B. TECH. PROJECT REPORT

On

Design of a Novel VTOL Concept for Higher Thrust and Agility

By

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DISCIPLINE OF MECHANICAL ENGINEERING

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Design of Novel VTOL Concept for Higher Thrust and Agility

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of
BACHELOR OF TECHNOLOGY
in

MECHANICAL ENGINEERING

Submitted by:
Gudivada Akash

Guided by:
Dr. Devendra Deshmukh
Associate Professor

INDIAN INSTITUTE OF TECHNOLOGY INDORE
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CANDIDATE’S DECLARATION

We hereby declare that the project entitled **“Design of a Novel VTOL concept for Higher Thrust and Agility”** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in ‘Mechanical Engineering’ completed under the supervision of **Dr. Devendra Deshmukh, Associate Professor, Department of Mechanical Engineering,** IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

Signature and name of the student(s) with date

27-5-2022

Gudivada Akash

CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of my knowledge.

Signature of BTP Guide(s) with dates and their designation

Dr. Devendra Deshmukh,
Associate Professor

PREFACE

This report on "Design of a Novel VTOL concept for Higher Thrust and Agility" is prepared under the guidance of Dr. Devendra Deshmukh. Through this report, I have tried to give a detailed explanation of the concept and the mechanisms involved. Even though my work was focused on using compressor and nozzle it can continued in many ways as mentioned in the future scope.

This thesis shall guide all those who wish to continue this project. I have tried to provide all the details of the work that I have done so far for the reference of the students who wish to carry forward. The codes and other material will be submitted to Dr. Deshmukh. I have tried my best to explain the content in lucid manner, whereas if some confusion persists feel free to reach out to me in that regard. I will be glad to help.

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ABSTRACT

The industry of aerial robotics is growing at a very high rate with new inventions coming every now and then. However, the thrust generated by these UAVs are only sufficient to carry payloads of low weight. This situation can be improved by using combustion as a source to generate thrust. Thus comes a model using compressor, combustion, and nozzle with a better scope of maneuverability as an added benefit. This project is concerned only about the working of the model. Hence, only compressor and nozzles are used excluding the combustion making the prototype simpler and easy to analysis.

The UAV has three nozzles, and each nozzle has a separate compressor. One nozzle is swivel nozzle making the UAV a VTOL (Vertical Takeoff and Landing) and the other two nozzles are attached to the compressor duct via a simple revolute joint. The nozzles are actuated by servo motors which are controlled by the control system. Roll, Pitch, and Yaw of the UAV are controlled by nozzles positions and rpm of the compressors. First thrust from one compressor and nozzle is theoretically calculated and then verified by an experiment. In the next step, the whole UAV can be built, and some motion planning operations can be implemented.

By including combustion this UAV has enormous applications in different fields. In Defense, this can be used to transport heavy armory to unreachable sites. In construction, this can be used to carry heavy equipment in very large sites and tall buildings. This can be also used as a flying car for commercial transportation. The list goes on. Given the applications this project could have a huge impact in the near future.

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Chapter 1

Introduction

Given a situation, an army is at war on a mountain forest. To carry the weaponry to the top of mountain we generally use vehicles driven my officers to deliver these weapons. Here, autonomous aerial vehicles that can carry heavy weaponry can be used to deliver them to top of a mountain over the trees or through the trees of forest. The same can be implemented in different situation by army. For example, Navy can use these kinds of autonomous vehicles to search high risk ships, these can be used as an emergency escape pods. Similar type of autonomous vehicles can be used in construction, with some modifications they can also be used as flying cars by the civilians.

Unmanned Aerial Vehicles are widely used in the search and rescue operations. They should pass through rough terrain and close spaces. Many times, sharp turns are to be made according to the terrain. The UAV also should carry different sensors, for instance, camera to show the injured, thermal sensors to capture invisible objects in dark, etc. Here, the UAV should be as small as possible and should be capable of making sharp turns with payloads. Drones are nowadays used in photography mainly to take aerial shorts. For this the drone should be agile to cover different camera angles and it should also carry different cameras based on the requirement of shoot, same as surveillance drones.

As mentioned above, the present UAVs are for low payloads and has low maneuverability. Classic quadcopter has less maneuverability. That is, it cannot go forward without tilting a bit. The research is still going on to increase this maneuverability by introducing different mechanisms. Even though the maneuverability is increased by tilting the motors using a servo motor, the payload remains low. There are VTOL tricopters with tilting motors which can achieve the maneuverability, but the payload is low.

The solution to the low payloads is to use combustion as a source to produce more thrust. The burning of fuel can increase the energy of the air many times and expanding this air leads to greater thrust. Generation of thrust would be similar to the thrust generation of jet engines. Where, we use compressor to compress the air from the inlet, and then combust the injected fuel to increase the temperature and pressure of the air, then expand the air through the nozzle to produce the thrust.

However, the mechanism which that should be used will be different from a conventional aircraft. A conventional aircraft cannot perform a side translation motion, it can only take turns which includes tilting of the aircraft. To attain high agility a different mechanism is used i.e., by using thrust vectoring. There are many ways to attain thrust vectoring but the Vertical Take Off and Landing (VTOL) can only be attained by using a swivel nozzle. VTOL is another property to be considered since an UAV for a forest war zone is designed as there will be no runways.

A novel mechanism is proposed where a 6-DOF can be achieved by an aircraft. Also, translation can be achieved without tilting of the aircraft. It does not have wings and works on three compressors and three nozzles. A swivel nozzle is attached to the duct from center compressor and normal nozzles are attached to the ducts from side compressors via a revolute joint. This project aims to verify this model by theoretical analysis and perform some experiments. To avoid complications, combustion chamber is removed from the pipeline. Hence, compressors and nozzles are used in the model below.

The following are the capabilities and the features of the UAV:

1. Performing Vertical Take Off and Landing.
2. 6 Degrees of Freedom.
3. Translation without tilting of the UAV.
4. Carrying high payloads.

Unlike a conventional drone this UAV is a combination of Aeroplan and a Helicopter. It has features from both of them and a smaller version of this model can be used autonomously as an added benefit.

In the coming chapter, Literature review has been performed and the existing UAVs and need for the new design has been explained in Chapter 2. In Chapter 3, mechanism for the new design is explained through different operations. In Chapter 4 the mathematical modeling is done where the exact equations are done and thrust expressions are arrived. Chapter 5 gives the weight estimation and the thrust needed. Chapter 6 shows the sample calculations and gives an estimated thrust value. Chapter 7 explains how the propeller is selected. In Chapter 8 the experiment is explained along with the experimental setup. In Chapter 9 the results are given and observations are explained. Chapter 10 gives the future scope of the project.

Chapter 2

Literature Review

The UAVs used in different areas are mainly of two types. One is winged UAVS, where the aerodynamic lift is generated because of the speed of the UAV. Here, the roll, pitch, and yaw of the UAV is controlled by the mechanisms attached to the wings of the UAV and the UAV can only go in the forward direction. This type of the UAVs needs a runway to fly making them dependent which is not available all the time. The length of the runway required can be decreased many folds by implementing the concept of thrust vectoring. Here, deflectors can be used to air flow and generate the thrust in required direction. On a larger scale this is like the aircraft where jet engines are used. Here, thrust vectoring is achieved by tilting the nozzle of jet engine a bit.

There are many different mechanisms to tilt the nozzle but many of them cannot perform vertical takeoff and landing. One method is to use a flap at the end of the nozzle. When the flap is operated due to the coanda effect the air from nozzle diverts from the usual path and hence thrust vectoring is achieved. In another way, a bypass is used and the air flow in the bypass is controlled to get the vectored thrust. The recent fighter jets use swivel nozzle for thrust vectoring and can achieve vertical takeoff and landing.

Another type of UAV where wings are used is bird inspired UAVs. Here, wings are modeled in the structure of the bird and a motion similar to the motion of the bird is built to generate the lift. The lift generated is less so only important sensors are put in the body of the bot. This type of UAV is perfect for the surveillance of an unknown terrain. Hence, this UAV is used by army to spy on the neighboring region or the possible terrorist sites. This type of the UAV cannot lift heavy payloads; hence it is useful to miniseries it which increases its spy properties.

The second type is to use propeller as a source to produce thrust. There are different models that uses propeller as the main source to produce thrust. The number of propellers in a UAV can range from one to eight. The most used UAV is the quadcopter with four propellers. In the classic quadcopter the motors are fixed to the frame of the UAV. Here, the forward motion is achieved only by tilting a bit in that direction. The motion planning can be done, and the required path can be followed but the UAV tilts while moving.

The tilting problem is solved by introducing a mechanism where the propeller motor assembly is rotated about the frame using a servo motor. This is an example of thrust vectoring as the produced thrust can be divided into two components and one component helps in generating translation without tilting. The tricoper of this kind can be build using a fixed wing system which increases the payload capacity a bit. To build this type of UAV for high payloads the size of the propeller is drastically increased, and the moving parts are outside the frame and not protected from something like bird strikes.

Considering all the above and keeping in mind that required payload and agility should be high, all the useful properties from the above are picked and the mechanism for a new UAV is designed. To decrease the drag and keep the UAV compact the wings are not used. Three nozzles are used, and each nozzle can be tilted to get thrust vectoring; hence the vertical take of and landing is achieved. The compressed air can be sent to the nozzles, but it will limit the distance the UAV can travel; hence the compressors are used, and combustion is proposed to increase the thrust. This also keeps all the moving parts inside, and the risk of bird strikes is avoided as the jet engines are already tested for that. The mechanism is explained in the following chapter.

Chapter 3

Mathematical Modeling

3.1 Introduction

Before going to actual aircraft mechanism, looking into the working of different nozzles would give a better understanding of the model.

3.1.1 Swivel nozzle

As represented in the fig. The swivel nozzle is made up of four ducts. The first duct is attached rigidly to the duct from the compressor on one side and second duct on the other side via a revolute joint. The second duct has a gear at the beginning which is connected to the motor fixed on first duct via a simple spur gear mechanism. Working of the motor rotates the second duct over the first. The other side of second duct is cut at an inclination which is attached to the third duct via a revolute joint. The third duct is cut on both ends with the same inclination angle as the second duct. The motor gear arrangement is like the first and second joining system. The fourth duct has the nozzle on one side and a cut of same inclination on the other side which is attached to the third duct via a revolute joint and motor and gear mechanism.

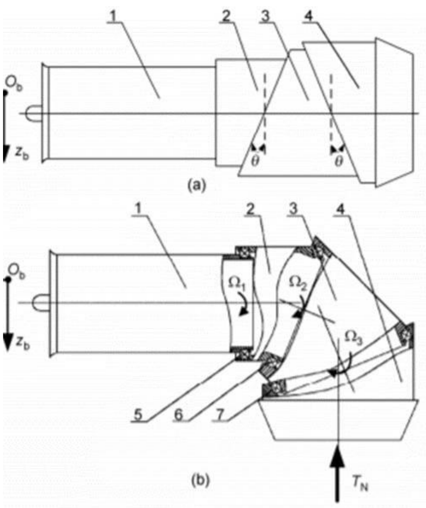


Figure 1: Swivel nozzle from side view

The swivel nozzle can point in any direction which is in the half hemisphere of the start of the swivel nozzle. The main function of the nozzle is to provide a component of thrust which generates forward motion. There will always be a component of thrust from swivel nozzle which compensates the weight of UAV and balances the net torque on the UAV.

3.1.2 Side Nozzle

Both the side nozzles are simple nozzles connected to a duct in L shape. This duct joins the duct from the compressor via a revolute joint. The motor is fixed on the duct from compressor and the gear is fixed to the motor shaft. This gear locks to the gear fixed on the L shaped duct via a spur mechanism.

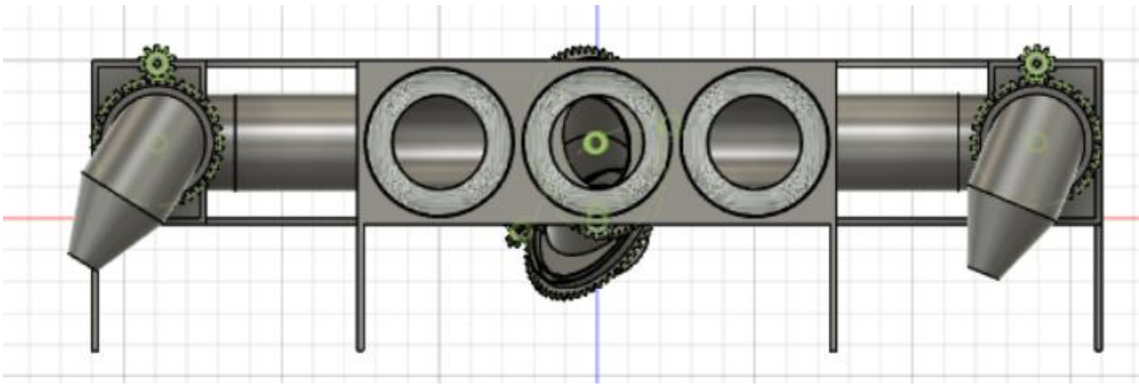


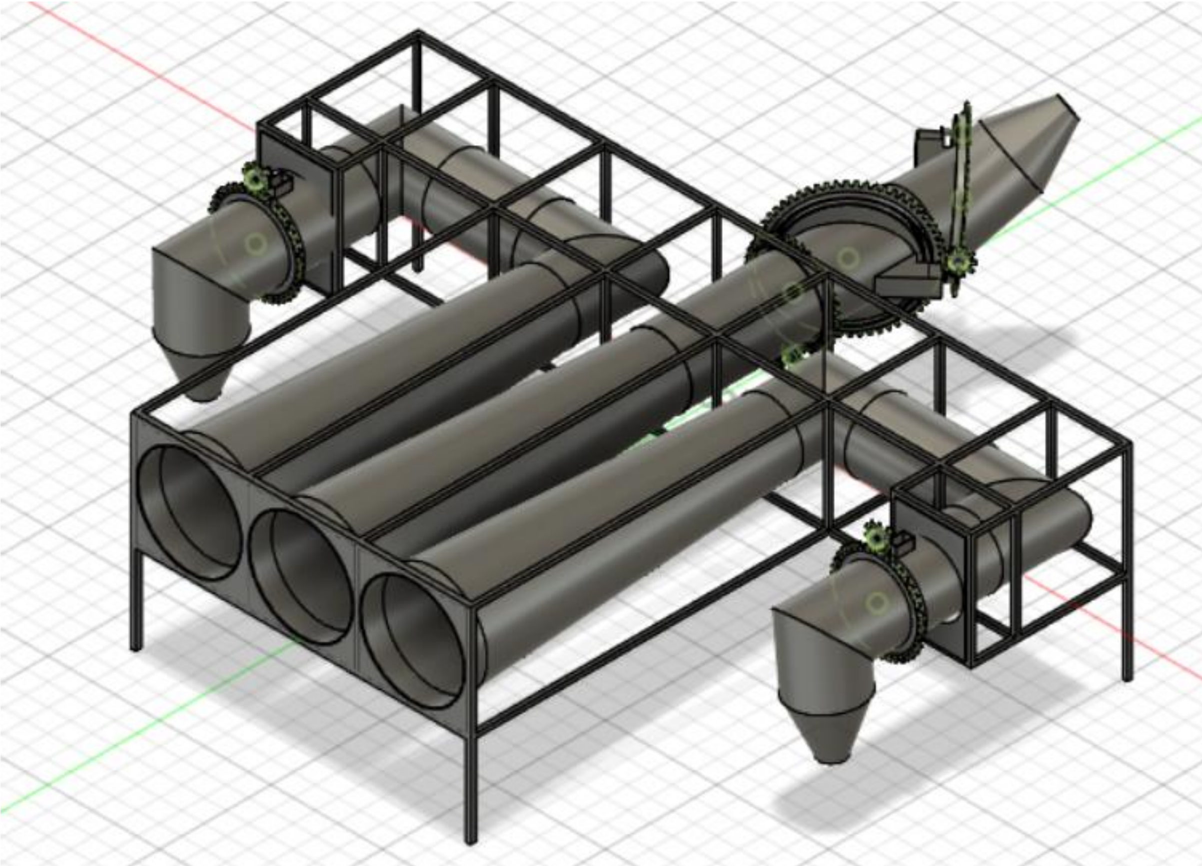
Figure 2: Side nozzles from front view

Figure 3: Side nozzles from side view

The side nozzle can be pointed to any direction in the plane passing through both the nozzles. However, the precision depends on the gear ratio of the spur gears. The main function of the side nozzles is to control the roll of the UAV, which is done by increasing the thrust from either of the nozzles. Both the swivel nozzle and side nozzles combined act together to control the remaining motions of the UAV.

3.1.3 Mechanism

The proposed UAV can translate in any direction and can tilt by any angle about the center of mass. The following are the operations the UAV can perform which includes all three translation motions and all the three rotation motions. Hence, the proposed UAV has a 6 DOF (Degrees of Freedom).



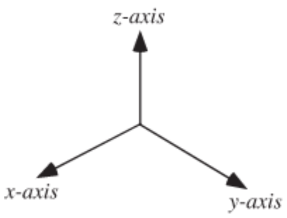


Figure 4: The UAV

Hover

The hovering position can be achieved when all the nozzles are positioned to the -ve z axis direction. The thrust from the nozzles will be in the +ve z direction and the weight of the UAV will be in the -ve z axis direction. The rpm of the compressor is set such that the forces are balanced, and the thrust is balanced. Hence, the hovering position can be achieved.

Forward Motion

The forward motion can be achieved from the hovering position by directing the swivel nozzle in the xz plane and at an angle α with the -ve x axis. The thrust from the swivel nozzle is divided into two components. One in the +z axis direction and other in +x axis direction. The +z axis thrust component helps in balancing the weight and ensures there is no couple about the center of mass. The +x axis thrust component helps in producing the force in x direction. Hence the UAV moves in forward direction. The acceleration of the UAV depends on the speed of the compressor and the angle with which nozzles are rotated. The translation achieved by the UAV is without the rotation or tilting of the UAV.

Side Translation

For side translation all the nozzles are directed in the yz plane at some angle. The thrust produced by all the nozzles is divided into two components. The component in +z axis direction will balance the weight of the UAV and counter any couple torques present about the center of mass. The component in the +y axis direction will cause the side translation of the UAV. Again, the acceleration of the UAV depends upon the speed of the compressor and the angle with which nozzles are rotated. The translation achieved by the UAV is without the rotation or tilting of the UAV.

Roll

The thrust from either of the side nozzles in increased. Hence, we get a torque about the x axis and the roll is achieved. The amount of roll and acceleration of the roll depends on the speed of the compressor. Also there will be no translation when the roll is performed.

Pitch

The thrust from the swivel nozzle is increased or the thrust from the side nozzles is increased to achieve the pitch about the y axis. The amount of pitch and acceleration of the pitch depends on the speed of the compressor. Also, there will be no translation when the pitch is performed.

Yaw

All the nozzles are directed in a similar way. Thus, the thrust is divided into two components. One of the thrust components will balance the weight and the other component causes the torque about the z axis. The amount of yaw and the acceleration of the yaw depend on the speed of the compressor and the angle with which nozzles rotated.

Mathematical modeling is crucial in the process of building an UAV because it helps in understanding the working of the UAV and helps in building control system.

Two right-handed frames are considered: **o**- The generalized earth coordinate system of axes (X_o, Y_o, Z_o), and **b-** The body-fixed coordinate system in which the origin coincides with the centre of mass of the UAV (X_b, Y_b, Z_b). The different lengths and angles of the UAV which are useful in the derivations are named below and shown in different views.

x is the distance between the centre duct and the adjacent duct. **y** is the distance between the centre line and the side nozzle exit. **a** is the distance between the front tip and the Centre of Mass of the UAV. **b** is the distance between the C.M and the head of back nozzle. **c** is the total length of the back nozzle. These lengths can be seen in the top view as sown in fig.

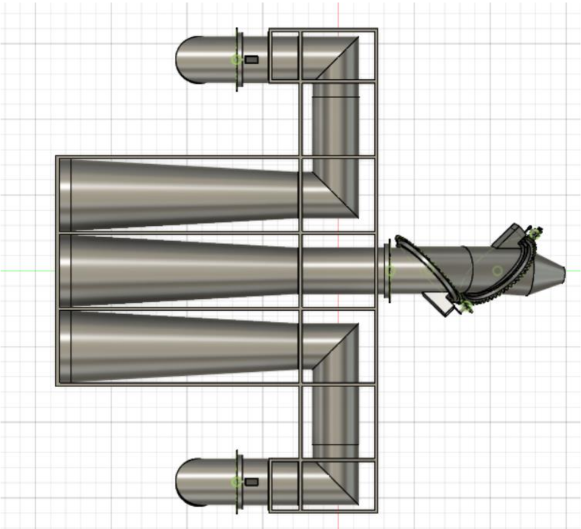
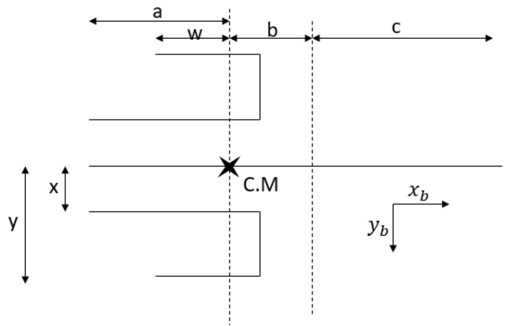



Figure 5: The top view of the UAV

z is the length of the side nozzle. ***β*** is the angle made by the right nozzle w.r.t to the vertical. ***γ*** is the angle made by the left nozzle w.r.t to the vertical. These lengths can be seen in the top view as sown in fig, consider the directions showed in the fig as positive.

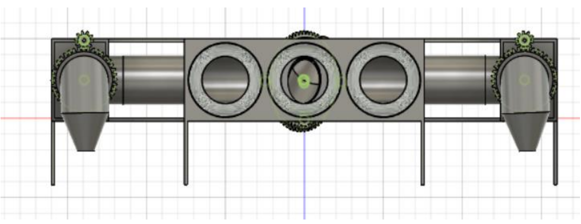
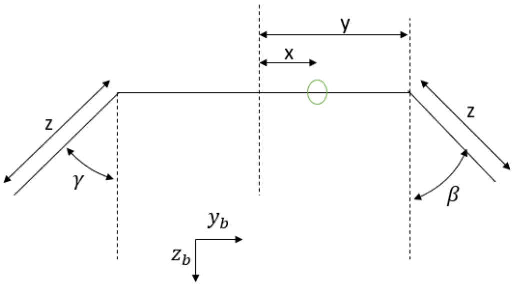



Figure 6: The front view of the UAV

w is the distance between the front tip and the side nozzle in the x axis direction. z is the depth of the side nozzle exit. These lengths can be seen in the side view of the UAV. A better control can be achieved if **w** is less than **a** making the centre of mass in between the thrust from side nozzle and swivel nozzle.

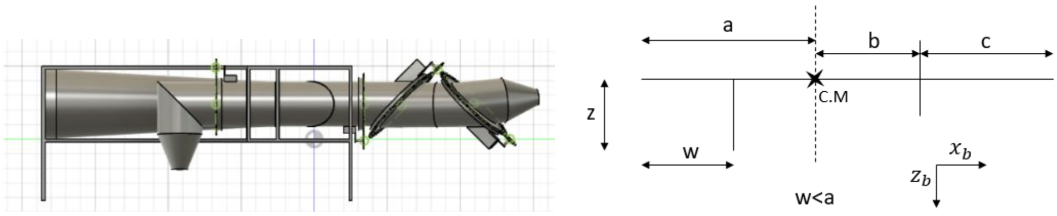


Figure 7: The side view of the UAV

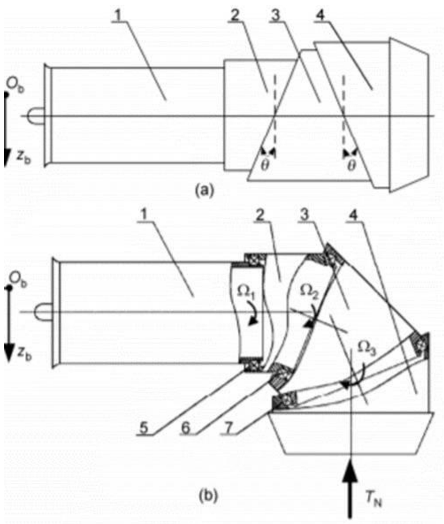
Introducing to the terms involved in the swivel nozzle, θ denotes the inclination angle of the end sections of each duct. ***Ω***1, ***Ω***2, and ***Ω***3 denote the rotation angles of the adjacent ducts i.e. the angle with which one duct rotates about other angle. $T_N(F_b)$ denotes the thrust vector generated by the nozzle. The direction of F_b is considered to be along the outlet of nozzle. α denotes the angle between T_N and x_b. ***δ*** denotes the angle between T_N and the $O_b x_b y_b$ plane.

The required α and δ can be achieved by setting the rotation angles through servo motors. For which, knowing the relation between these angles is important. The nonlinear relationship between the deflection angle/direction of the nozzle and the rotation angles of the revolute pairs is presented as follows: -

$$\Omega_1 = -\tan^{-1}(\tan\frac{\Omega_2}{2} \times \cos\theta) + \delta$$

$$\Omega_2 = \cos^{-1}(\frac{\cos\frac{\alpha}{2} - Cos^2\theta}{(\sin\theta)^2})$$

$$\Omega_3 = -\Omega_2$$



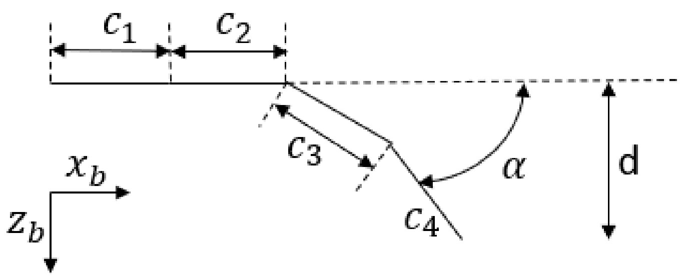


Figure 8: Swivel nozzle from side view

The value of θ is taken as 45 degrees making the triangle formed by the third duct an isosceles triangle. Length c (the length of back nozzle in top plane) is not constant and depends on $\boldsymbol{\alpha}$ (nozzle angle). c1, c2, c3, c4 are four segments of the back nozzle. Depth of back nozzle exit is d. Side of back nozzle is e. c' is the length in x axis from the point where c4 extension meet x axis and the perpendicular drawn to x axis from c4.
Equations for c, d, e, c' are as follows:

$$c = c_1 + c_2 + c_3 \cos\frac{\alpha}{2} + c_4 \cos\alpha$$

$$d = \cos\delta * \left[c_3 \sin\frac{\alpha}{2} + c_4 \sin\alpha\right]$$

$$e = \sin\delta * \left[c_3 \sin\frac{\alpha}{2} + c_4 \sin\alpha\right]$$

$$c' = d \cot\alpha$$

The rotation matrices between the defined coordinate systems are denoted by R_o^b: the rotational matrix from frame o to frame b. It's assumed that actuators are very fast, so it's dynamics are neglected.

3.2 Forces:

There are three types of forces:

1) **Thrust forces:**

The magnitude of force from right side nozzle be Fr. The magnitude of force from left side nozzle be Fl. The magnitude of force from back nozzle be Fb. From the free body diagram of the right nozzle (fig.) the force vector from the right side nozzle can be written as following.

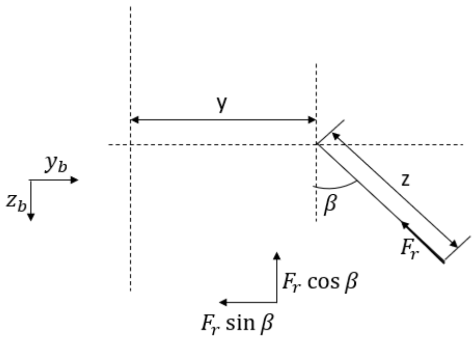


Figure 9: FBD of right nozzle

The individual force from right side nozzle is: $F_b^{Sr} = \begin{bmatrix} 0 \\ -Fr\sin\beta \\ -Fr\ \cos\beta \end{bmatrix}$.

The free body diagram of the left side nozzle will be similar to the right side nozzle. The individual force from right side nozzle is:

$$F_b^{Sl} = \begin{bmatrix} 0 \\ Fl\sin\gamma \\ -Fl\ \cos\gamma \end{bmatrix}.$$

Revolute angle between ducts 1 and 2 is $\boldsymbol{\delta}$. A, B are angles between diagonal and bottom plane, and diagonal and 'e' side of bottom rectangle respectively, as shown in figure.

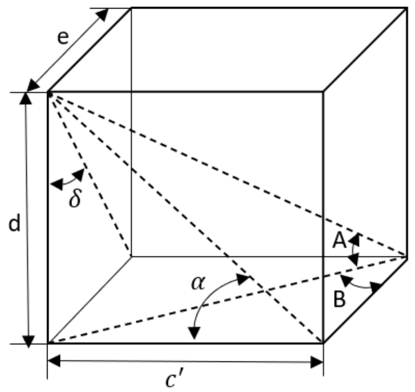


Figure 10: Angles made by swivel nozzle

$$\cos A = [\frac{(\cot\alpha)^2 + (\tan\delta)^2}{1 + (\cot\alpha)^2 + (\tan\delta)^2}]^{1/2}$$

$$\sin A = [\frac{1}{1 + (\cot\alpha)^2 + (\tan\delta)^2}]^{1/2}$$

$$\cos B = [\frac{1}{1 + (\cot\alpha)^2 * (\cot\delta)^2}]^{1/2}$$

$$\sin B = [\frac{(\cot\alpha)^2 * (\cot\delta)^2}{1 + (\cot\alpha)^2 * (\cot\delta)^2}]^{1/2}$$

The individual force from back nozzle is: $F_b^B = \begin{bmatrix} -Fb\cos A\sin B \\ Fb\cos A * \cos B \\ -Fb\sin A \end{bmatrix}$.

The total thrust force is:

$F_b^T = F_b^{Sr} + F_b^{Sl} + F_b^B$

2)**The gravity force:**

$F_g^o = \begin{bmatrix} 0 \\ 0 \\ gM_{total} \end{bmatrix}$ and $F_g^b = R_o^b F_g^o$ where, R is rotation matrix.

3) **The thrust from Duct or intake:**

Neglected as its value is very small

The total force on drone in body frame is:

$F^b = F_g^b + F_T^b$.

3.3 Torque:

1) The torque from right side nozzle:

$$\tau_{Sr}^{b} = \begin{bmatrix} [-(y + \text{z} * \sin\beta) \times Fr\ \cos\beta] + [Fr \sin\beta * z * \cos\beta] \\ -(a - w) \times Fr\ \cos\beta \\ (a - w) \times Fr \sin\beta \end{bmatrix}$$

2) The torque from left side nozzle:

$$\tau_{Sl}^{b} = \begin{bmatrix} [(y + z * \sin\gamma) \times Fl\ \cos\gamma] - [Fl \sin\gamma * z * \cos\gamma] \\ -(a - w) \times Fl\ \cos\gamma \\ -(a - w) \times Fl \sin\gamma \end{bmatrix}$$

3) The torque from back nozzle:

$$\tau_{B}^{b} = \begin{bmatrix} [-d \times Fb \times \cos A \cos B] + [e \times Fb \sin A] \\ [(c + b) \times Fb\ \sin A] - [d \times Fb \cos A \sin B] \\ [(c + b) \times Fb \times \cos A \cos B] - [e \times Fb \cos A \sin B] \end{bmatrix}$$

4) The torque because of force from propeller: neglected.

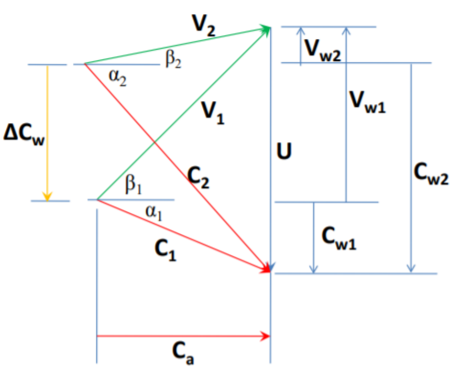
The total torque acting on drone is:

$$\tau^{b} = \tau_{Sr}^{b} + \tau_{Sl}^{b} + \tau_{B}^{b}$$

3.4 Force value calculation

Assuming pressure at inlet and outlet is same. Let A_i and $V_i$be the inlet area and velocity and A_e and V_e be the outlet area and velocity. A_i and A_e are fixed with design. Approximate V_i to be equal to the velocity of the vehicle. Axial compressor is used in the UAV hence the analysis is made w.r.t the axial compressor. The analysis will be carried out at the mean height of the blade (r_{mean}), where the peripheral velocity or the blade speed is, U.
The absolute component of velocity will be denoted by C and the relative component by V. The axial velocity (absolute) will be denoted by C_a and the tangential components will be denoted by subscript w (for eg, C_w or Vw)
α denotes the angle between the absolute velocity with the axial direction and β the corresponding angle for the relative velocity.

Velocity triangles



By considering the change in angular momentum of the air passing through the rotor, work done per unit mass flow is

$$W = U * (C_{w2} - C_{w1})$$

where $C_{w1}$and C_{w2} are the tangential components of the fluid velocity before and after the rotor.
Torque given to propellor is $T = K * \omega^2$
Work done by the torque = T* ω
Hence, $r_{mean} * \ \omega * (C_{w2} - C_{w1}) = \ K * \omega^3$
Assume, axial inflow of air.
$(C_{w2}) = \frac{K*\omega^2}{r_{mean}}$ is tangential velocity and V_i is axial velocity.
Absolute velocity V=$\sqrt{{C_{w2}}^2 + {V_i}^2}$
So, exit velocity is (Assume area of inlet and fan exit area as same) $V_e = V \times \frac{A_i}{A_e}$
Force at nozzle end F is: Air of momentum (Q* ρ)*Ve exits nozzle

$$F = \rho * A_e * V_e * (V_e - V_i)$$

Chapter 4

Analysis

All the components required to build the UAV are considered and corresponding weights are taken. Since the UAV to be build has no reference, an approximated weight for the chassis is taken. An additional weight is also considered to include the weight of wires and other small parts used during the fabrication.

Payload is taken as 500 grams as a bare minimum and the weight of the whole UAV is 4kg. As the UAV is built to aim for higher payloads the thrust produced should be able to handle the heavy payloads. Including this the payload can go higher than 500 grams and the UAV is designed to lift a payload of 6.5kg. hence, the total weight of UAV will be 10kg. The thrust produced should be 100N and considering a factor of safety of 30N it is decided to design the compressors to achieve a maximum thrust of 130N at maximum speed of motor.

Components	**Weight(g)**
battery	500
3.ducted fans (70mm)	600
Raspberry pi	50
Esc (3+5)	90
Transceiver	50
Additional	300
Chassis	1500
Payload	500
Servo motors (5)	50
Total	3640

Table 1: Weights of different components of UAV

Next step is to manually solve the equations for different operations to see whether the operations are possible or not. We also get an idea on how much force needs to be generated and the next step would be to analyze how this force should be generated and compressor selection. The following are the sample calculations for the mentioned operations:

The lengths are considers as following based on the cad models prepared and some approximated lengths are assumed. a-w= 20, w=20, b=30, c1=c2=5, c3=15, c4=10, y=42. The weight of the UAV is taken as 4kg i.e., the minimum payload conditions for the calculations.

4.1Hover

The following is the free body diagram of the UAV in the side view. F_r and F_l will be equal and there will be no roll of the UAV.

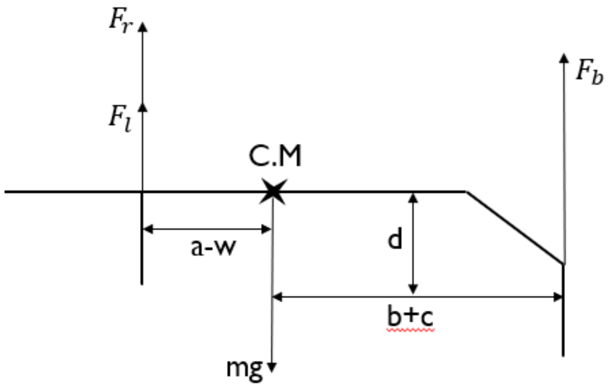


Figure 11: FBD in the side view

Nozzle length in the x direction will be $c = c_1 + c_2 + c_3 \cos\frac{\alpha}{2} + c_4 \cos\alpha$

$$c = 5 + 5 + 15\cos\frac{90}{2} = 20.61cm$$

From the FBD of the UAV, we get two equations

Balancing forces: $2F + Fb = 40$

Balancing the moments: $2F(a-w) = (b+c)Fb$

Solving the above equations,

$$Fb = 40 * \frac{a-w}{a+b+c-w} = 40 * \frac{20}{20.61+30+20} = 11.32N$$

$$F = 20 * \frac{b+c}{a+b+c-w} = 20 * \frac{50.61}{70.61} = 14.34N$$

4.2 Forward Motion

Now, consider a situation where forward motion is tried to achieve from hover position. Here, the swivel nozzle is rotated in the xz plane and at an angle α with the x axis. The thrust is divided into two components. For the calculation purpose the value of α is taken as 30 degrees. The following is the free body diagram of the UAV used for the calculation.

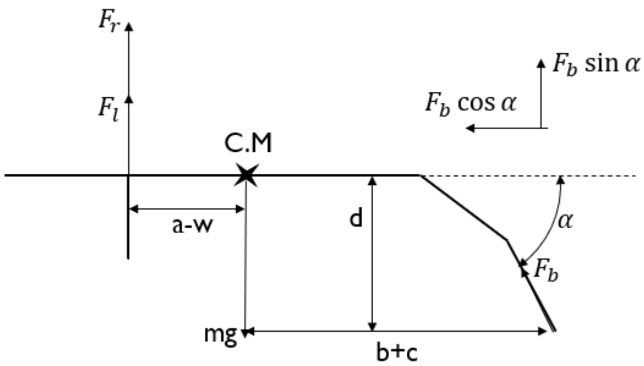


Figure 12: FBD in the side view

Balancing forces:

$$2F + Fb * \sin 60 = 40$$

$\rightarrow 4F + \sqrt{3}Fb = 80$ for no y direction motion
Acceleration in x direction is $a_x = \frac{Fb \cos 60}{4} = \frac{Fb}{8}$.

$$d = \cos \delta * [c_3 \sin \frac{\alpha}{2} + c_4 \sin \alpha] = 1 * [15 * \sin 30 + 10 * \sin 60] = 16.16$$

Balancing moments:

$$2F(a - w) + Fb * \cos 60 * d = (b + c) * Fb * \sin 60$$

$$\rightarrow \quad 4F(a - w) + d * Fb = (b + c)Fb * \sqrt{3}$$
$$\rightarrow \quad 4F(a - w) = \left((b + c) * \sqrt{3} - d\right)Fb$$

Solving the equations

$$Fb = 80 * \frac{a - w}{\left((b + c) * \sqrt{3} - d\right) + [(a - w) * \sqrt{3}]}$$

$$\rightarrow Fb = 80 * \frac{20}{\left(50.61 * \sqrt{3} - 16.16\right) + \left[20 * \sqrt{3}\right]} = 15.226N$$

$$F = 20 * \frac{(b + c) * \sqrt{3} - d}{\left((b + c) * \sqrt{3} - d\right) + [(a - w) * \sqrt{3}]}$$

$$\rightarrow F = 20 * \frac{50.61 * \sqrt{3} - 16.16}{\left(50.61 * \sqrt{3} - 16.16\right) + \left[20 * \sqrt{3}\right]} = 13.472N$$

4.3 Yaw

Now, consider a situation where yaw is tried to achieve from hover position. Here, the swivel nozzle and the side nozzles are rotated in the similar manner to achieve the torque about the z axis. The net force should be zero ($F_{net} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$) and the net torque should be about the z axis ($T_{net} = \begin{bmatrix} 0 \\ 0 \\ T_z \end{bmatrix}$). The swivel nozzle is rotated by a δ of 5 degrees and the angle of the side angles (β=-γ=h) is assumed to be same and the is found from calculations. Since the motion is from hover the α value will be 90 degrees.

Forces:

$$\cos A = [\frac{(\cot\alpha)^2 + (\tan\delta)^2}{1 + (\cot\alpha)^2 + (\tan\delta)^2}]^{1/2} = \frac{\tan 5}{(1 + \tan 5^2)^{1/2}} = 0.0872$$

$$\sin A = [\frac{1}{1 + (\cot\alpha)^2 + (\tan\delta)^2}]^{1/2} = \frac{1}{(1 + \tan 5^2)^{1/2}} = 0.9962$$

$$\cos B = [\frac{1}{1+(\cot\alpha)^2 * (\cot\delta)^2}]^{1/2} = 1$$

$$\sin B = \left[\frac{(\cot\alpha)^2 * (\cot\delta)^2}{1 + (\cot\alpha)^2 * (\cot\delta)^2}\right]^{\frac{1}{2}} = 0$$

$$F_b^{Sr} = \begin{bmatrix} 0 \\ -Fr\sin\beta \\ -Fr\ \cos\beta \end{bmatrix} = \begin{bmatrix} 0 \\ -F\sin h \\ -F\ \cos h \end{bmatrix}.$$

$$F_b^{Sl} = \begin{bmatrix} 0 \\ Fl\sin\gamma \\ -Fl\ \cos\gamma \end{bmatrix} = \begin{bmatrix} 0 \\ -F\sin h \\ -F\ \cos h \end{bmatrix}.$$

$$F_b^{B} = \begin{bmatrix} -Fb\cos A\sin B \\ Fb\cos A * \cos B \\ -Fb\sin A \end{bmatrix} = \begin{bmatrix} 0 \\ Fb\cos A \\ -Fb\sin A \end{bmatrix}.$$

$$F_g^{o} = \begin{bmatrix} 0 \\ 0 \\ gM_{total} \end{bmatrix}$$

To avoid y-direction motion:

$$2F\sin h = Fb\cos A$$

And to avoid z-direction motion:

$$2F\cos h + Fb\sin A = 40$$

Moments:

The torque from right side nozzle:

$$\tau_{Sr}^{b} = \begin{bmatrix} [-(y + \mathrm{z} * \sin\beta) \times Fr\ \cos\beta] + [Fr\sin\beta * z * \cos\beta \\ -(a-w) \times Fr\ \cos\beta \\ (a-w) \times Fr\sin\beta \end{bmatrix}$$

$$\tau_{Sr}^{b} = \begin{bmatrix} [-(y + \mathrm{z} * \sin h) \times F\ \cos h] + [F\sin h * z * \cos h \\ -(a-w) \times F\ \cos h \\ (a-w) \times F\sin h \end{bmatrix}$$

The torque from left side nozzle:

$$\tau_{Sl}^{b} = \begin{bmatrix} [(y + z * \sin\gamma) \times Fl\ \cos\gamma] - [Fl\sin\gamma * z * \cos\gamma] \\ -(a-w) \times Fl\ \cos\gamma \\ -(a-w) \times Fl\sin\gamma \end{bmatrix}$$

$$\tau_{Sl}^{b} = \begin{bmatrix} [(y - z * \sin h) \times F\ \cos h] + [F\sin h * z * \cos h] \\ -(a-w) \times F\ \cos h \\ (a-w) \times F\sin h \end{bmatrix}$$

Total torque from left and right together= $\begin{bmatrix} 0 \\ -2 * (a-w) \times F\ \cos h \\ 2 * (a-w) \times F\sin h \end{bmatrix}$.

The torque from back nozzle:

$$\tau_{B}^{b} = \begin{bmatrix} [-d \times Fb \times \cos A\cos B] + [e \times Fb\sin A] \\ [(c+b) \times Fb\ \sin A] - [d \times Fb\cos A\sin B] \\ [(c+b) \times Fb \times \cos A\cos B] - [e \times Fb\cos A\sin B] \end{bmatrix}$$

Sin B =0 and cos B =1;

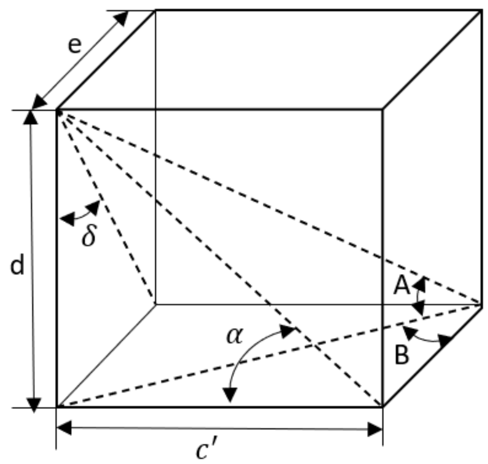
$$\tau_{B}^{b} = \begin{bmatrix} [-d \times Fb \times \cos A] + [e \times Fb\sin A] \\ [(c+b) \times Fb\ \sin A] \\ [(c+b) \times Fb \times \cos A] \end{bmatrix}$$

Rotation about X direction is avoided as:

Therefore $[-d \times Fb \times \cos A] + [e \times Fb\sin A]\ should\ be\ 0$

$$\frac{d}{e} = \tan A = 1/\tan 5$$

Which is automatically satisfied from the following figure



To avoid rotation about y direction:

$$[(c+b)\times(40-2F\cos h)] = 2*(a-w)\times F\ \cos h$$

$$40*(c+b) = [(a-w)+(c+b)]\times 2F\ \cos h$$

$$F\ \cos h = \frac{20*(c+b)}{(a-w)+(c+b)} = \frac{20*58}{78} = 14.87$$

Angular acceleration about z axis is:

$$\alpha_z = \frac{[(c+b)\times Fb\times\cos A] + 2*(a-w)\times F\sin h}{\mathrm{I}}$$

Solving the following equations: -

$$F\ \cos h = 14.87$$

$$2F\cos h + Fb\sin A = 40$$

$$2F\sin h = Fb\cos A$$

We get,

$$Fb\sin A = 40 - 2F\cos h = 40 - 2*14.87 = 10.26$$

$Fb = 10.299N$

Substituting value in the equation,

$$2F\sin h = Fb\cos A$$

$$2*\frac{14.87}{\cos h}*\sin h = 10.3*0.0872$$

$$\tan h = 0.030$$

h=1.73

$$F = \frac{14.87}{\cos h} = 14.88$$

Hence the force and the angle values are known, and the required speed of the motor can be set.

4.4 Side Translation

Now, consider a situation where side translation is tried to achieve from hover position. Here, the swivel nozzle and the side nozzles are rotated in the zy plane to get a thrust component in y axis direction. The net force should be in only y direction ($F_{net} = \begin{bmatrix} 0 \\ F_y \\ 0 \end{bmatrix}$) and the net torque should be zero ($T_{net} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$). The swivel nozzle is rotated by a δ of 5 degrees and the angle of the side angles (β=-γ=h) is assumed to be same and the is found from calculations. Since the motion is from hover the α value will be 90 degrees.

Forces:

$$\cos A = [\frac{(\cot\alpha)^2 + (\tan\delta)^2}{1 + (\cot\alpha)^2 + (\tan\delta)^2}]^{1/2} = \frac{\tan 5}{(1 + \tan 5^2)^{1/2}} = 0.0872$$

$$\sin A = [\frac{1}{1 + (\cot\alpha)^2 + (\tan\delta)^2}]^{1/2} = \frac{1}{(1 + \tan 5^2)^{1/2}} = 0.9962$$

$$\cos B = [\frac{1}{1+(\cot\alpha)^2 * (\cot\delta)^2}]^{1/2} = 1$$

$$\sin B = \left[\frac{(\cot\alpha)^2 * (\cot\delta)^2}{1 + (\cot\alpha)^2 * (\cot\delta)^2}\right]^{\frac{1}{2}} = 0$$

$$F_b^{Sr} = \begin{bmatrix} 0 \\ -Fr\sin\beta \\ -Fr\ \cos\beta \end{bmatrix} = \begin{bmatrix} 0 \\ -F\sin h \\ -F\ \cos h \end{bmatrix}.$$

$$F_b^{Sl} = \begin{bmatrix} 0 \\ Fl\sin\gamma \\ -Fl\ \cos\gamma \end{bmatrix} = \begin{bmatrix} 0 \\ -F\sin h \\ -F\ \cos h \end{bmatrix}.$$

$$F_b^{B} = \begin{bmatrix} -Fb\cos A\sin B \\ Fb\cos A * \cos B \\ -Fb\sin A \end{bmatrix} = \begin{bmatrix} 0 \\ Fb\cos A \\ -Fb\sin A \end{bmatrix}.$$

$$F_g^{o} = \begin{bmatrix} 0 \\ 0 \\ gM_{total} \end{bmatrix}$$

Acceleration in y-direction:

$$a = \frac{Fb\cos A - \ 2F\sin h}{I}$$

To avoid z-direction motion:

$$2F\cos h + Fb\sin A = 40$$

Moments:

The torque from right side nozzle:

$$\tau_{Sr}^{b} = \begin{bmatrix} [-(y + z * \sin\beta) \times Fr\ \cos\beta] + [Fr \sin\beta * z * \cos\beta \\ -(a-w) \times Fr\ \cos\beta \\ (a-w) \times Fr \sin\beta \end{bmatrix}$$

$$\tau_{Sr}^{b} = \begin{bmatrix} [-(y + z * \sin h) \times F\ \cos h] + [F \sin h * z * \cos h \\ -(a-w) \times F\ \cos h \\ (a-w) \times F \sin h \end{bmatrix}$$

The torque from left side nozzle:

$$\tau_{Sl}^{b} = \begin{bmatrix} [(y + z * \sin\gamma) \times Fl\ \cos\gamma] - [Fl \sin\gamma * z * \cos\gamma] \\ -(a-w) \times Fl\ \cos\gamma \\ -(a-w) \times Fl \sin\gamma \end{bmatrix}$$

$$\tau_{Sl}^{b} = \begin{bmatrix} [(y - z * \sin h) \times F\ \cos h] + [F \sin h * z * \cos h] \\ -(a-w) \times F\ \cos h \\ (a-w) \times F \sin h \end{bmatrix}$$

Total torque from left and right together= $\begin{bmatrix} 0 \\ -2 * (a-w) \times F\ \cos h \\ 2 * (a-w) \times F \sin h \end{bmatrix}$.

The torque from back nozzle:

$$\tau_{B}^{b} = \begin{bmatrix} [-d \times Fb \times \cos A \cos B] + [e \times Fb \sin A] \\ [(c+b) \times Fb\ \sin A] - [d \times Fb \cos A \sin B] \\ [(c+b) \times Fb \times \cos A \cos B] - [e \times Fb \cos A \sin B] \end{bmatrix}$$

Sin B =0 and cos B =1;

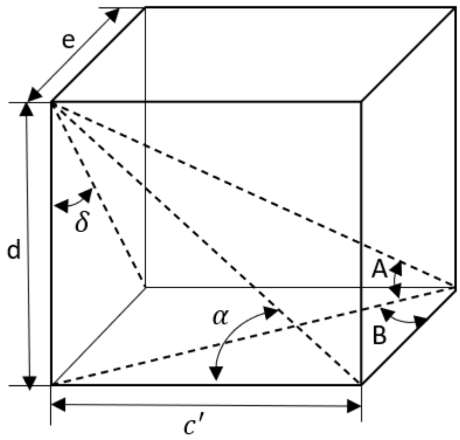
$$\tau_{B}^{b} = \begin{bmatrix} [-d \times Fb \times \cos A] + [e \times Fb \sin A] \\ [(c+b) \times Fb\ \sin A] \\ [(c+b) \times Fb \times \cos A] \end{bmatrix}$$

Rotation about X direction is avoided as:

Therefore $[-d \times Fb \times \cos A] + [e \times Fb \sin A]\ should\ be\ 0$

$$\frac{d}{e} = \tan A = 1/\tan 5$$

Which is automatically satisfied from the following figure



To avoid rotation about y direction:

$$[(c+b)\times(40-2F\cos h)] = 2*(a-w)\times F\ \cos h$$

$$40*(c+b) = [(a-w)+(c+b)]\times 2F\ \cos h$$

$$F\ \cos h = \frac{20*(c+b)}{(a-w)+(c+b)} = \frac{20*58}{78} = 14.87$$

To avoid rotation about z direction:

$$-[(c+b)\times Fb\times\cos A] = 2*(a-w)\times F\sin h$$

Solving equations:

$$F\ \cos h = 14.87$$
$$2F\cos h + Fb\sin A = 40$$
$$-[(c+b)\times Fb\times\cos A] = 2*(a-w)\times F\sin h$$

We get,

$$Fb\sin A = 10.26$$

$Fb = 10.299N$

$$F\sin h = \frac{-[(c+b)\times Fb\times\cos A]}{2*(a-w)}$$
$$\tan h = \frac{-[(c+b)\times Fb\times\cos A]}{2*(a-w)*14.87} = -\frac{58*10.299*0.0872}{2*20*14.87} = -0.876$$

$h = 5.005\ degrees$

$$F\ \cos h = \frac{14.87}{\cos h} = \frac{14.87}{\cos 5.005}.$$

$F = 14.927\ N$

Hence the force and the angle values are known, and the required speed of the motor can be set.

Chapter 5

Experiment

A BLDC motor is used to run the compressor of the UAV. Using the motor at higher speeds and for longer durations the flight time of the UAV decreases drastically. It also causes high heating and can result to melting of components gradually damaging the motor. The BLDC motor can go as high as 30,000 rpm, but because of the above-mentioned issues the maximum speed of the motor is set as 20,000 rpm. A thrust of 130N is to be produced at the maximum speed of compressor i.e., 20,000rpm. This condition is checked for the propellers ranging from 6in to 12in and the appropriate propeller is chosen. The following table gives the thrust values for different propellers for a motor speed of 20,000rpm.

Propeller model and size	Thrust at 20,000 rpm
6*4.5	4.17 N
7*9	15.03 N
8*4.5	30.58 N
9*4.7	131.64 N
10*4.5	157.78 N
11*9	1527.29 N
12*9	3142.86 N
12*4.5	1080.56 N

Table 2: Thrust for different propeller sizes

From the above table it can be observed that a thrust of 130N can be generated by 9in propeller. 10in propeller can produce even more thrust but to reduce the size of the UAV 9in propeller is chosen.

Till now theoretical analysis was done to find the thrust of the compressor and nozzle assembly. Now, an experiment is done to find out and verify the theoretical thrust. For which the setup is made as shown in the figure. CAD models were prepared in Fusion 360 and the parts were 3D printed. The nozzle diameter is 5cm and the length of the assembly is about 30cm. The assembly of the compressor and nozzle was made by joining the prints using the glue gun. The motor mount was also 3D printed. This assembly is attached to the U- shaped wooden planks which in turn is attached to the wooden base via a slider.

Figure 13: The experimental setup

EMAX Black RS2306 2400KV BLDC motor is used for the experiment because of its high KV value. A 4A ESC is used and a LIPO battery of 5200mAh is used. A potentiometer is used to control the speed of the UAV. Arduino was used to write the code and control the ESC of the motor. A weight balance is attached at the back of the wooden plank to measure the thrust of the assembly. The experimental setup is as shown in the figure.

Chapter 6

Results and Conclusion

The values of the thrust produced when a single propeller is used are represented in the following table.

Potentiometer (Throttle) (%)	Thrust (grams)
10	40
15	80
20	120
25	160
30	200
35	240
40	280
50	360
60	400
70	440

Table 3: Experimental thrust values for different throttle percentages.

The results were not as expected and are similar even when two propellers were used. The analysis is that there is huge back pressure because of the short compressor and nozzle assembly. The air sucked in the system is coming out through the propeller. The gap between the propeller and the duct is reduced and the experiment was performed again. Even now the air coming upstream because of high back pressure. Two propellers were used instead of one and the problem of back pressure persists.

An experiment with a longer nozzle is proposed but because of lack of resources the experiment was not conducted. Using a different propeller may solve the issue. Another problem found was there was melting observed at the motor mount because of high temperatures of motor. For next time, it is advised to use a metallic mount instead 3D printing.

Chapter 7

Future Scope

Currently, compressor and nozzle system are designed to generate the thrust. As a continuation to the experiment the length of the nozzles can be increased, and the propeller can be changed to decrease the back pressure. The mounts can be modified and can be made using steel. The whole UAV can be fabricated which includes the swivel nozzle, side nozzles, and the chassis. The swivel nozzle can be experimented, and a deep understanding of the swivel nozzle can be made. The control system of the UAV can be designed and implemented with the hardware. Different motion plans can be designed and implemented. The testing of the UAV will be exciting.

Now, compressor, combustion chamber, and nozzle system can be studied and designed. Fuel selection and rate of fuel consumption can be studied. The bodies should be designed in a metallic form which would be challenging. Noise reduction can be studied, and different nozzles can be designed. Integrating everything and designing the control system can be quite difficult but exciting.

References

[1] Wang, Xiangyang et al. “Coordination control strategy based on characteristic model for 3-bearing swivel duct nozzles.” *Science China Technological Sciences* 57 (2014): 2347-2356.