DESIGN AND DEVELOPMENT OF SWARM NETWORK FOR MONITORING AND SURVEILLANCE

A Final Year Project Report

Presented to

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

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In Partial Fulfillment
of the Requirements for the Degree of
Bachelors of Mechanical Engineering

by

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ABSTRACT

Using UAVS, especially drones for monitoring and surveillance is much more efficient and reduces the response time by almost 44%. This project aims to design and develop a workable swarm system which can serve the purpose of surveillance by observing research and development in this field. Introduction of swarm technology for surveillance can help reduce damage in case of disaster to a great extent and serve a wide range of other purposes. The project consisted of selection of appropriate components for assembly of drones. Selection of motors was based on the takeoff weight of the drone. For the flight automation, a virtual drone was spawned and controlled on ROS which is to be simulated and then fed to the microcontrollers for each drone. Gazebo coupled with ROS noetic was used for simulation of drones in environments. CFD of drone frame and propeller was performed to calculate drag, pressure, and wake region of the drone and determine minimum distance between the drones. The drag coefficient was approximately 1 and the minimum distance was 300mm.

ACKNOWLEDGMENTS

First and foremost, praises and thanks to Allah, the Almighty, for His showers of blessings throughout our final year project to complete the research successfully.

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Finally, our thanks go to all the people who have supported us to complete the research work directly or indirectly.

Abdul Moiz Javed

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Arfa Eeman

ORIGINALITY REPORT

We assure that this report titled "design and development of swarm network for monitoring and surveillance" is our work based on our own research and experimentation. All the sources used for this report have been duly attached.

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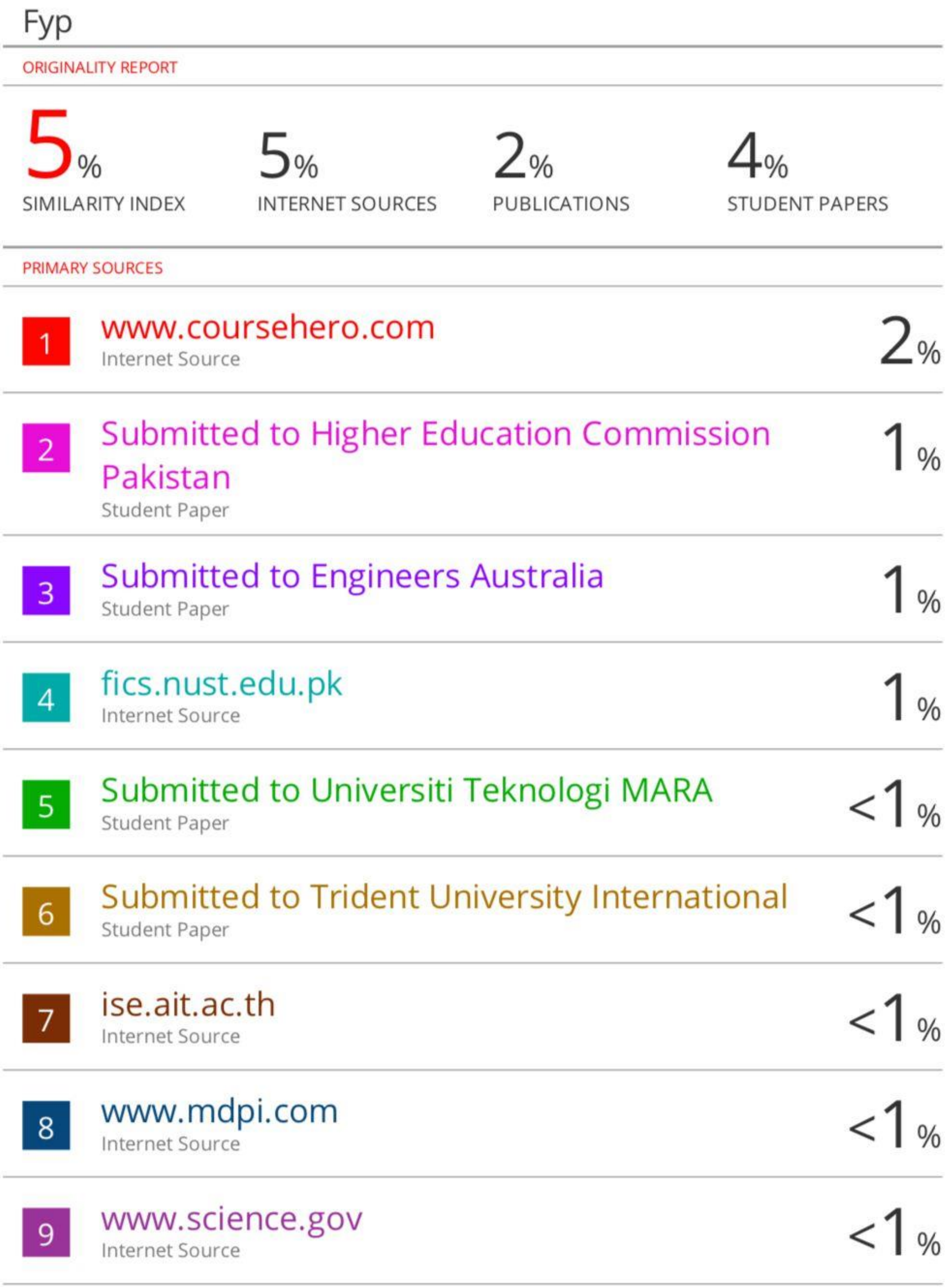

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CONTENTS

ABBREVIATIONS

DRR	Disaster Risk Reduction
AOI	Area Of Interest
UAV	Unmanned Aerial Vehicle
NDMA	National Disaster Management Authority
2D/3D	Two Dimensional/Three Dimensional
IR	Infrared
GPS	Global Positioning System
OS	Operating System
ODE	Ordinary Differential Equations
PDE	Partial Differential Equations
API	Application Programming Interface
ROS	Robotic Operating System
GNC	Guidance, Navigation and Control
GCS	Ground Control System
RPM	Revolutions Per Minute
ESC	Electronic Stability Control
PDM	Power Distribution Module
IMU	Inertial Measurement Unit
GB	Gigabyte

GUI	Graphic User Interface
L-F	Leader- Follower formation
CFD	Computational Fluid Dynamics
CW	Clockwise
CCW	Counterclockwise
CAD	Computer Aided Design
PCD	Polycrystalline Diamond
RGB	Red Green Blue

NOMENCLATURE

Ψ	yaw
θ	pitch
Φ	roll
m	Max. thrust generated by propellers
ρ	Density
D	Diameter of propeller
P	Power transmitted by battery to propeller
g	Gravitational acceleration (9.81 m/s)
π	22/7
k	Kinetic energy
ε	Dissipation

CHAPTER 1: INTRODUCTION

The period after 2019 has made us aware of the fact that any of the most unexpected things could happen to this world at the most unexpected times and therefore, has changed and therefore proper Disaster Risk Reduction (DRR), awareness and preparedness have gained more importance in the public-eye [1]. Drones are significantly in use for the purposes of disaster preparedness and management all around the world as they can take on the tasks where manned vehicles and relief workers fall short. For Pre-DRR, drones can be utilized for surveys, mapping risk profiles and identification purposes. For DRR, drones come in handy in risk mitigation, disaster preparedness etc.

UAVs can possibly reduce the overall disaster response time by 44.46% [1]. Surveillance with drones can help us detect any anomaly in a much less time than other practices. It is approximately 5 times faster than manned surveillance [2]. Additionally, drones can instigate on-ground action in case of disasters/other anomalies much faster than the manual process. Strategical application of drones can also contribute to efficient consumption of resources and saving more lives. Moreover, drones can be utilized in medical emergencies for surveillance and then aiding on-ground teams. UAVs are much more beneficial than just manual work in case of rescue and search operations as they can cover a much larger area at once and even cover hard to reach areas, thus reducing staff number and costs to some extent.

1.1 Problem Statement

The current system of Pakistan does not provide a safe and efficient procedure for post-disaster damage assessment. The available inventory does not support real time communication between disaster sites and planning departments.

According to the latest annual report of NDMA, almost all the disaster management operations were manual/on-ground [3]. Drone-enabled operation make us aware about the situation faster and therefore, right decisions can be made faster and at the right time. This could be a huge factor in saving more lives and economy. There is a dire need of 3D mapping and proper visual imaging for our areas that are prone to large scale disasters such as earthquakes and floods. Now for these purposes, aircraft are too expensive and inefficient to use, and the satellite imaging/mapping cannot meet the high-resolution needs in this case. Therefore, UAVs are the best option considering all the criteria.

After the 2015 Nepal Earthquake, drones were used in assessment of the overall damages, operation search, evacuation missions, reconstruction, and preservation [4]. In cases of fire, manned operations can obviously not be the most efficient due to factors like high stress, low visibility, and high temperatures etc. So, if UAVs are applied in such cases, it could help both the relief teams and the victims to a great extent. Recently, drones have been utilized for surveillance and other purposes in many of the wildfire accidents across the world.

1.2 Objective of this Project

The aim of this project is to design and develop swarm network for monitoring and surveillance which can provide real time communication between disaster site and planning department through multiple unmanned aerial vehicles that scout the disaster site and simultaneously transmit data of people in distress. The application of swarm system can revolutionize Pakistan’s disaster management methods to a great extent and can be of substantial importance in saving lives and economy.

The objectives of this project are design and development of two drones to make them flight-ready and have them operate in leader-follower formation

CHAPTER 2: LITERATURE REVIEW

We conducted a detailed literature review focusing on all the steps required to make the drones flight ready and coordinating them in swarm. Overall, it included design considerations, control systems, formation approaches and further software and hardware choices.

Table 1: Research papers used

Research Paper	**Abstract**
Design and development of Unmanned Aerial Vehicle for civil Applications	Initially drones were majorly serving military purposes but now we can see them being introduced for commercial applications like weather monitoring, surveillance, disaster management and delivery services. This thesis focuses on the development process of a drone which works using a radio frequency controller and sends real-time feedback to the user. Different hardware and software approaches are discussed and compared to decide the most suitable approaches for the project [5].

Classifications, applications, and design challenges of drones – a review	This paper focuses classification of drones with respect to multiple design characteristics including their size, weight, material, flight time and more while discussing their impact and suitability for various missions. Different approaches for GNC systems (guidance, navigation, control systems) have been studied. This paper also discusses research and experiments which concluded as microdrones (drones with weight < 5 kg) being one of the most suitable options for swarming. Although there are other options like solar energy and fossil fuels, keeping the budget, total weight and other constraints in view, lithium batteries are the most suitable power source for micro drones [6].
Swarms of Unmanned Aerial Vehicles – a survey	A swarm of UAVs consists of multiple drones working in collaboration to complete a specific job. Depending on the sensors and other auxiliaries attached, swarms can serve numerous purposes. This paper studies different categories of drones and their suitable application fields. UAVs are classified into four types in terms of their

	basic structure: single rotor, multi rotor, fixed wing, and fixed wing hybrid. Considering factors such as availability of resources and ease to build, multi rotors are a good option. Currently these drones have a flight time of up to 30 minutes for a normal payload. This research also compares two basic propeller organizations: ‘x’ and ‘+’ configurations. ‘x’ configuration produces more rotational acceleration as compared to ‘+’ as it is more stable. Additionally, with ‘x’ configuration, aerial photography is more convenient as compared to ‘+’ configuration as propellers stay out of screen all the time in ‘x’ configuration. Therefore, we have decided to go with ‘x’ configuration [7].
Multirotor wake propagation and flow development modeling – a review	This research discusses different multi-rotor configurations in detail using proximity effect studies, CFD and experimentation. Considering these studies and important factors such as commercial availability, payload capacity, flight time and required costs traditional quadcopter is one of the most suitable options for an outdoor experimental swarm project (like ours) [8].

Present state and future prospect of autonomous control technology for industrial drones	In this research, the GNC system is extensively explained for multiple environments and applications by discussing autonomy class of drones. Autonomy levels of drones (ranging from the ones that are remotely operated constantly to the ones which can operate fully just based on their vision) have been classified into 5 classes: Class A-E. Class D drones are based on Control Systems and can fully function and even communicate using GPS. This approach is very suitable for the people who do not work in the field of machine learning. Additionally, GPS is mostly available at all places and time [9].
Ground Control System based routing for reliable and efficient multi-drone control system	This paper recognizes the superiority of using multiple coordinated drones over single drone in the field. It then goes on to propose a ground control system which is suitable for high mobility swarms: considering factors as neighbor discovery, network connectivity and overall cost estimation. Multiple tests and simulations are conducted in different scenarios to evaluate the control system for drones, proving that the GCS system is much more reliable and efficient than other protocols available right now [10].

UAV swarm coordination and control using Grossberg Neutral Network	Path planning for aerial swarms is a widely researched topic. This paper discusses and compares various formations and concludes that leader-follower approach is a very useful approach considering UAV swarms. Reasons include convenient implementation method, greater efficiency, and minimal chance of path deviation. In this approach, the leader UAV's path should be specified, and follower UAV(s) will follow the leader's path as dictated [11].
Leader – Follower formation control of two quadrotor UAVs.	This paper discusses design and formation of L-F control for two quadrotors: *Parrot AR drone 2.0*. The leader drone basically tracks the path commanded by the ground control station and the follower drone tracks leader's path while maintaining a certain distance for safety purposes. System architecture for research conducted to study leader-follower approach for two parrot drones, employed three main components: Ground control system, WIFI access point, drone [12]
Feature and Performance Comparison of V-	Choosing the most suitable simulator for our work is important to make the right practical decisions and predictions. This research has done and extensive comparison for three robot simulators as named in

REP, Gazebo and ARGoS robot simulators	the title. After going through the paper and considering important factors (including availability, relevant work and more), we chose Gazebo for our project. Gazebo allows 3D model imports and relies on ROS which is an open source for us to work with, therefore it is a good option for us [13].

2.1 CFD Analysis

With CFD analysis being used to estimate the impacts of forces operating on the whole drone structure, it defines overall deformation, elastic stress, and strain as well. All these results aid in the design and decision-making process to attain a safe distance among the vehicles in swarm.

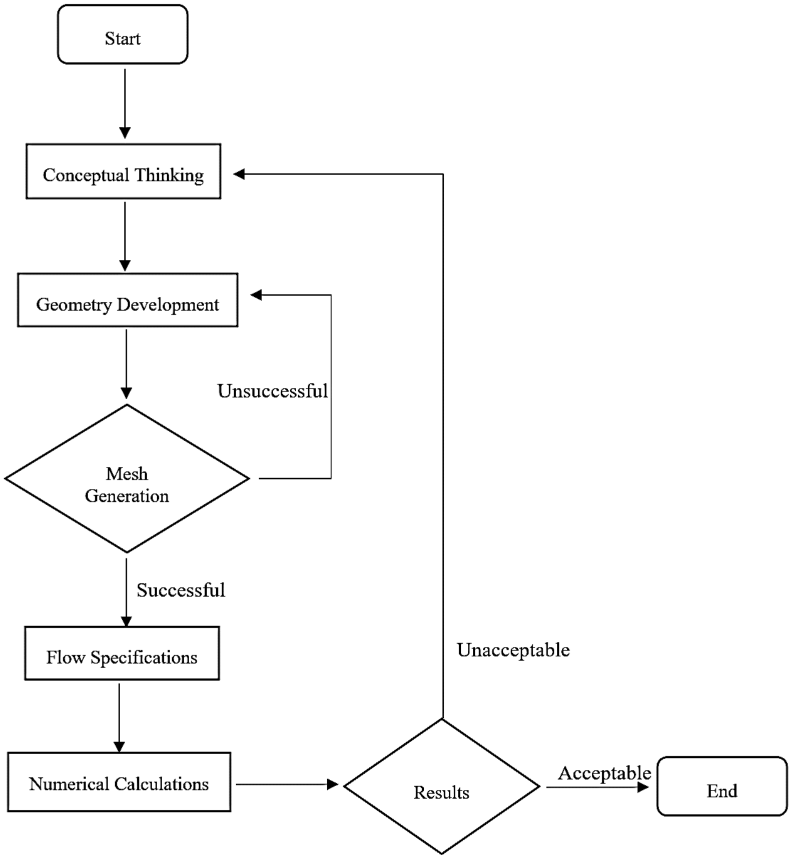


Figure 1: Flowchart for CFD analysis

2.2 Simulation:

- World modelling in Gazebo

Gazebo allows us to spawn our drones in many different environments. We can get open-source gazebo model from OSRF and add the model’s path to .bashrc file. Then the new world can be launched using .sdf code followed by addition of a launch file. Multiple models can be added and repositioned as required [14].

- Quadcopter simulation using ROS - Gazebo

The model of Quad is identical to DJI F450 considering mass, inertia, and other notable parameters. So, we can import this model in Gazebo simulator. The procedure begins by initiating a workspace, creating its necessary files, and adding the workspace to the Linux environment. A ROS package should be created to download all the required files in. Once this is completed, the terminal should be closed and another one is to be opened, where the quadcopter can be loaded in simulator. We can use further commands to put the quadcopter into motion as required [15].

- Spawning multiple drones

Multiple UAVs can also be launched in Gazebo by calling a spawn service. Usually, the service takes a string argument that states the vehicle ID, configuration, and sensors. With new features, multiple vehicles can be spawned as once using code similar to this one:

```
rosservice call /mrs_drone_spawner/spawn "1 2 3 4 5 --t650 --enable-bluefox-camera --enable-rangefinder"
```

where mrs_drone_spawner works as the spawn service [16].

2.3 Path Planning:

Mission Planner has convenient implementation, and we can see simulations and change parameters if needed in Mission Planner. We can create a new path using multiple waypoints or load an already available multi-waypoint mission [17]. Mission Planner is also helpful in hardware setup and coordination.

- Compass Calibration

We can find the option for compass under mandatory hardware. In start section, choose onboard mag calibration. After positioning the UAV in the 6 required orientations if calibration is successfully completed, we can hear three rising tones and a window stating ‘Please reboot the autopilot’ will appear. It may take a few more tries in some cases [18].

- Radio Control Calibration

In the use of 3DR radio telemetry, after completing the transmission setup, we can go to mandatory hardware options in Initial Setup and choose calibrate radio. At that point we can check and modify controls if needed. As we are done, a summary of calibration data is shown in a window [19].

- ESC calibration and Motor testing

Mission Planner also allows to calibrate Electronic Speed Controllers with proper protocols [20]. After completing that, motors should be tested whether they are spinning in the required directions or not [21]. For both these tasks, propellers should not be attached to the drone at all.

QGroundControl:

QGroundControl is a GUI that provides setup and complete flight control for a wide range of vehicles and firmware [22]. It allows path planning and provides a detailed flight map display [23]. A multiple vehicle mission can be planned on QGC and the whole mission can be simulated.

CHAPTER 3: METHODOLOGY

The project consists of a mechanical part as well automation. Off the shelf products were taken to assemble the drone and programming for swarm communication and leader-follower formation was worked on.

Considering time and resources, we divided the whole project into modules. For this project we will be working with design and development of two UAVs and making them ready for coordinated flight in leader-follower formation.

Preliminary Design Approach

- Basic Airframe Configuration

Quadcopter was chosen for this project as it has a more robust controls system than fixed-wing controls system. In case of any calamity, quadcopter can hover, tilt at 90° to pass through tight spaces, take sharp turns and be more resilient to cross winds in comparison to fixed wing.

- Quadcopter Configuration

Quadcopter configuration "x" was chosen over "+" configuration because it is a more stable configuration. "+" configuration has easier maneuverability for the purpose of acrobatics, but a project in which next phase shall be mounting of camera and real-time data collection and processing through the camera, a more stable drone is required for the job.

- Basic Programming Algorithm

In higher research stage, automated drone flight has shown better results with reinforcement learning approach when it comes to maneuvering around an obstacle. However, it is not suited for this project considering the requirement of time and expertise.

Machine learning approach causes the drone to crash back into the obstacle right after it has crossed the obstacle's starting plane because it needs to keep itself on its path.

Control Systems approach is best suited for this case because it is easier to implement, has more research done in the area to refer to, and results in the drone flying past an obstacle with minimal error.

Basically, during the whole flight process, a Ground Control System will be communicating with the UAVs via the 3DR Radio Telemetry attached, which in turn guides the flight controller (Pixhawk 2.4.8) as required. In short, GCS guides the leader and follower vehicles to their assigned GPS coordinates as they complete their mission while keeping a safe distance between them to avoid any accidents.

Though this project does not cater for obstacle detection and avoidance, the extension to this project will require this feature and hence the approach should be chosen right from the start.

- Swarm Algorithm

For swarm surveillance and reconnaissance, simulations have shown that Voronoi Partition Algorithm is best suited as it divides the AOI and sends each drone at a designated node. However, real-time data sinking causes unpredictable issues and the imbedded systems required to handle such data inflow and outflow are not available in the market yet. Hence a simpler, formation flight approach i.e., leader follower formation, is selected as the starting point of swarm communication with room to improve and expand.

3.1 Hardware Components

- Airframe

For basic quadcopter outdoor flying, DJI FlameWheel 450 Quadcopter Frame was selected. Its material is PA66+30GF with frame weight of 282g and takeoff weight carrying capacity is 1600g. Drag calculations were made on the frame in ANSYS to verify the aerodynamic proficiency at our required speed. The assembled drone weighs 1200g which is within the safe limits.

- Motor

For an F450 drone of takeoff weight around 1kg, motors of 920-1500 KV are generally used. For this project, DJI 2212 920 KV motor was used. Final thrust calculations are mentioned in [insert heading number]

- Bolts

Screw Sizes for DJI 450 are M3x8 and M2.5x6. Different parts of frame have different thread depth. for motors, M3x8 screws were used. These are recommended in the DJI F450 User Manual.

- Propellers

1045 Multiaxial CW CCW ABS Blade propellers (diameter:10 in, thread pitch:4.5inch) were used as they are most compatible with 920 KV motor.

- Electronic Speed Controllers

To control the rpm of each motor, a DJI specified ESC was used.

- Battery

LiPo battery (11.1 V) 3S 5500 mAh is most compatible with ESCs and 920 KV motor.

- Power Distribution Module

0m50 PDM is connected to the Power Distribution Board of the frame to provide stable Voltage throughout the circuit.

- Flight Controller

For flight stability Pixhawk 2.4.8 is used.

- GPS Module

Since it is an outdoor drone system, for Localization and Navigation of each drone, a GPS Module M8N was mounted on it. It couples with IMU Sensor of Pixhawk to minimize localization errors.

3.2 Circuitry

DJI F450 user manual has instructed upon the following circuitry for motors and ESCs:

The ESC live wires do not go into Pixhawk to avoid any heating issues and esc burning issues that may occur.

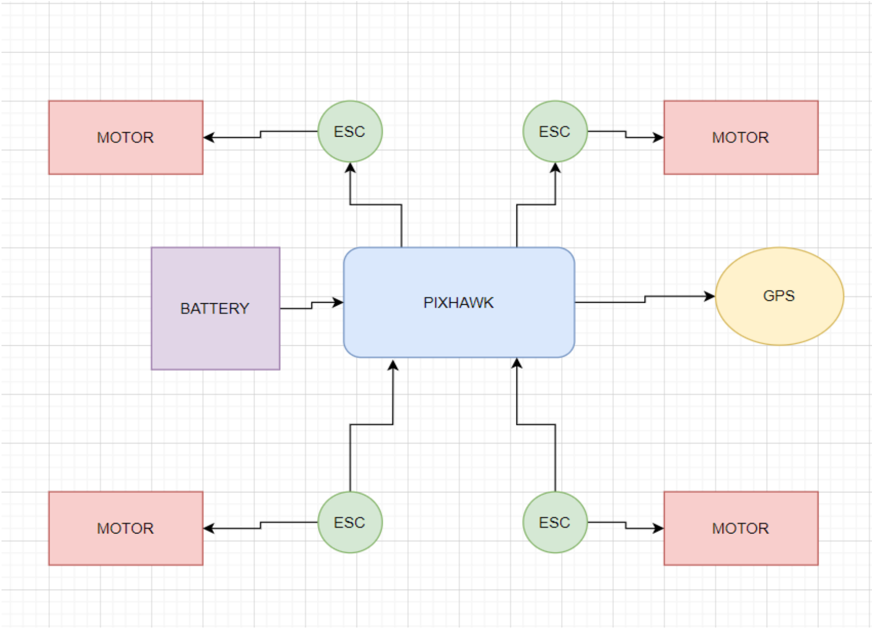


Figure 2 Electrical Circuitry

3.3 Analysis of motor

Motor Specifications

Rating 920 rpm/V

Shaft 8.0mm

Weight 56g

Max Current 30A

Max Thrust 900-1000 gram (with Li-Poly 11.1V 3s, 10x4.5)

Operating Voltage 7-12 V

Battery operating voltage = 7-12V

Max Power = 370W

Max rpm =w = 920*(11.1-7) = 3772 rpm = 395 rad/s

Drone Weight = 1.2 kg

Torque

Assuming motor efficiency of 30%

$T.w = 0.3.\max\_power$

Max torque by each motor for given rpm = 0.28 Nm

Max thrust generated by the propellers

$$m = \frac{\left[\frac{\pi}{2} D^2 \rho P^2\right]^{1/3}}{g}$$

Where g=9.81m/s^2.

Figure 3 Thrust formula

Thrust for each motor **= 1.174 kg = 1174g approx.**

Total thrust for 4 motors = 4698g approx.

Weight of the drone = 1200g

Max Thrust to weight ratio = **4:1 approx.**

Upward Velocity Calculation

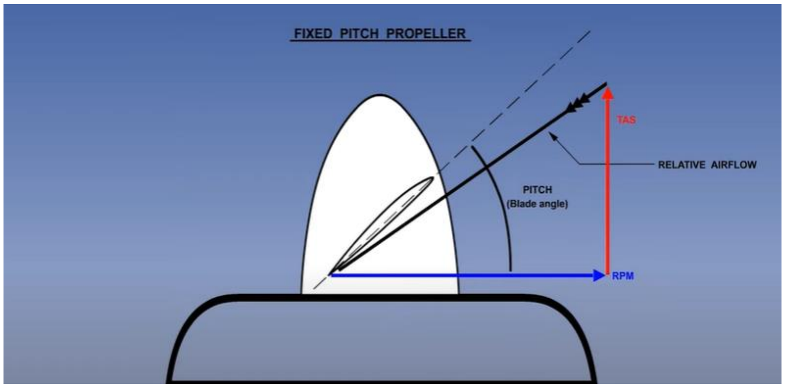


Figure 4 Velocity diagram

Propeller Blade radius = 5in = 0.127 m

Pitch angle (1045 propeller) = 15 degrees

Rpm_vel = 3772 x (2*pi/60) x 0.127 = 50.16 m/s

Tan (15) = flow_vel / rpm_vel

Flow_vel = rpm_vel x tan 15

= **13.4m/s approx.**

3.4 CFD Analysis

- Propeller Analysis

The 1045 propeller being used was analyzed for the calculated rpm of 3772 to see the forces and pressures exerted on the propeller blades during operation. The propeller was enclosed in a disk-shaped environment and then subtracted from the environment via a Boolean subtraction operation. Mesh refinement was used with finer elements on the propeller wall and coarser elements away from the propeller.

The environment was rotated at the given rpm and the model used was transient since propeller rpm increases up to the given rpm and time effects cannot be ignored for this rotational motion. The viscous model used for the analysis was k-epsilon with scalable wall functions. The model uses two PDEs (partial differential equations and gives mean flow characteristics for a turbulent flow by solving the following equations:

For turbulent kinetic energy k[4]

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right] + 2\mu_t E_{ij} E_{ij} - \rho\varepsilon$$

For dissipation ε[4]

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij} E_{ij} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

Figure 5 K-epilson equations

The model was used for its superior performance for wall bounded flows, robustness, and lower computational loads.

- Airframe Analysis

The airframe analysis was performed to determine drag coefficient of the drone frame and to calculate the minimum distance at which a follower drone could be placed behind the leader. For this the wake effects of the leader drone were determined. Wake region is the region of disturbed flow (turbulence) behind a body (downstream) travelling in a fluid. For our application of swarm drones, each drone needed to be out of the wake region created by the drone upstream of it.

The drag coefficient and wake region effects (eddy viscosity and velocity in the wake) were calculated at the drone travel velocity of 10m/s. The Drone geometry was enclosed in a box shaped environment. The dimensions of the box were chosen based on the CFD convention that the enclosure should be such that it can hold one more body (same as being analyzed) upstream, three more bodies downstream, two more bodies top, and two on the bottom. Mesh refinement with finer elements on drone wall and coarser elements far from it was used. Moreover, mesh inflation was used to carter for boundary layer thickness.

Steady state simulation was used, meaning the time effects were discarded. Since the analysis was for a constant 10m/s velocity steady state analysis was more suitable for the calculations. The viscosity model used was Spalart-Allmaras Turbulence model which is a linear eddy viscosity model that solves the following equation:

$$\frac{\partial \hat{\nu}}{\partial t}+u_j\frac{\partial \hat{\nu}}{\partial x_j}=c_{b1}(1-f_{t2})\hat{S}\hat{\nu}-\left[c_{w1}f_w-\frac{c_{b1}}{\kappa^2}f_{t2}\right]\left(\frac{\hat{\nu}}{d}\right)^2+\frac{1}{\sigma}\left[\frac{\partial}{\partial x_j}\left((\nu+\hat{\nu})\frac{\partial \hat{\nu}}{\partial x_j}\right)+c_{b2}\frac{\partial \hat{\nu}}{\partial x_i}\frac{\partial \hat{\nu}}{\partial x_i}\right]$$

Figure 6 Spalrat-Allmaras equation

The model was chosen since the analysis is steady state and a low Re flow. The model solved eddy turbulent viscosity for the wall bounded flow in our case.

Contours of velocity and viscosity were plotted at planes 500mm behind the drone, and both these variables were also graphed along a streamline starting from inlet, going past the drone towards the outlet.

- Calculation of Minimum Distance Between 2 Drones

The calculation of wake region led to determination of minimum distance between two drones. The downstream drone needs to be out of the wake region caused by the upstream drone for smooth operation, otherwise the downstream drone would be caught in a turbulent region which would disrupt normal flight operations. The distance was determined by studying the plots of velocity and eddy viscosity along a streamline moving past the drone and the distance was determined by seeing where the eddy viscosity reduced to its minimum and velocity restored its initial 10m/s value.

3.5 Drone Assembly

Since the drones do not have additional features such as payload, camera etc. mounted on it, the assembly was standard. The ESCs were soldered on to the PDM. 2 opposite motors were connected normally whereas for the other 2 motors each, any 2 wires were interchanged while connecting to the ESCs to keep 2 motors CW and other 2 CCW. The propellor blades were also fixed respectively. The propellor hole was filed according to the motor shaft and indent to an interference fit. A Stabilizer was mounted on the base on which the Pixhawk was joined through an adhesive film. The whole structure was made compact through zip ties where needed.

3.6 Single Drone Simulation (spawn and control)

The procedure is that first, a single drone be programmed for flight simulated in ROS Neotic through Linux OS. Results are to be shown on Gazebo. Single drone is spawned by installing catkin workspace and using its droneOnly environment. The code for spawn and control is:

```
roslaunch iq_sim droneOnly.launch

~/startsitl.sh

roslaunch iq_sim apm.launch
```

The first line of the above written code launches the iq_sim simulation package for the droneOnly environment. It also spawns the quadcopter in the environment. The second command launches the “software in the loop” setup that allows simulation in a virtual environment. The last command then launches ardupilot control for command, control, and maneuvering of the quadcopter.

3.7 Multi drone spawn

After the simulation spawn and control of one single drone, multiple drones were spawned in a runway environment using catkin workspace and iq_sim. The following codes were used:

```
roslaunch iq_sim multi_drone.launch

~/startsitl.sh

roslaunch iq_sim apm.launch
```

The commands work in the same way by opening a multi drone world via the iq_sim repository and couples it with ardupilot for control and maneuvering.

NOTE

The computation power and graphics required for automation were not available in-house hence we had to shift to mission planner as a result of these technical hurdles.

3.8 Single drone flight simulation

Single drone mission simulation was performed in mission planner as well due to the technological constraints of Qgoundcontrol and Gazebo. After connecting the drone and getting a 3DR fix on GPS the simulation window was opened in mission planner. A real time satellite view map was shown, and the path was given by a single click selection of waypoints on the map. The simulation was then played, and the drone travelled the given waypoints and the real time parameters were shown close to what is expected during real flight.

3.9 Single drone calibration

Before flight testing the following components of the assembled quad the following components were calibrated with mission planner.

- Compass
- Accelerometer
- Level sensor

- Esc (electronic speed controllers)

Compass calibration was performed by rotating and moving the assembled drone in different positions till the green calibration mark is shown on the mission planner screen. Green means that compass has been successfully calibrated.

The accelerator and level sensor are one click calibration where mission planner does the calibration for you.

For ESC calibration propellors are removed and drone is connected to mission planner via telemetry or USB cable. The calibrate button is pressed and drone is disconnected from both battery and mission planner. The drone is reconnected to the battery and ESC gives short beeps (one beep for each battery cell). The short beeps are followed by a single long beep indicating that ESC has been calibrated.

3.10 Single drone flight

After calibration single drone path planning and flight was performed via mission planner. The drone was connected to mission planner and GPS 3DR lock was achieved. In the plan menu of mission planner, a real time map was displayed via GPS. The drone path was given by selecting a series of waypoints on the real time map. After loading the mission consisting of waypoints into the drone, the mission was started, and the drone followed the given path. The initial flight test was done in a straight line for a single drone. The throttle, yaw, roll, pitch, and altitude parameters were shown in real time as the drone followed the given waypoints. The drone lands after reaching the last waypoint.

3.11 Multi drone flight

Swarming is supported in mission planner although it is not as advanced as qgroundcontrol or apm. Two drones were flight tested by swarming in mission planner. Both telemetries were connected to laptop via USB cable. The leader telemetry was connected to mission planner swarm option was selected by pressing Ctrl+F. Leader drone was established by clicking “select leader” button. Afterwards using the “connect MAVs” button. The offset was set by clicking and dragging on the interface. Afterwards a path was given by selecting waypoints. The offset was maintained by passing GPS position information from one drone to another.

3.12 Minimum Distance Between Drones

CFD results show that the drones can be flown within 1m of each other when only taking into account the effects of air interacting with the drones. On the other hand, the accuracy of 1 GPS module is in the range of 1-5m. Combined with the 3DR, computing at ground control station and response time of the flight controller of the follower drone at such a speed, the minimum distance or the offset between the drones was set to be 10m.

CHAPTER 4: RESULTS AND DISCUSSIONS

Results were obtained from Computational Fluid dynamics analysis of the drone frame performed in Ansys Fluent and comprised of drag coefficient for a cruise velocity of 10m/s, vorticity, drag pressure on the drone, and the velocity of air behind the drone (wake region). Furthermore, CFD (Computational Fluid Dynamics) of the rotating propeller was performed to obtain pressure on propeller, and the velocity of air leaving the propeller.

A single drone remote controlled flight was also successfully simulated in Gazebo for a drone only environment using ROS Noetic.

4.1 CFD Analysis

Two types of CFD analysis were performed in Ansys Fluent:

- CFD of the drone frame (with motors, and without propellers)
- CFD of a rotating 1045 propeller for an rpm of 3772.

CFD Analysis of Drone Frame

Drone Frame Geometry:

The frame geometry and CAD model are as follows:

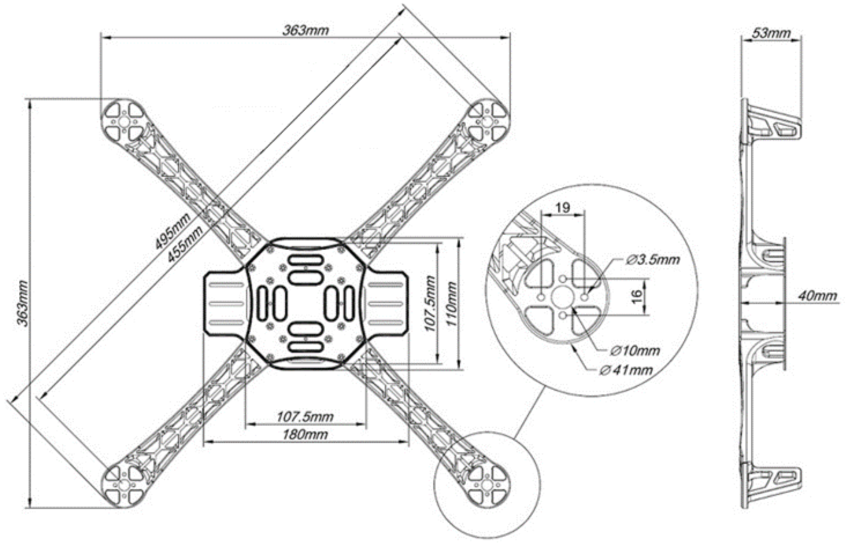


Figure 7 Drone frame dimensions

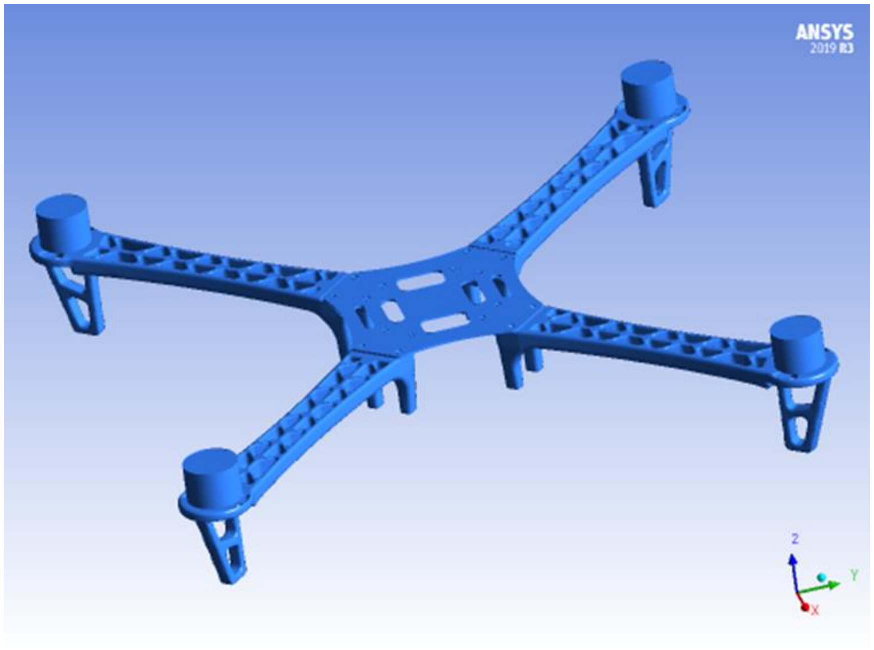


Figure 8 Drone Frame CAD

The motors were replaced by cylinders of same height and diameter to make the model and analysis simple.

Analysis and results of analysis

The analysis was performed for a cruise speed of 10m/s in a steady pressure-based field with gravitational effects considered as well. The viscosity model chosen for calculations was Spalart-Allmaras model, which is a one equation model solving for kinematic eddy turbulent viscosity for wall bounded flows. The obtained results and their discussion are presented:

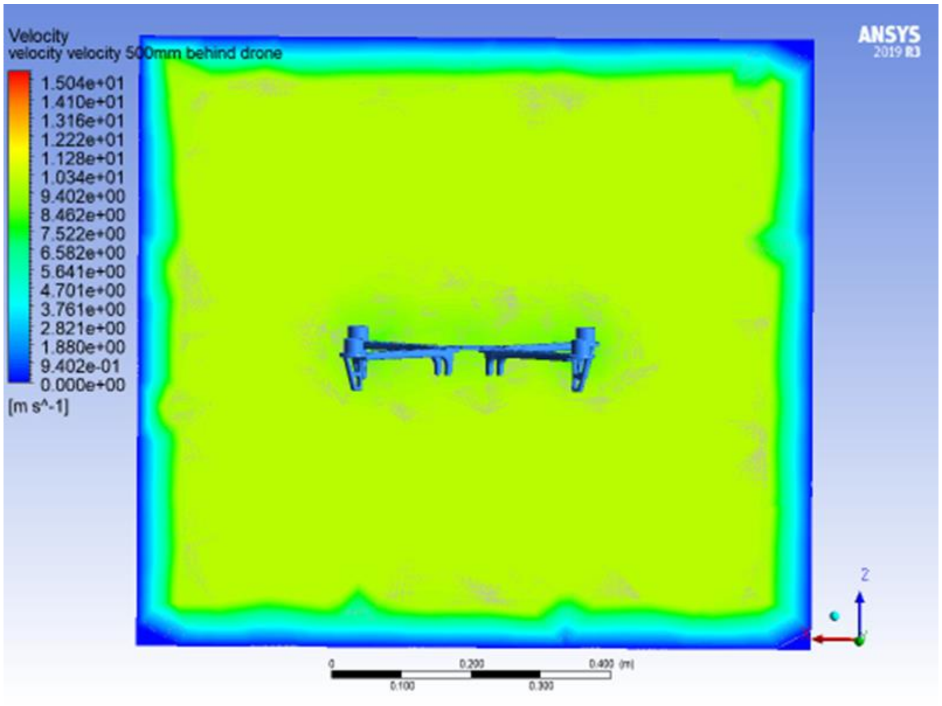


Figure 9 Velocity 500mm behind drone

The velocity contours 500mm behind the drone body were obtained and show that only a small reduction in velocity occurs behind the drone and hence a small wake region is produced due to the done. A detailed graph presented below shows the progression of velocity:

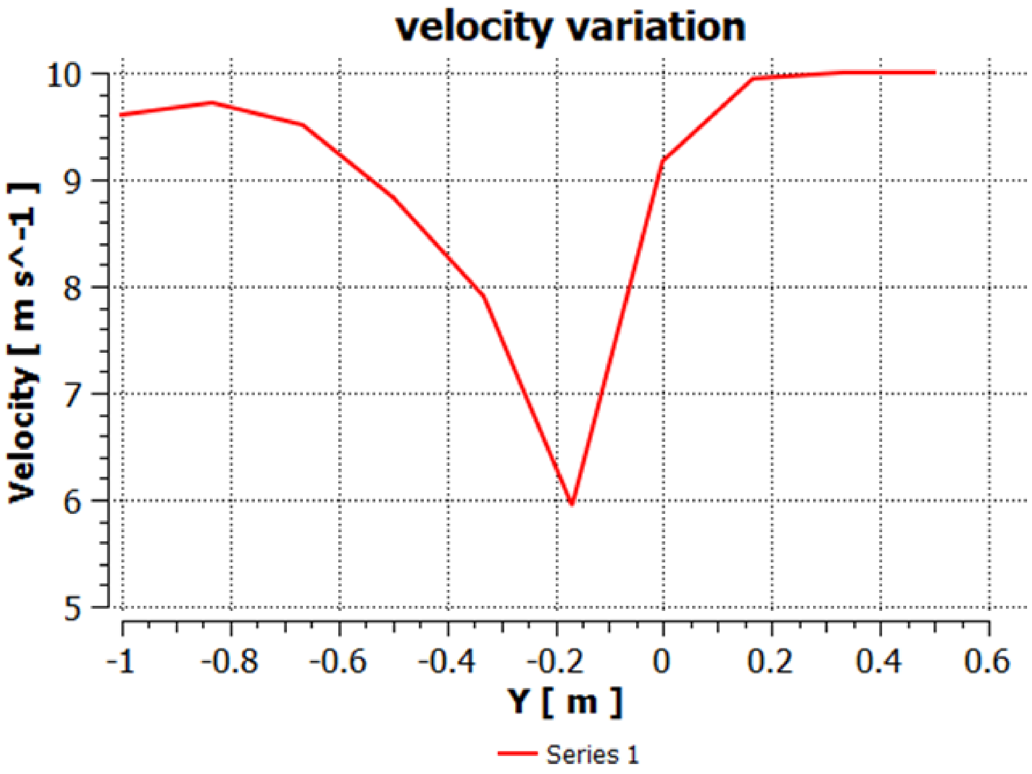


Figure 10 Progression of Velocity

The figure shows that velocity behind the drone restored to its original 10m/s value at approximately 0.3m behind drone which is a very small wake distance. The velocity reduced to 6m/s at the drone wall.

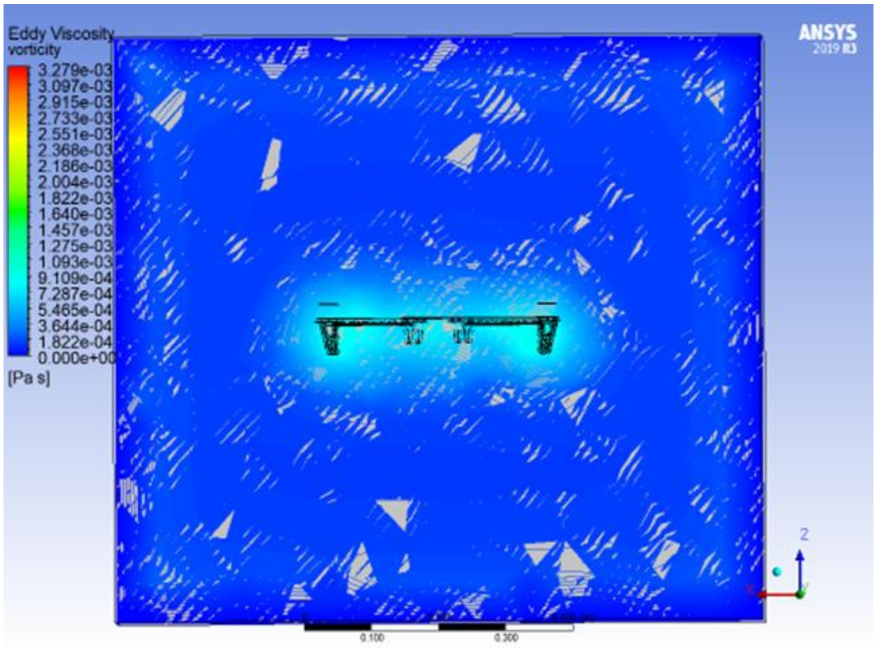


Figure 11 Vorticity 500mm behind drone

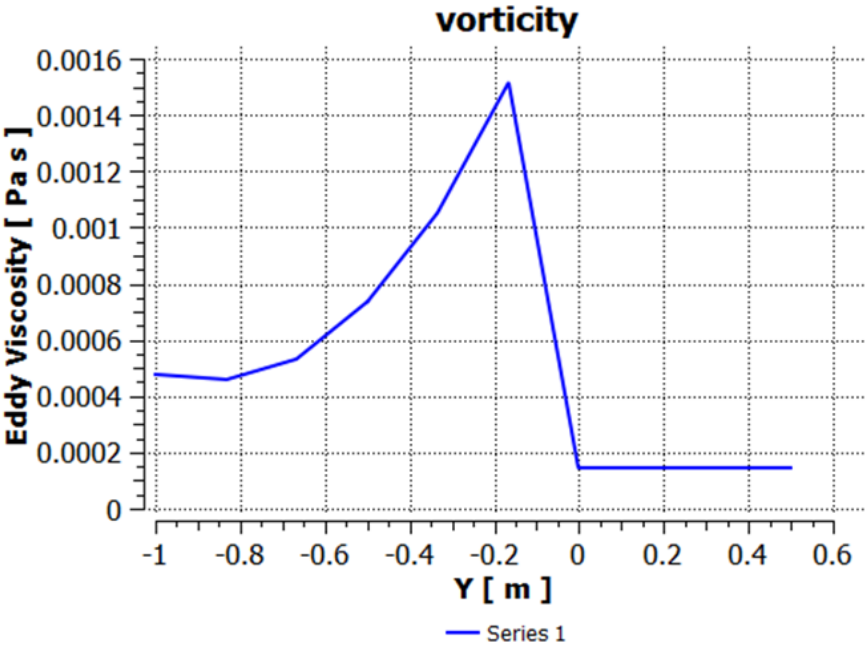


Figure 12 Vorticity progression

To get an account of disturbed flow region behind the drone (wake) eddy viscosity was calculated and its contours were plotted. The eddy viscosity was in the order of 10^{-4} at 500mm behind the drone. The progression of eddy viscosity (vorticity) was also plotted to see where the wake influence died out. This gave the idea of where the second drone in swarm (follower) needed to be placed. The eddy viscosity reduced to its minimum at about 150mm (0.15m) behind the drone.

The major portion of CFD analysis was drag calculation for the specified cruise speed, the solution stabled over a 25-iteration range and the drag coefficient came out to be almost one. The drag coefficient and drag pressure on drone body are presented below:

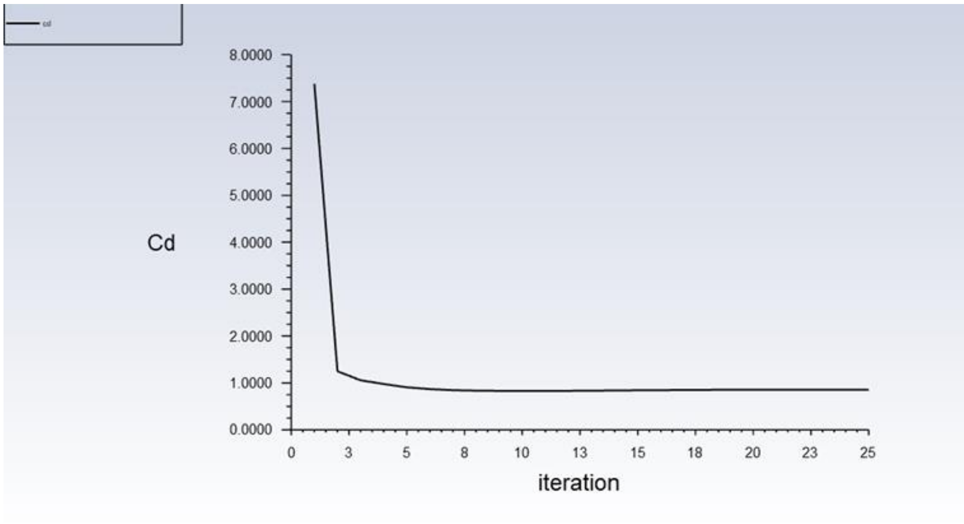


Figure 13 Drag Coefficient

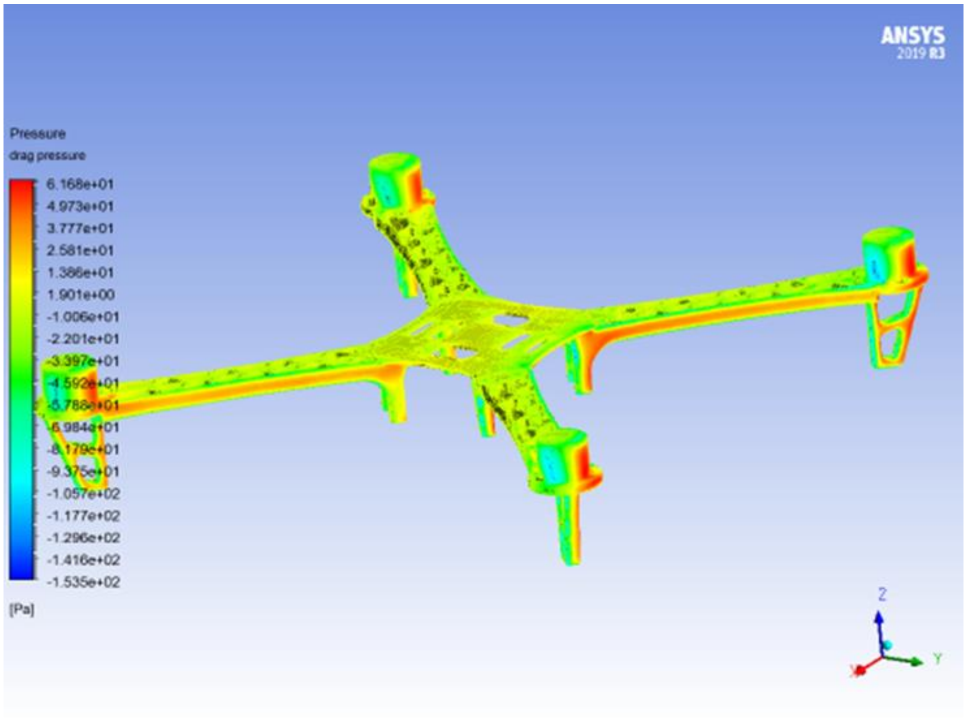


Figure 14 Drag Pressure

The drag pressure reaches a max value of 6.2 Pa at the drone wall. The overall results obtained from the analysis of drone frame suggested that the drone frame is fit for use in the current application.

CFD of Propeller

Geometry of propeller

The propeller used is 1045, meaning it has 10-inch diameter and 4.5-inch pitch, with a pitch angle of 15 degrees.

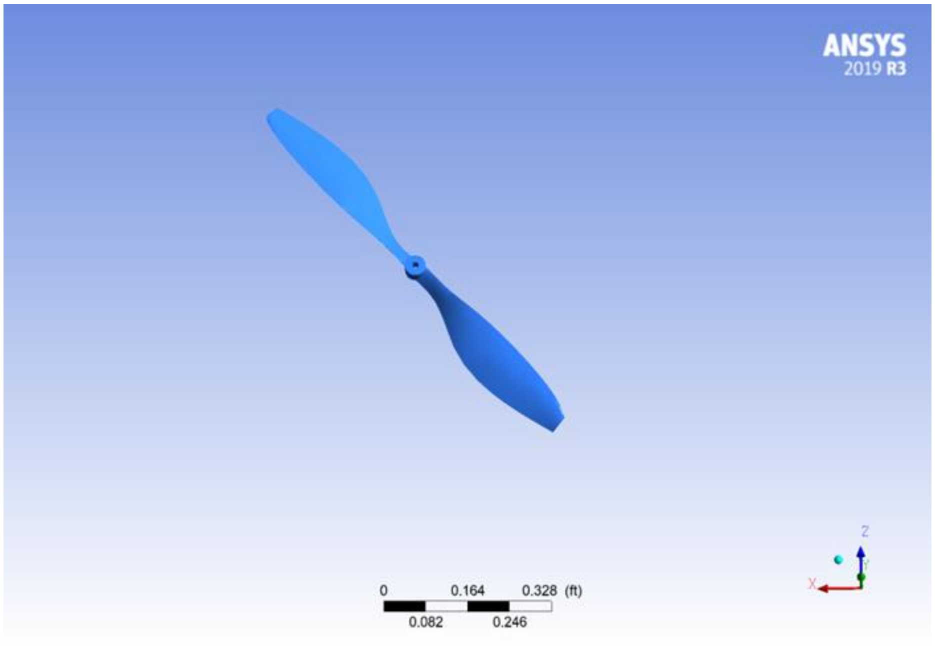


Figure 15 Propeller Geometry

Analysis results of analysis

The propeller was analyzed in transient state and the viscosity model used was k-epsilon with scale able wall functions and the effects of gravity were included. The contours of pressure on propeller and velocity in vicinity of propeller were plotted.

The velocity comes out to be around 15m/s from the blade and upwards in a positive y direction.

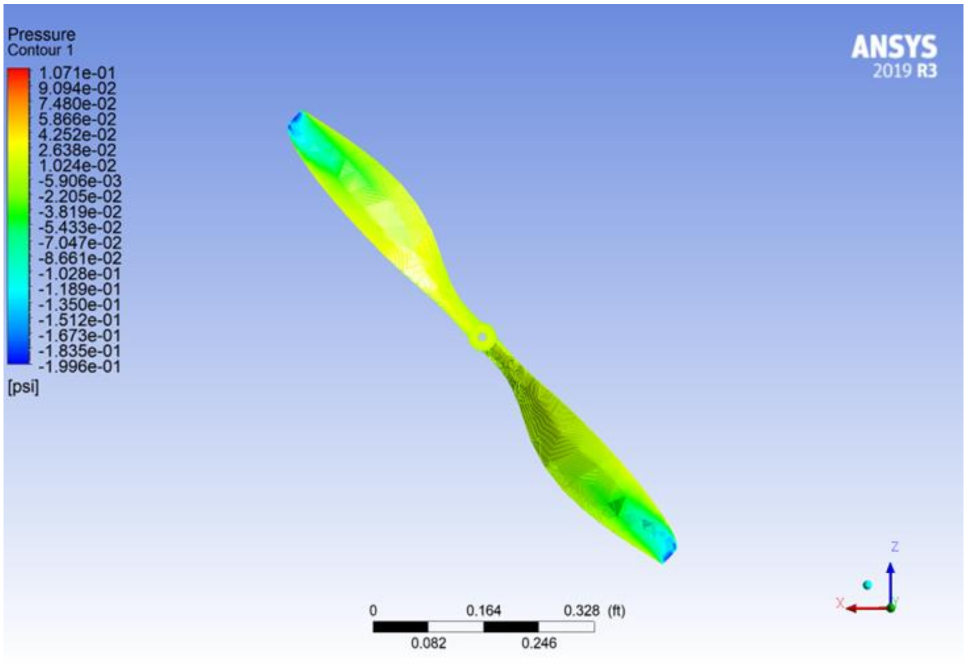


Figure 16 Pressure on Propeller

At the specified rpm of 3772, the blades of propeller are subjected to positive pressure of about 200Pa and at the tips a negative pressure of about 930 Pa. The contours of velocity of air leaving the propeller in the positive y direction are shown:

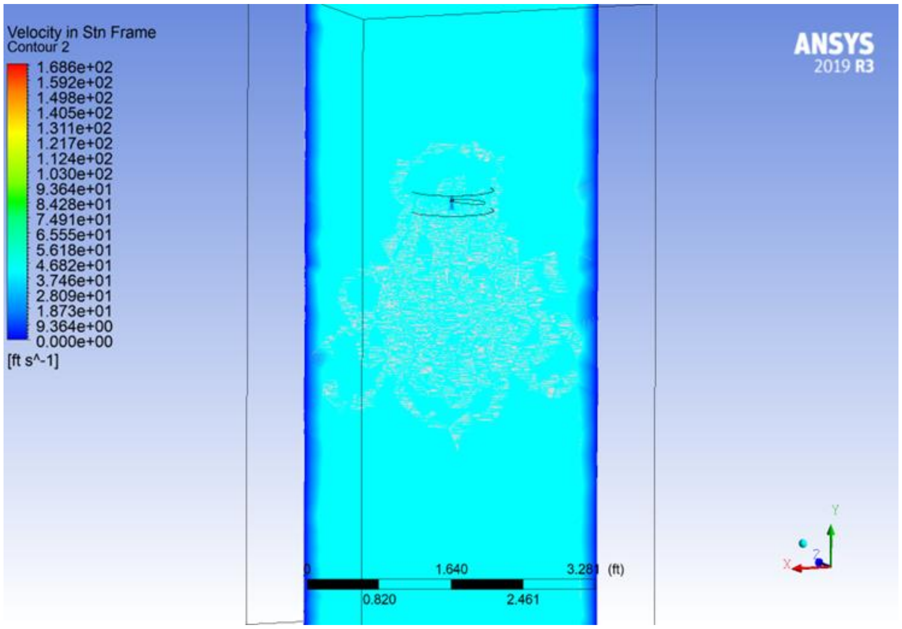
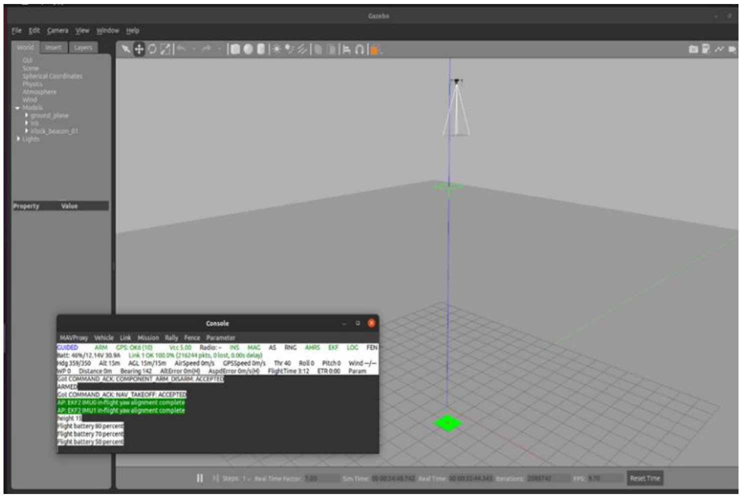


Figure 17 Velocity above Propeller

4.2 Single Drone Spawning and Control

One drone spawn and control were simulated in Gazebo using ROS noetic in a drone only environment. Drone only environment means there are no obstacles in the environment. The spawned drone was successfully coupled with ArduCopter (the flight controller) and controlled via terminal commands in Guided mode.



```
GUIDED      ARM    GPS: OK6 (10)     Vcc 5.00   Radio: -   INS   MAG   AS   RNG   AHRS   EKF   LOC   FEN
Batt: 46%/12.14V 30.9A    Link 1 OK 100.0% (216244 pkts, 0 lost, 0.00s delay)
Hdg 359/350   Alt 15m    AGL 15m/15m    AirSpeed 0m/s    GPSSpeed 0m/s    Thr 40    Roll 0    Pitch 0    Wind --/--
WP 0    Distance 0m    Bearing 142    AltError 0m(H)    AspdError 0m/s(H)    FlightTime 3:12    ETR 0:00    Param
Got COMMAND_ACK: COMPONENT_ARM_DISARM: ACCEPTED
ARMED
Got COMMAND_ACK: NAV_TAKEOFF: ACCEPTED
AP: EKF2 IMU0 in-flight yaw alignment complete
AP: EKF2 IMU1 in-flight yaw alignment complete
height 15
Flight battery 80 percent
Flight battery 70 percent
Flight battery 50 percent
```

Figure 18 Drone Spawn in Gazebo

This concluded the first step in the simulation (successful spawning and control of a single remote-controlled drone in an obstacle-less environment). The drone was successfully armed (throttle) and moved to a certain height and successfully returned to the original position (base).

4.3 Single Drone Automated Flight

Using ArduPilot Mission Planner, the single automated drone was given test waypoints. Then according to the commands provided by the ground control station, the drone underwent successful arming and take off. The mission was carried out with negligible errors in way point accuracy. On landing command, the drone landed successfully.

4.4 Multi-Drone Automated Flight

Using the same setup, multi drone flight was successfully undertaken with an average offset of 9m.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion:

The calculations and CFD done suggested the drone frame were optimal for the project and the motor and propeller analysis also concluded that the selected motors and propellers were adequate for the project objectives.

As mentioned earlier, the whole idea to develop a swarm was further divided into modules, as the whole project requires a lot more than the available time and resources. So, for this module, the project objectives set were duly achieved with the successful fabrication, path-planning, and demonstration of two automated drones in a leader-follower formation.

5.2 Recommendations:

Since the project was scalable, after successful flight testing of swarm drone network, the following recommendations are drawn to further work with this project.

- Use of Voronoi path planning for future applications and scaling.
- Using Computer vision and data from multiple sensors like RGB cameras and thermal sensors to avoid obstacles and perform more efficiently.
- Working on data collection and data processing and display.
- Using a battery with enough power to support the live audiovisual feedback process for the UAVs.
- Removing data choking risk from a bigger network of drones and multiple sensor data.

- Improving energy consumption and battery timing and possible integration of solar charging to improve flight times.
- Using a good graphic card (10-12 GB), to work with Gazebo or heavier flight simulation softwares.
- Employing a suitable failsafe mechanism for the swarm to operate safely.

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