resistor network

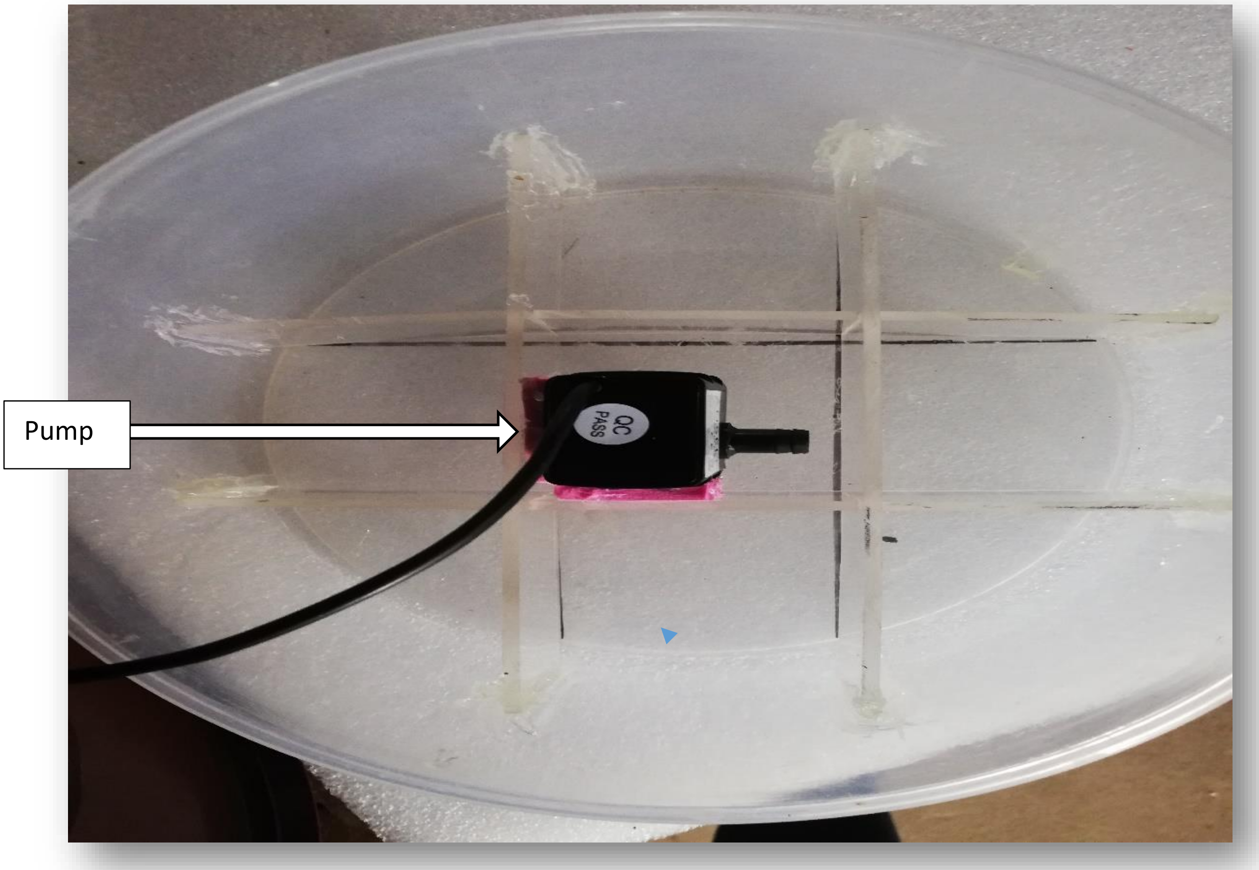

Figure 45:Pump in tank

NOZZLE

The choice of nozzle is not a straight forward decision. It is a function of liquid particle fineness desired, fluid velocity at nozzle intake, nozzle horizontal travel speed, fluid exit shape required, etc. For this reason, an adjustable pre-orifice nozzle was chosen. The fact that the nozzle is adjustable allows varying spray regimes to be achieved with the same nozzle.

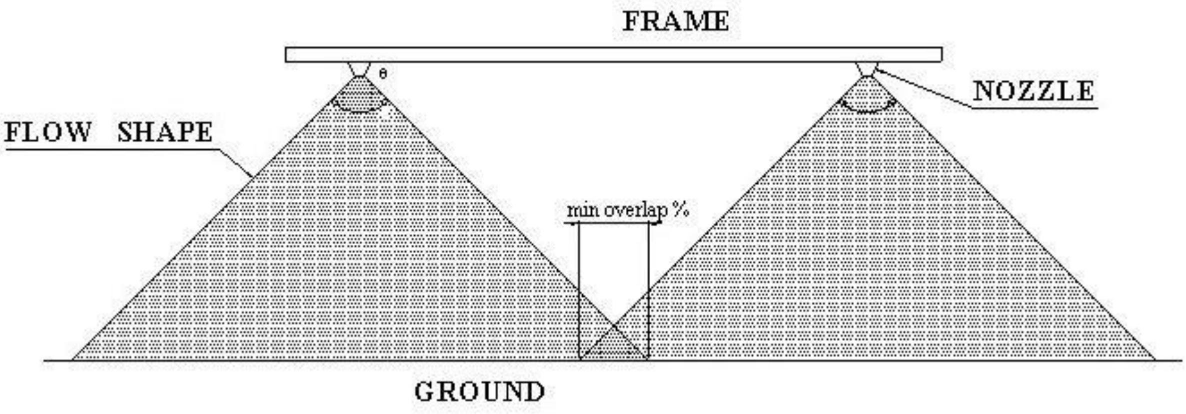

Figure 46: Illustration of flow pattern

As discussed earlier, the pressure at the inlet of the nozzle influences the spray distribution. Below is simple calculation showing the nozzle inlet pressure.

The flow inside the tubes and nozzle is subsonic. Hence, Bernoulli's equation can be used to determine flow parameters.

$$\mathbf{P_1 + \frac{1}{2}\varrho V_1^2 = P_{atm} + \frac{1}{2}\varrho V_2^2} \qquad \text{Equation 17}$$

$$\mathbf{P_1 = P_{atm} + \frac{1}{2}\varrho V_2^2 - \frac{1}{2}\varrho V_1^2} \qquad \text{Equation 18}$$

But volume flow rate is given by Q=V.A where V= flow velocity and A = cross-sectional area. For an incompressible flow such as this, Q = constant. Hence,

$$\mathbf{V1 = {}^{Q}/_{A_1} \quad \& \quad V2 = {}^{Q}/_{A_2}} \qquad \text{Equation 19}$$

$\boldsymbol{Q_{max} = 4l/min = 6.6 \times 10^{-5}\ m^3/s}$

$$\mathbf{A} = \frac{\pi * D^2}{4}$$ *Equation 20*

$D_1 = 4 \times 10^{-2}\ m \quad \& \quad D_2 = 1 \times 10^{-2} m$

Hence from equations 17 through to 20,

$P_{1,min} = 101676.55\ Pa \approx 1.02\ bar$

Figure 47: Cross section view of nozzle with some flow parameters.

Figure 48: Nozzle

LOW LEVEL INDICATOR CIRCUIT SUBSYSTEM

This basically consists of a circuit that senses the emptiness of the tank and alerts the pilot by means of a buzzer. Signals are sent via radio waves from the hexacopter in midair to a receiver attached to the pilot's transmitter. Below is the circuit diagram.

TRANSMITTER + LOW WATER LEVEL INDICATOR CIRCUIT

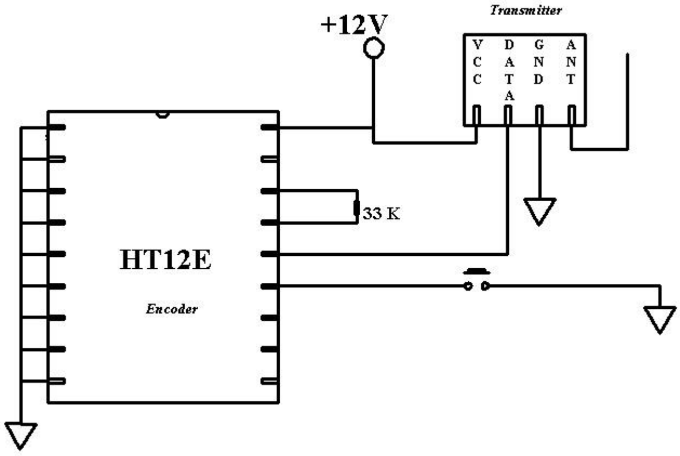

Figure 49: Low Level Indicator Circuit Diagram

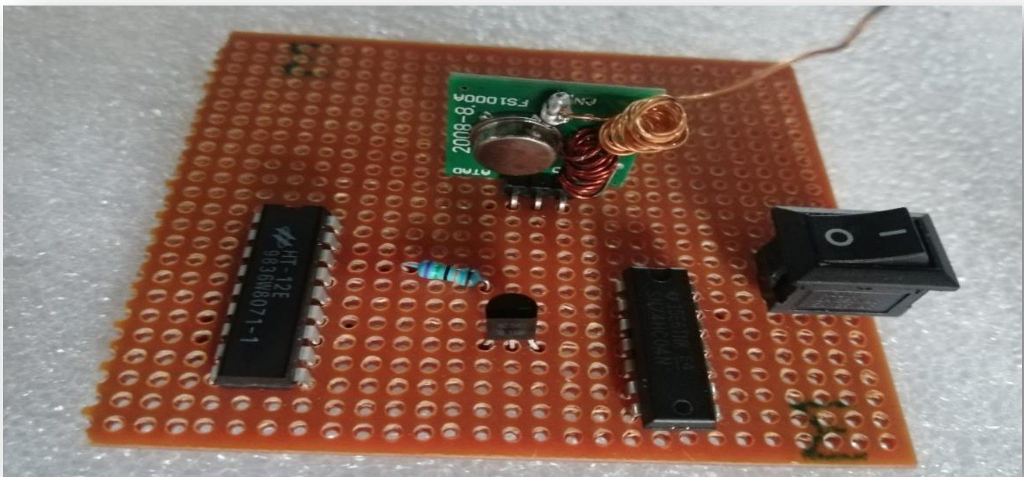

Figure 50: Low Level Indicator Circuit Board

RECEIVER + BUZZER CIRCUIT

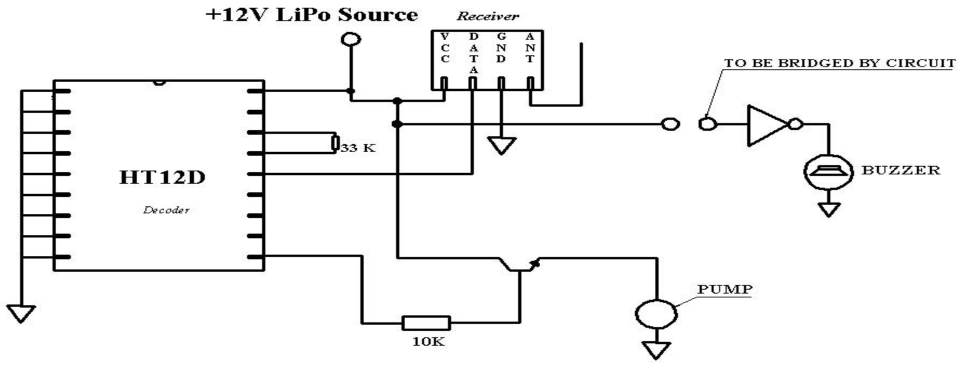

Figure 51: Receiver and buzzer circuit diagram

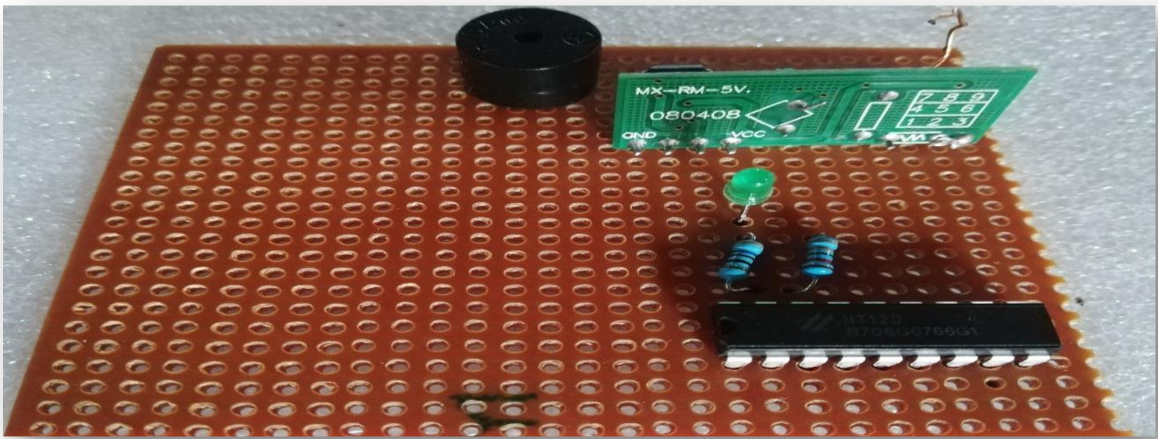

Figure 52: Receiver and buzzer circuit board

4.4 RESULTS, ANALYSIS AND DISCUSSIONS

Shear stress

A minimum shear stress analysed in XY plane was 0.0000032Pa for the flange and a minimum shear stress of -0.0000033402Pa was recorded for the root with similar loading criterion as described in figure 4.3.1.1.2 below. Taking the yield strength of Aluminium Alloy which is 280MPa in comparison to the result derived from the analysis, this shows that the arm's shear stress is insignificant. Furthermore, the maximum shear stress is less than the ultimate tensile strength which is 310MPa. Therefore, the arm will not fail at maximum performance of the Hexacopter.

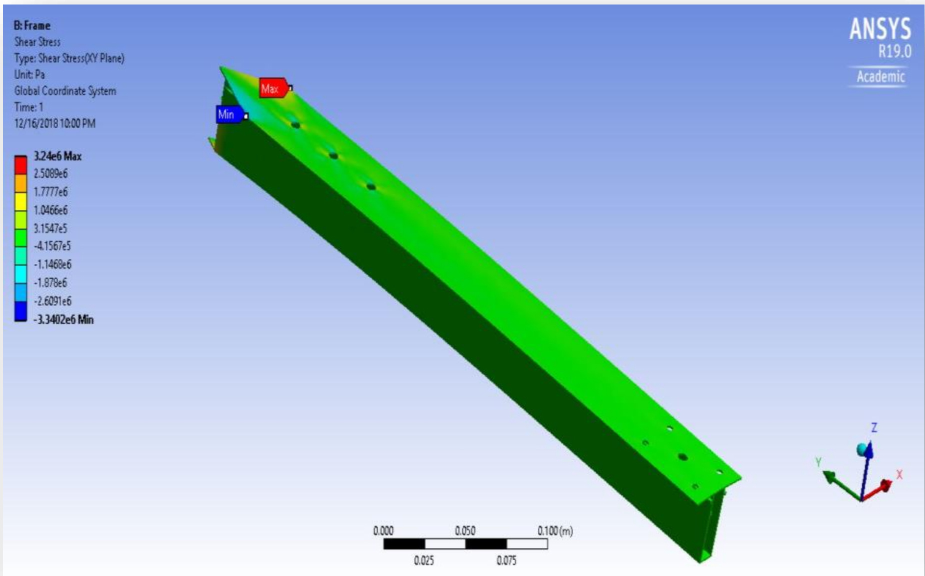

Figure 53: Shear stress of Arm

Von Mises stress

A minimum von-Mises stress of 0.0000010837Pa was recorded for the tip and a maximum of 0.00000097534Pa was recorded for the root of the arm. Comparing the modulus of elasticity of Aluminium alloy of 210GPa to the result, it shows that the arm will deform elastically. This is minimal to cause failure of the arm during flight.

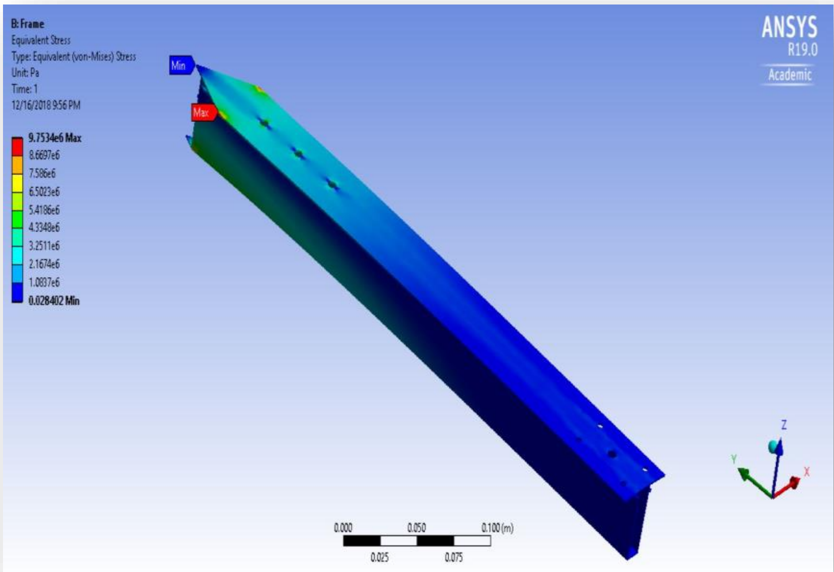

Figure 54: Von-Mises Stress on Arm

Stress analysis of Landing gear

An assumed thermosetting plastic was used for the fabrication of the landing gear. Various stresses were simulated and analyzed under maximum loading criteria.

Shear stress

A minimum value of -40295Pa shear stress in the XY plane and a maximum value of 41519Pa was achieved. Comparing this value to the shear modulus of 210 GPa of thermosetting plastic, it shows that the landing gear can withstand the shear stressed applied on it.

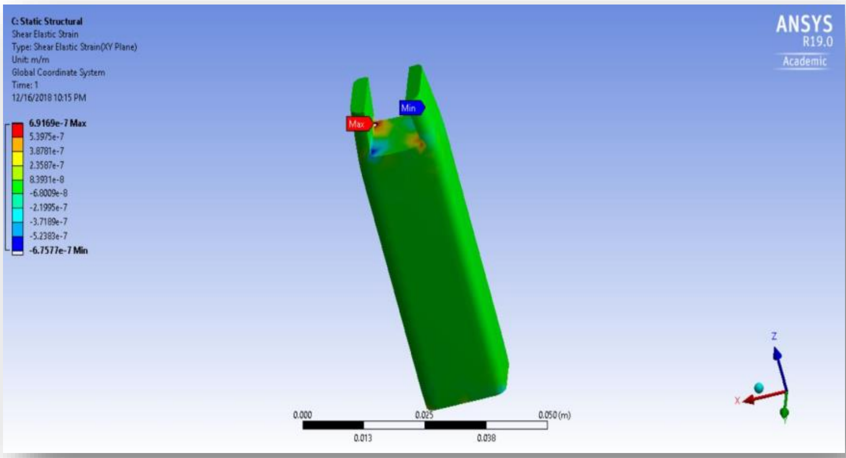

Figure 55: Shear stress of Landing gear

Total Deformation

A maximum total deformation of 0.00000012051 was achieved at the apex and a minimum of 0.00000001339m was recorded at the base of the landing gear. The difference in value implies a less failure effect on the landing gear under maximum landing loading conditions.

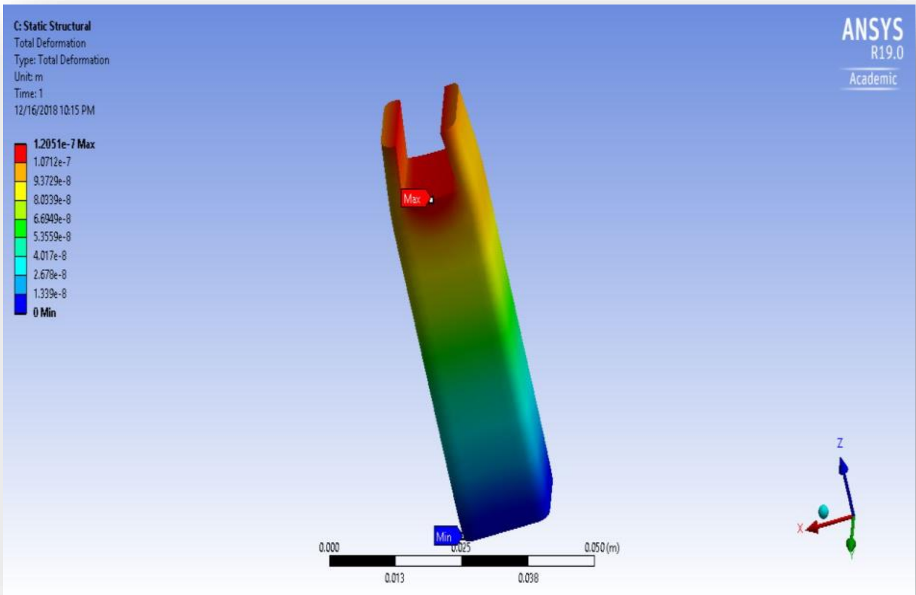

Figure 56: Total Deformation of arm

FINAL CONSTRUCTION AND ASSEMBLY

The image below indicates an exploded view of the final hexacopter construction. Subsequent images indicate the various construction stages of the drone including various ground and flight tests, which were undertaken to ensure the functionality of the hexacopter.

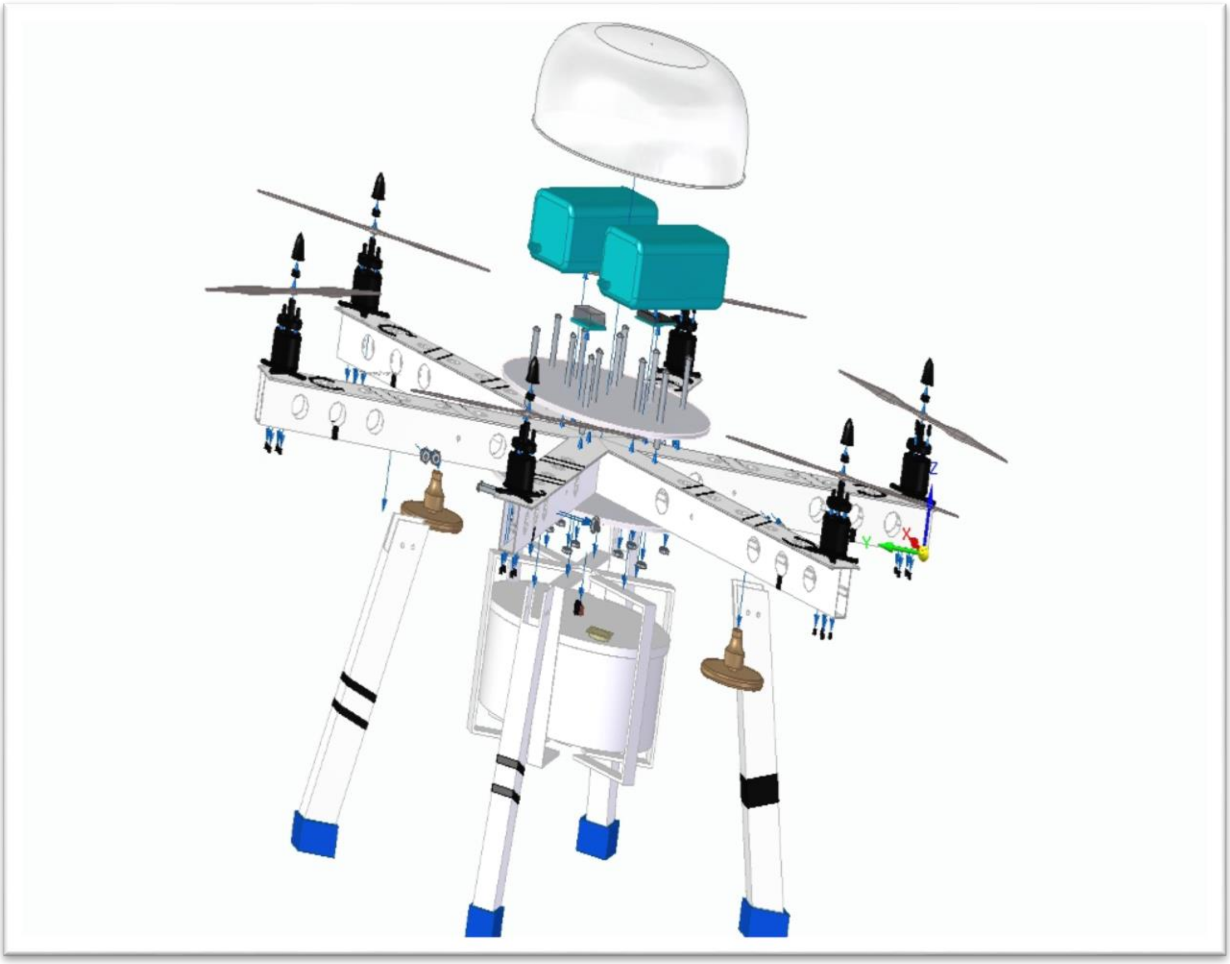

Figure 57: Exploded view of hexacoper

Figure 58: Attachment of hub to arms

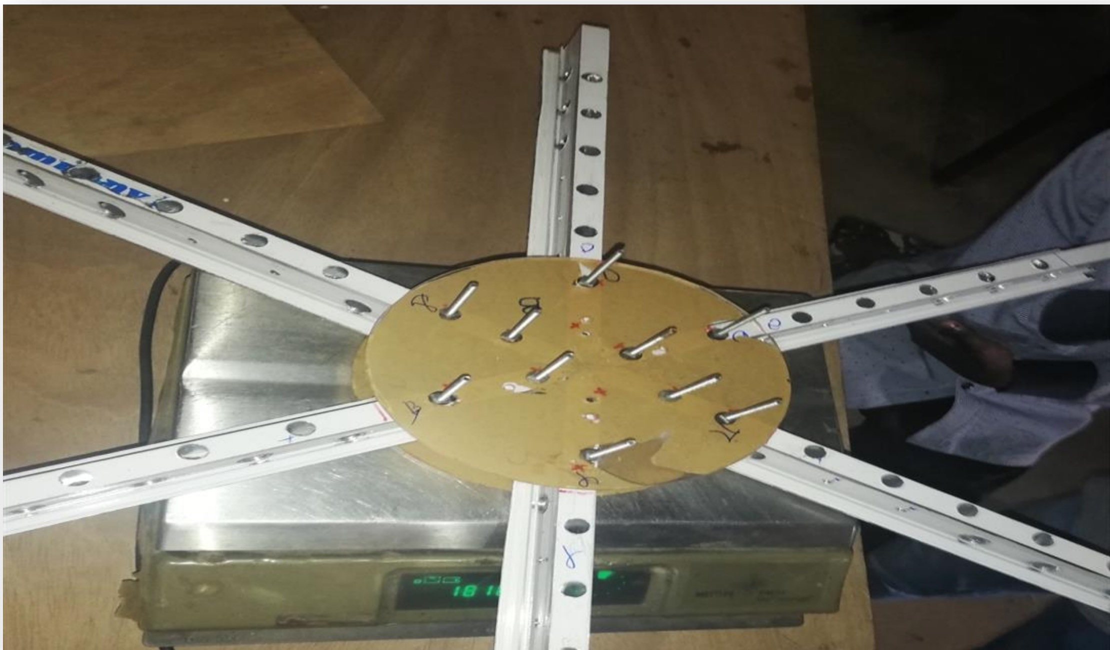

Figure 59:Weighing of hexacopter frame

Figure 60: Wiring of frame

Figure 61: Mounting of motors and propellers

Figure 62: Motor and Propeller Ground Test

PROJECT TESTING

Ground Test

A ground test was successfully carried out prior to the free flight test to ascertain the yawing, pitching, and rolling capabilities of the hexacopter after the flight controller and receiver interfacing; and ESC calibration.

Flight Test

The free flight test was successfully carried out to observe the hexacopter's performance. The first test was the hovering (low altitude flight) test which was done to observe the stability characteristics; and the second test was the high altitude flight test done to observe the performance of the device in full operation.

Figure 63: Hexacopter on Ground

Figure 64: Hexacopter at Take Off

Figure 65: Hexacopter Hovering

Figure 66: Hexacopter in flight

PAYLOAD TEST

A payload test was carried out to ascertain the vehicle was capable of carrying a 2 kilogram load in flight. Below are pictures indicating the various flight stages of the test.

Figure 67: Hexacopter with payload at take off

Figure 68: Hexacopter hovering with payload

Figure 69: Hexacopter with a payload of 2kg in flight

ON GROUND SPRAY TEST

A ground spray test was undertaken to ensure the proper functioning of the light weight submersible pump which was to deliver at a maximum of four litres per minute when fed with

Figure 70: Spray test of Pumps

a 12V DC supply with a desired flow rate (with respect to the tank capacity) however, of about 0.5 per minute.

Free Flight Test Observations

During the flight test, it was observed that, the hexacopter was not very stable as expected and quite uneasy on controls and this was due to uneven load distribution on the hub of the vehicle.

Discussion of Flight Test Findings

A quick investigation was done after the flight test was over to analyse the cause of instability of the vehicle. It was observed that the batteries and other electronic components on the hub were not properly arranged in considering the centre of gravity of the hexacopter.

Recovery

The centre of gravity of the hexacopter was determined using static balancing and the electrical components were rearranged. The controls were also trimmed to ensure easy control of the vehicle in flight.

PROJECT ECONOMIC CONSTRAINTS

The fluctuation of the dollar equivalence to the Ghana Cedi affected the purchasing value of the initial budget. Additional monies were added to make up for the value.

- The cost of shipping and delays
- The cost of customs and transport
- Material cost and acquisition of materials from different retailers
- Inadequate tools and equipment leading to extra purchases for these items were control parameters of the total cost of the project.

The money provided in the table below was using in funding the project.

Table 9: Project Cost Table

COST	AMOUNT (GH₵)
SHIPPING COST	*980.00*
CUSTOM AND TRANSPORT	*550.00*
COMPONENTS COST	*4250.00*
TOTAL COST	***5780.00***

CHAPTER 5

RECOMMENDATIONS AND CONCLUSION

In a nutshell, the specific objective of the project which was to design and build a light-weight (7 kg) yet strong remotely controlled electric hexacopter capable of carrying about 2 litres of agro-chemicals, spray onto vegetable fields with high endurance and stability to ensure good spraying results was achieved.

The gross weight of the vehicle was 6.5kg as against the estimated 7 kg. A 2 kg load was carried by the hexacopter in flight with a spraying capacity of 4 litres per minute in flight.

The entire design and fabrication process was not an easy one. Various challenges were encountered in the process. Right from deciding on the final design for fabrication, financing of the project through to shipping of ordered parts and finally, assemblage.

CHALLENGES

Due to the fact that the project is the first hexacopter to be fabricated, we had to rely on the existing drone technology from past years and device various ways to configure the hexacopter and decide on the best frame design and controls for the vehicle. A lot of time was spent during these stages since they were very critical stages in the fabrication process.

There was also difficulty in joining the six individual frame into one body for holding the entire vehicle. The aim was to join the individual arms together as strongly as possible in order for it to withstand the load it was going to be subjected to.

A tank which was to hold the liquid for spraying was difficult to come by. Various plastic containers were purchased in an attempt to suit the final design until finally, a tank was chosen and tank holders were designed and fabricated to hold the tank. These holders were fastened to the hub of the hexacopter to ensure safety of the tank and stability as well.

A total of about GH₵6000 was spent in funding the project. This amount was solely raised by group members with no sponsorship or assistance which led to delay in ordering and shipping of parts. This in return resulted in the late assembly of ordered parts onto the frame of the vehicle.

The controls of the hexacopter had to be trimmed severally because the software available was for that of quadcopter designs. After several attempts and research into existing hexacopter designs, configuration of the vehicle was achieved.

Lastly, shear stress experiment was not carried out on the frames and landing gears due to unavailability of apparatus.

ACHIEVEMENTS

Regardless of the challenges faced during the design and fabrication process, the project was completed within the expected completion time with various ground and flight tests successfully undertaken. There was a weight reduction of 6.5 kg as against 7 kg from estimation. Also, a flight time of 1 minute 26 seconds was achieved during flight test on a 10000mAH battery.

Efficient spraying was achieved in flight where the hexacopter was made to spray onto a vast area with the aid of a submersible pump and two nozzles positioned at the extreme ends of two arms on the vehicle.

RECOMMENDATIONS

In as much as the project target has been met, there are a number of strides that can be taken to make it better and lead on to other successes. Against the backdrop of the challenges and achievements, the following are recommendations for the project and laboratory:

i. Higher capacity batteries should be used to improve upon the endurance (flight time) of the vehicle

ii. Funds should be made available for very expensive project works to ease the pressure on project members and also to aid in the fast tracking of the

iii. Last but not the least, the RC aircraft pilot training program that was started should be continued and improved upon.

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APPENDICES

APPENDIX A

Nomenclature

1. UAV – unmanned aerial vehicle

2. GPS – global positioning system

3. RPM – revolutions per minute

4. I/O – Input/Output

5. MEMS – Microelectromechanical system(s)

6.IMU – Inertial Measurement Unit

7. DoF – Degree(s) of Freedom

8. ADC – Analogue-Digital Converter

9. R/C – Remote controlled

10. CG – Centre of Gravity

11. Li-Po/LiPo – Lithium Polymer (Cells/Batteries)

12. RC – Remote control

13. ESC – Electronic Speed Controller

14. BEC – Battery Eliminator Circuit

15. VTOL – Vertical take-off and landing

16. CCW – Counter clockwise rotation

17. CW – Clockwise rotation

18. CL0 – Lift coefficient at zero pitch

19. CLa – Linear fit of CL to α

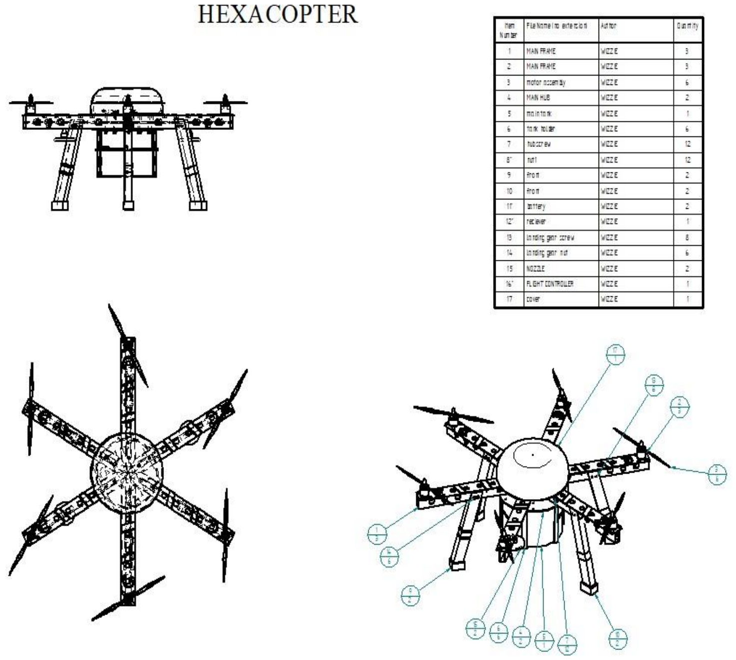
20. CLmin – Minimum lift coefficient

21. CLmax – Maximum lift coefficient

APPENDIX B

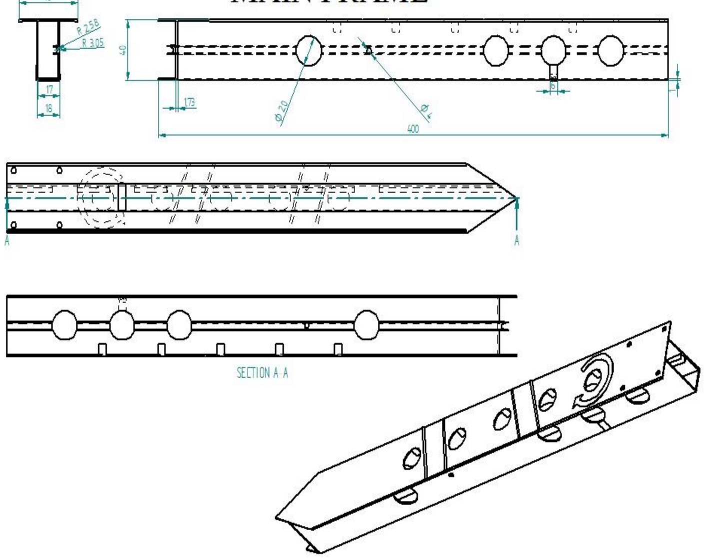
ORTHOGRAPHIC VIEWS OF VARIOUS PARTS OF THE HEXACOPTER

HEXACOPTER

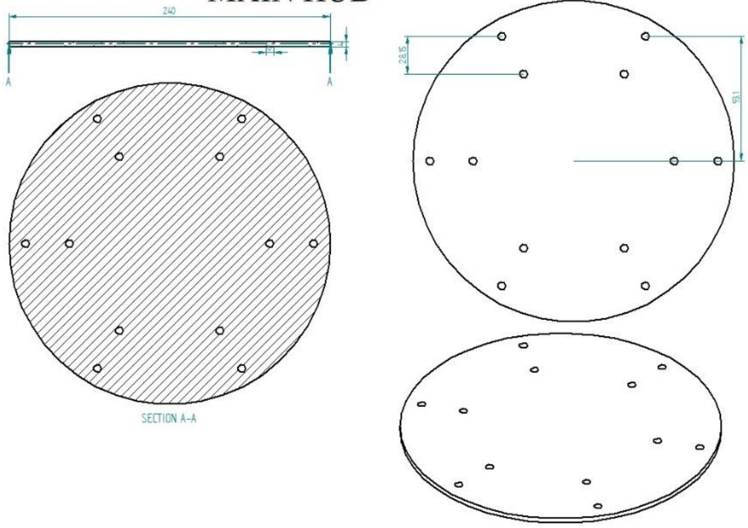


Item Number	File Name (no extension)	Author	Quantity
1	MAIN FRAME	WIZZIE	3
2	MAIN FRAME	WIZZIE	3
3	motor assembly	WIZZIE	6
4	MAIN HUB	WIZZIE	2
5	main tank	WIZZIE	1
6	tank holder	WIZZIE	6
7	hubscrew	WIZZIE	12
8	nut1	WIZZIE	12
9	front	WIZZIE	2
10	front	WIZZIE	2
11	battery	WIZZIE	2
12	reciever	WIZZIE	1
13	landing gear screw	WIZZIE	8
14	landing gear nut	WIZZIE	6
15	NOZZLE	WIZZIE	2
16	FLIGHT CONTROLLER	WIZZIE	1
17	cover	WIZZIE	1

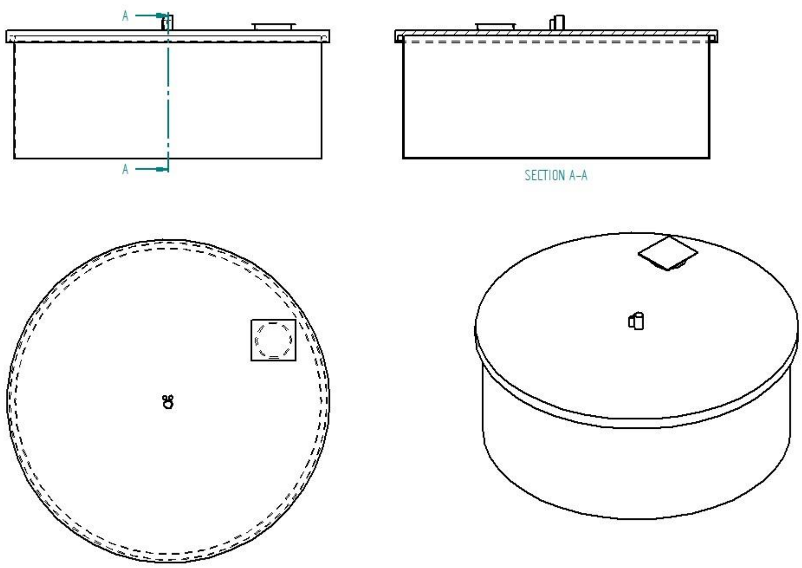
MAIN FRAME



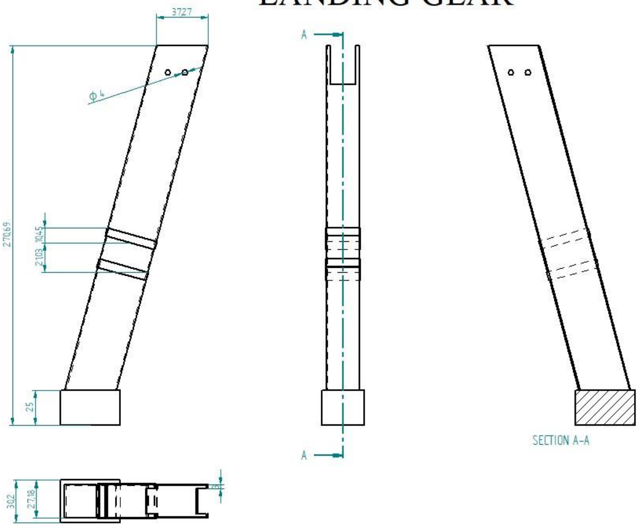
MAIN HUB



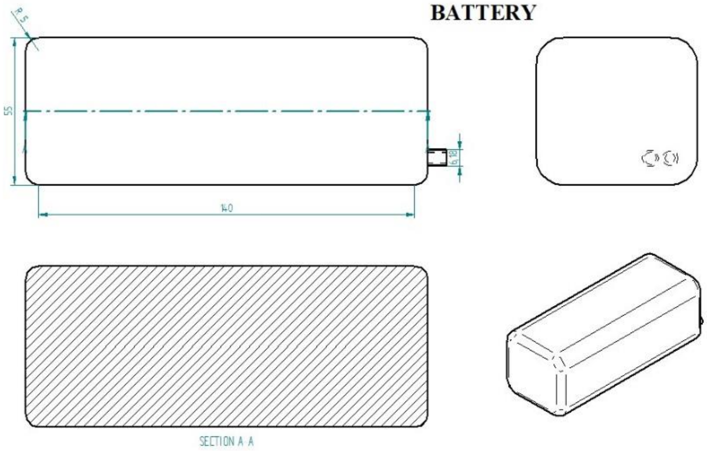
TANK



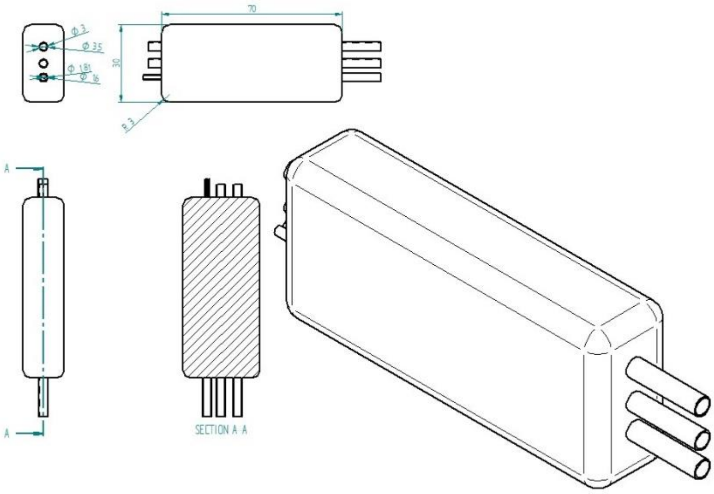
LANDING GEAR



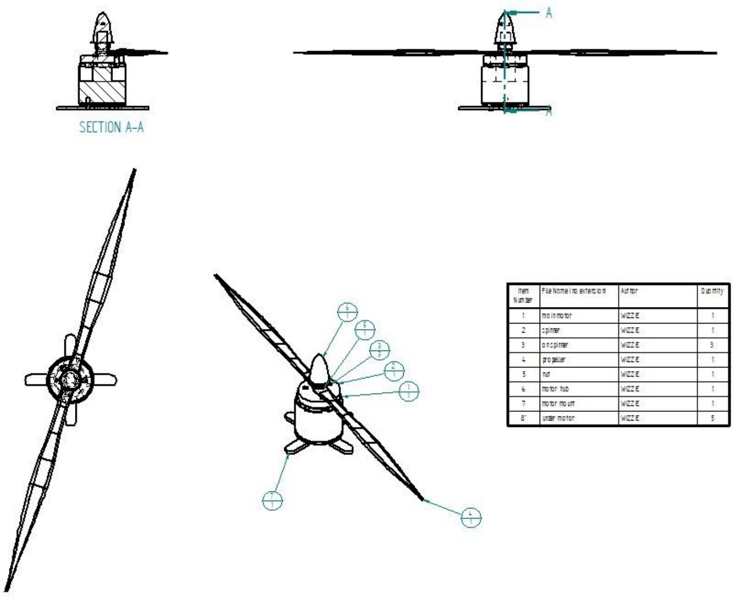
BATTERY



ELECTRONIC SPEED CONTROLLER



MOTOR AND PROPELLER ASSEMBLY



Item Number	File Name (no extension)	Author	Quantity
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2	spinner	WIZZIE	1
3	on spinner	WIZZIE	3
4	propeller	WIZZIE	1
5	nut	WIZZIE	1
6	motor hub	WIZZIE	1
7	motor mount	WIZZIE	1
8'	under motor	WIZZIE	5