

# A PROJECT REPORT ON VTOL

Team Aero : Drishti

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**DRISHTI**

*A Revolutionary Concept*

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We are grateful towards team Drishti and fortunate enough to get constant encouragement, support and guidance from all the peers and colleagues who helped us to work on our project.

**Team Aero**

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## Abstract

The idea of this project is to design and construct a VTOL Vehicle that is able to fly without any runway or using a minimum runway. Initially, we started the research on the types of VTOL and decided the most feasible one to construct and its material. Then we moved to calculations and finally, made the design and analysed it. Also, we have designed the flight controller for QuadCopter and then VTOL. Designing control system includes analyzing mechanics of Quadcopter and studying its differential equations which satisfactorily describe physical laws acting on it i.e. mathematical model. Mathematical model predicts the behaviour of the Quadcopter. The designed Control system is tested and analysed in a 3D simulated environment. After getting successfully tested and functioning control system, we are going to design a flight controller for various designs of VTOL systems. Also, our aim is to do its hardware implementation.

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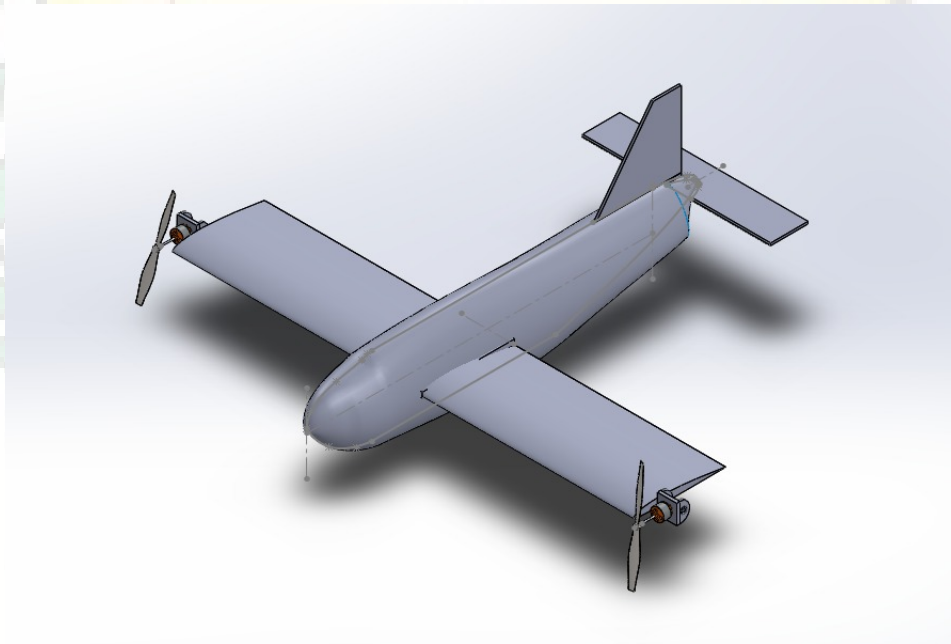
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# 1 Introduction

A vertical take-off and landing (VTOL) aircraft is one that can hover, take off, and land vertically. To control VTOL in dynamic environment effectively Control System is needed. So, **Aim** of this project was to design and construct a VTOL Vehicle that able to fly without runway or using a minimum runway. Also, to design a Control System for QuadCopter and then for VTOL. Designing Flight Controller includes analyzing mechanics of Quadcopter and studying its differential equations which satisfactorily describe physical laws acting on it also known as mathematical model. Mathematical model predicts the behaviour of the Quadcopter.



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## 2 Quadcopter Physics

The Rotors act as wings. They generate thrust by rotating at Fast speeds, which pulls the air downwards and keeps the quad in the air.

- The Thrust cancels out the acting weight and the quad hovers.
- A directional Thrust causes the quad to move in that direction.
- Or a decrease in Thrust overall causes the Drone to lose height.

### Setup:

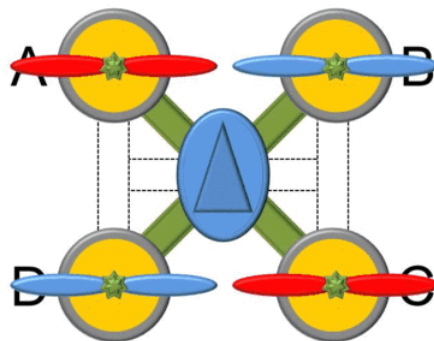
The setups for Flying is simple:

- Two adjacent motors spin in the opposite direction.
- Two opposite motors spin in the same direction.

A,C spin Clockwise (From our point of view)

B,D Spin Counter-Clockwise

because, Physics says to be in stability the net forces acting on a body should be zero. So if all the rotors were to spin in the same direction, it would result in a net Torque causing the complete Quad to rotate.

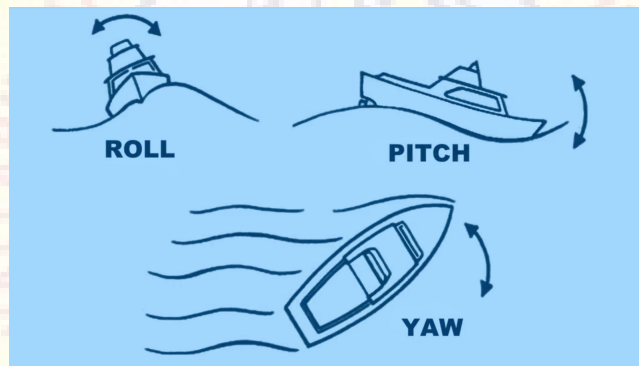


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## 2.1 Attitude:

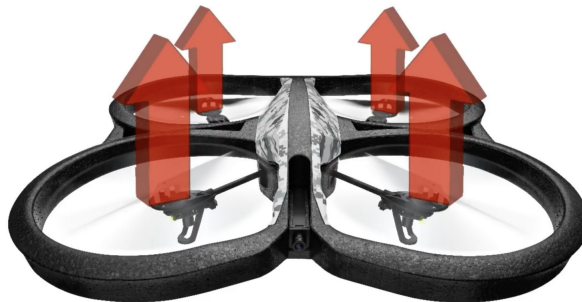
We will use these terms to define the motions of our drone.

- Roll: Moving to left or Right with respect to the Front.
- Pitch: Moving Forward or Backwards.
- Yaw: Rotation about the centre.



### Taking-off

- To Rise above the ground, we need a net upward Force.
- The Motors generate Thrust that is greater than the Weight, making the quad rise upwards.





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## Hover

Hovering in Air is simple.

- Motors generate Thrust.
- The Thrust should equal the weight of the System.
- The two forces cancel and our drone Hovers.



## Roll

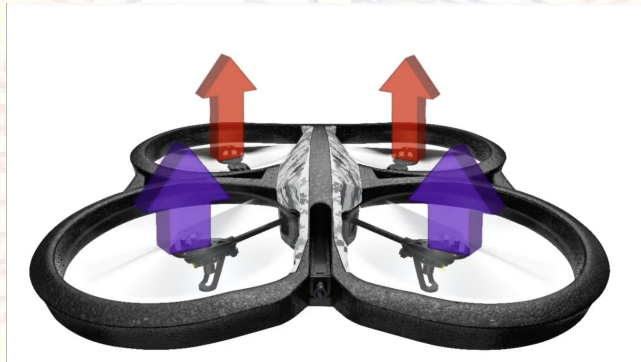
- To Roll towards the Left (Our Left), the Thrust is increased on the Motors on the Right, We also decrease the Thrust on the motors on the Left, To keep the Net Torque zero and allowing an Leftward Net Force.



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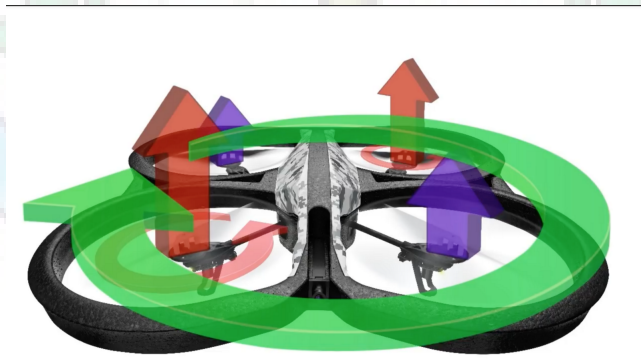
## Pitch

- To Pitch Forwards (Towards us) the Power to the motors rear motors is increased. This creates a net forward force which causes the Drone's nose to Pitch Downward.
- We also decrease the power to the two front motors to keep the angular momentum conserved.



## Yaw

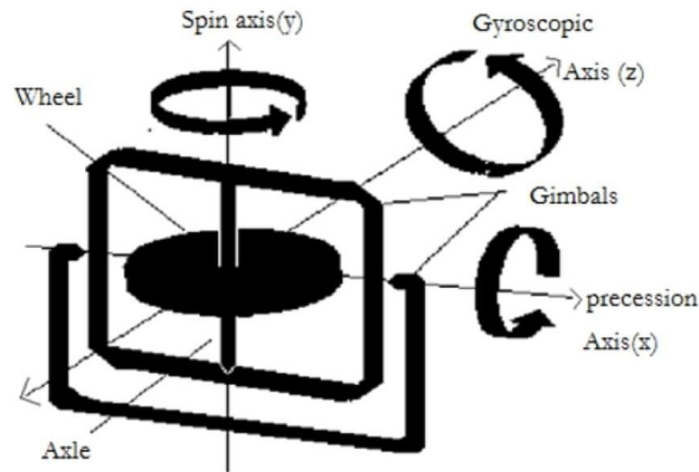
- To Yaw Clockwise we increase the Thrust on the Anti-Clockwise moving Motors decrease the Thrust on Clockwise Rotating Motors.



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## 2.2 Gyroscopic Couple

The turning moment which opposes any change of the inclination of the axis of rotation of a gyroscope. When a single-engined aeroplane turns to the left, the nose tends to dip; when the turn is to the right, the gyroscopic effect tends to raise the nose. Jet propulsion will lead to the removal of the gyroscopic action of the propellers



## 2.3 Cross Wind landing/takeoff

When there is a crosswind, there is an underserved moment acting upon aircraft, in order to control this, we trim that movement by the rudder. The rudder should be very influential to allow the pilot to trim for the particular crosswinds. For instance, the rudder needs to provide a sideslip angle to keep alliance with the centre line of the landing strip. The sideslip angle ( $\beta$ ) is denoted as the angle between the direction of the relative wind ( $vw$ ) and the aircraft path  $vf$ .

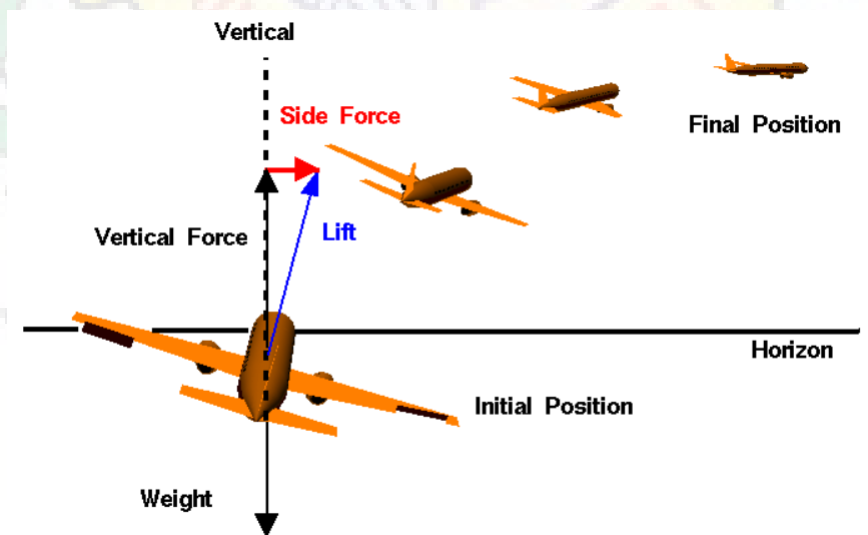
$$\beta = \tan^{-1}(vw/vf)$$

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Hence, the total aircraft speed ( $vt$ ) is equal to the vector summation of the path speed ( $vf$ ) and the crosswind speed ( $vw$ )

## 2.4 Banking turn and angle

A fundamental aircraft motion is a **banking turn**. This maneuver is used to change the aircraft heading. The turn is initiated by using the ailerons or spoilers to roll, or bank, the aircraft to one side. On the figure, the airliner is banked to the right by lowering the left aileron and raising the right aileron. The lift of the wings of the aircraft is a vector quantity which is always directed perpendicular to the flight path and perpendicular to the wings generating the lift. As the aircraft is rolled, the lift vector is tilted in the direction of the roll. We can break the lift vector into two components. One component is vertical and opposed to the weight which is always directed towards the center of the earth. The other component is an unopposed side force which is in the direction of the roll, and perpendicular to the flight path.



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As long as the aircraft is banked, the side force is a constant, unopposed force on the aircraft. The resulting motion of the center of gravity of the aircraft is a circular arc. When the wings are brought level by an opposing motion of the ailerons, the side force is eliminated and the aircraft continues to fly in a straight line along a new heading. Notice that the rudder is not used to turn the aircraft. The aircraft is turned through the action of the side component of the lift force. We can turn using a rudder also. But same as the steering effect, adverse Yaw makes the tip of nose along the flight path.

**Bank Angle:** It is the angle made by wings of aircraft with the horizontal.

**Slide slip angle of aircraft:** It is the angle between the relative wind velocity and the projection of the airplane's longitudinal axis. Due to this slide slip angle there will be respective movement on aircraft, these slip slip is helpful at landing.

Generally slide slip angle will be less than 20 degrees. This slide slip can be controlled by tilting the aircraft in the direction of wind.

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## 3 Selection Process of VTOL Aircraft

### 3.1 Different Types of VTOL :

1. Tilt wing
2. Tilt rotor
3. Vector thrust
4. Tail sitter
5. Tilt fuselage
6. Ducted fan
7. Separate engine
8. Tilt jet ( similar to tilt rotor , only propellers are replaced by turbojets.)



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## 3.2 Process of selection :

Out of all the VTOLs listed, we have discluded everything which includes combustion, jet engines , etc because they are complex to design and manufacture and also they require fuel to operate.

**And finally, we are with 4 VTOLs which seems feasible**

### 3.2.1 Tiltrotor Aircraft

#### Pros:

- Less weight compared to general “Quadcopters”
- Less power Requirement
- So high air time
- Have the advantages of both the aeroplane and a quadcopter.

#### Cons:

- Moment on the aircraft during transition.
- High speeds aren't possible because it decreases the thrust force.



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### 3.2.2 Tilt wing aircraft

#### Pros:

- At the time of hovering the drag will decrease because the exposed area of wing will decrease.
- We can control direction of thrust.

#### Cons:

- Its control is difficult because the direction of wing is changing and angle of attack also .
- It decreases wing root strength.
- Requires more moment for transition.
- Less stable during hovering due to environmental conditions.



### 3.2.3 Separate engine aircraft:

#### Pros:

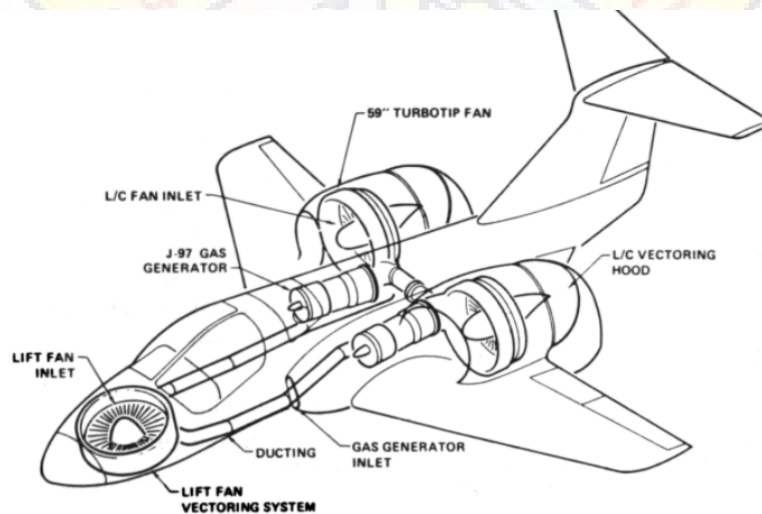
- Easy to control.
- Excludes rotor rotation



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**Cons:**

- We cannot control the direction of thrust in flight.
- It create difficulty in takeoff and landing.
- Wind breezes can affect the direction therefore stability of vtol during hovering.



**3.2.4 Ducted fan aircraft:**

**Pros:**

- More efficient than conventional propellers at low speed and high static thrust level.
- For same static thrust , it has smaller diameter than a free propeller.
- Ducted fans are quieter than propellers.

**Cons:**

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- Less efficient than a propeller at cruise.
  - Requires high RPM and minimal vibrations.
  - Complex duct design.



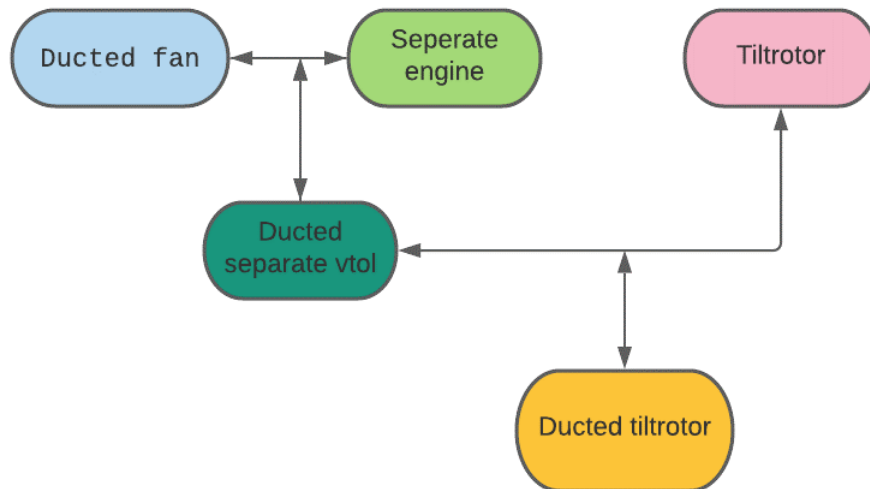
**Final selection:**

- From this list, we exclude the tilt-wing aircraft because of its complexity involved in it and it is unstable at hovering but it provides lesser drag when gaining altitude when compared to the tiltrotor.
- And next, we have fused the ducted fan engine and the separate engine as a “Ducted separate engine” aircraft.
- So that we can have all the advantages of ducted fan and separate engine aircraft.
- But this aircraft is too unstable at hovering conditions like if any strong breeze is present it affects the path of aircraft.
- And finally, we looked at tiltrotor aircraft which have very good pros and high stability and high manoeuvrability.



Artist's Concept

- And we finally fused the ducted fan aircraft and tiltrotor aircraft so that we get more thrust due to Ducted fans and we can have the stability of the tiltrotor and also its maneuverability.
- These aircraft can change the direction of thrust which is beneficial and it seems a perfect balance of everything.



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## 4 Calculation

$$F = \rho AV^2$$

$V_{exist} = V_e \rightarrow$  pitch velocity

$$V_e = (\varpi * \text{pitch})$$

$$\text{Thrust}(F) = 1.225 * \pi * (0.0254 * d/2)^2 * (RPM * 0.0254 * \text{Pitch}/60)$$

d  $\rightarrow$  diameter of propeller

Pitch and diameter are rated for propeller and the general calculation is done for (10\*4.5) propeller at 80% throttle.

Final static thrust after making corrections

$$\text{Thrust}(F) = 1.225 * \pi * (0.0254 * d/2)^2 * (RPM * 0.0254 * \text{Pitch}/60) * (d / (3.29546 * \text{Pitch}))^{1.5}$$

Voltage=11 V, RPM=19360, d=10 inch, pitch=4.5 inch

$$\text{Thrust}(F) = 1.225 * \pi * (0.0254 * 10/2)^2 * (19360 * 0.0254 * 4.5/60) * (10 / (3.29546 * 4.5))^{1.5}$$

$$F = 43.3N$$

Total = 86.6N  $\rightarrow$  This is the maximum static thrust that can be induced from the propeller

**Design Parameter:**

$$\text{Aspectratio} = b^2/A = b^2/b * c = b/c \Rightarrow (\text{for rectangular wing})$$

$$\text{Wingload} = m/b * c$$

$$b = (A.R) * c \text{ and } c = m / (b * WL)$$

$$b = A.R * m / (b * WL)$$

$$b = (m * A.R / WL)$$

---

$A.R = 5 - 9$  and  $W.L = 5 - 10kg/m^2$  General for RC plane

$b$  is  $100cm$ .

So,  $A.R = 5$ ,  $b = 1m$ ,  $s = 0.2m^2$ ,  $c = 0.2m$

Length of fuselage = 75% of  $b = 0.75 * 100 = 75cm$

Height of fuselage =  $17cm$

$$S_h = S/4 = 0.05m^2$$

$$S_v = 40\% \text{ of } S_h = 0.02m^2$$

$$S.M = x_{np}/c - x_{cg}/c$$

$$S.M = 0.05-0.18 \text{ (range)}$$

$L_h$  = horizontal tail moment arm

“for an aircraft with propellers on the wings the tail arm is about 50-55% of length of fuselage”

Assume it is 52%

$$l_h = 52 * 75/100 \text{ So, } l_h = 0.39m$$

$$V_h = S_h l_h / S * C \text{ and } V_h = 0.3-0.6 \text{ (range)}$$

$$V_h = 0.05 * 0.39 / (0.04)$$

$$V_h = 0.48 \text{ So, “ } V_h \text{ is in the range”}$$

$AR_h$  = horizontal tail aspect ratio

$$AR_h = b_h / c_h$$

“Assume  $AR_h = AR_w$ ”

$$AR_h = 2 * 5/3 = 3.33$$

$$S.M = x_{np}/c - x_{cg}/c$$

---

$$X_{np} = 1/4 + ((1 + (2/A.R_w))/1 + (2/A.R_h)) * (1 - (4/(A.R + 2))) * V_h$$

$$X_{np} = 0.25 + ((1 + 2/5)/(1 + 2/3.35)) * (1 - 4/7) * 0.48$$

$$X_{np} = 0.25 + 0.87 * 0.428 * 0.48$$

$$X_{np}/c = 0.428$$

$$X_{cg} = 0.3c$$

$$X_{cg}/c = 0.25$$

$$S.M = 0.428 - 0.25$$

$$\text{So, } S.M = 0.178 \text{ or } 0.3 * C$$



---

## 5 Material Selection

### Properties of different materials:

#### 1. Styrofoam:

- It's lightweight.
- It's cost effective.
- It's easily available.
- It's strength is not good.

#### 2. Thermocoal:

- It's lightweight.
- It's cost effective.
- It's brittle and we can easily cut.
- It's strength is not good.

#### 3. Depron:

- It contains high stiffness.
- It's price is high.
- More weight.
- It has good strength.

#### 4. Chloroplast:

- Very flexible in one direction.
- Stiff in one direction.
- Easily available.
- It's lightweight.

- 
- It contains less stiffness.

5. Balsa wood:

- It's lightweight.
- It's costly.
- It's stiff along the fibres.
- It's manufacturing is hard.
- It's cost is high.

6. PLA:

- It contains high strength.
- It's shaping capabilities are very good.
- It's stiff along columnar grains.

7. Carbon Fibre:

- It contains a high strength to weight ratio.
- It's very costly.
- It's heavier than balsa wood.
- 3-D printing is possible.

**Required properties of material for different parts of VTOL:**

1. Fuselage:

- It should be lightweight.
- Surface should be smooth.
- Strength should be high.
- Easily manufacturable .



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Depron and Styrofoam satisfy all above properties.

2. Wings:

- It should be lightweight.
- Strength should be high.
- Surface should be smooth.
- It should be rigid.
- should be manufacturable and aerodynamic

Depron and Balsa satisfy all above properties.

3. Tail:

- It should be lightweight.
- It should be rigid.

Depron and Balsa satisfy all above properties.

4. Rod:

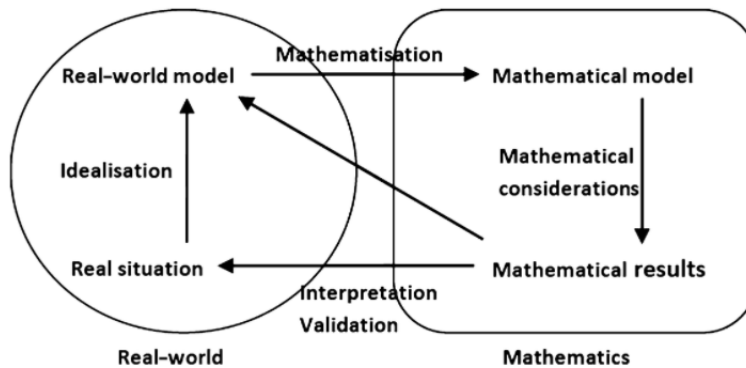
- It should be light weight.
- Toughness should be high.

Hollow aluminium is good for this work.

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## 6 Mathematical Model of UAV

It is a simplified mathematical representation of the complex real world systems using mathematical equations. It helps us to estimate the quantitative behaviour of the system.



In our project, we are using the mathematical model to understand the dynamics of VTOL completely and to tune the control system parameters automatically.

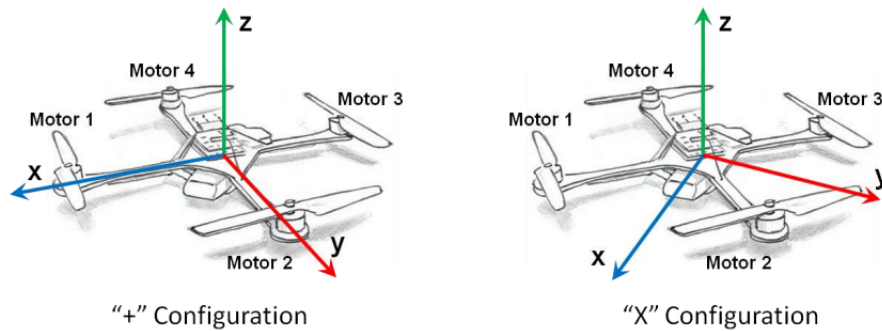
### 6.1 Assumptions

- The quadcopter is a rigid body.
- Quadcopter is symmetrical.
- Center of mass coincides with the geometric centre.
- Inertia of the motor is considered to be neglected.
- Earth is assumed to be flat

---

## 6.2 Coordinate System

Another important aspect of the math model is the coordinate system that is used. The coordinate system depends on whether we use a plus (+) or X configuration.



In this project we have used X configuration because

- In "+" configuration, the thrust forces are applied at a distance  $r$  in an X configuration, thrust forces are applied at distance of  $r \cdot \cos(45^\circ)$  i.e approximately  $0.71 \cdot r$  since the arms are at a 45 degree angle from the axis of rotation.
- The moment of inertia is the same.
- Difference is in torque with all four motors, and therefore have 1.414 more available torque to rotate. This means we get about 41% more rotational acceleration from an X than a "+".

## 6.3 Mass Moment of Inertia Matrix

Moment of Inertia matrix w.r.t body is denoted by  $J_b$ . Moment of Inertia w.r.t x is denoted by  $J_{xx}$ . Moment of Inertia w.r.t y is denoted by  $J_{yy}$ . Moment of Inertia w.r.t z is denoted by  $J_{zz}$ .

---

$$J^b = \begin{bmatrix} J_{xx} & 0 & 0 \\ 0 & J_{yy} & 0 \\ 0 & 0 & J_{zz} \end{bmatrix}$$

## 6.4 Thrust Coefficient( $C_T$ ) and Torque Coefficient( $C_Q$ )

### 6.4.1 Thrust Coefficient

The motors' thrust is the driving force behind all quadcopter maneuvers and thus is integral to control design and simulation. The thrust, provided by a single motor/prop system can be calculated as follows:

$$T = C_T \rho A_r r^2 \varpi^2$$

Where  $C_T$  is the thrust coefficient for a specific rotor

$\rho$  is the density of air

$A_r$  is the cross sectional area of the propeller's rotation

$r$  is the radius of the rotor

and  $\varpi$  is the angular velocity of the rotor.

For simple flight modeling a lumped parameter approach can be used to simplify the characterization process:

$$T = C_T \varpi^2$$

Here is the lumped parameter thrust coefficient that pertains to the individual motor/prop system.

### 6.4.2 Torque Coefficient

In order to understand motor effect on yaw, the torque force of the motor/prop system must also be determined, and can be done in a similar fashion to that of the thrust tests. The related lumped parameter equation

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is shown below:

$$Q = C_Q \varpi^2$$

In this case,  $Q$  is the torque created by the motor and  $C_Q$  is the torque coefficient for the motor/prop system. This torque provides a force that acts to yaw the system about the zaxis.  $C_T$  and  $C_Q$  values are calculated experimentally;

## 6.5 Thrust-Torque Matrix

After performing a range of tests, we can calculate these coefficients for characterizing our system. With this information we can create a matrix describing the thrusts and torques on the system like that shown below:

$$\begin{bmatrix} \sum T \\ \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} C_T & C_T & C_T & C_T \\ -dC_T & dC_T & dC_T & -dC_T \\ -dC_T & -dC_T & dC_T & dC_T \\ -C_Q & C_Q & -C_Q & C_Q \end{bmatrix} \begin{bmatrix} \varpi_1^2 \\ \varpi_2^2 \\ \varpi_3^2 \\ \varpi_4^2 \end{bmatrix}$$

Gyroscopic forces is neglected for simplicity.

## 6.6 State Equations

This equation describes the change in roll (P), pitch (Q), and yaw (R) rates of the quadcopter by taking into account the inertia, angular velocity, and the moments applied by the motor/prop systems.

### 6.6.1 Angular Velocity State Equation

$${}^b\dot{\omega}_{b|i} = (J^b)^{-1} [M_{A,T}^b - \Omega_{b|i}^b J^b \omega_{b|i}^b] = \begin{bmatrix} \dot{P} \\ \dot{Q} \\ \dot{R} \end{bmatrix}$$

---

${}^b\dot{\omega}_{b|i}$  is the angular acceleration across each axis in the body frame with respect to the inertial frame.

$$\Omega_{b|i}^b = \begin{bmatrix} 0 & -R & Q \\ R & 0 & -P \\ -Q & P & 0 \end{bmatrix}$$

$$\omega_{b|i}^b = \begin{bmatrix} P \\ Q \\ R \end{bmatrix}$$

Where, P is angular rate w.r.t x in body frame

Q is angular rate w.r.t y in body frame

R is angular rate w.r.t z in body frame

${}^b\dot{\omega}_{b|i}$  is the angular acceleration across each axis in the body frame with respect to the inertial frame

$\Omega_{b|i}^b$  is the cross-product matrix for rotational velocity

$\omega_{b|i}^b$  is the rotational velocity of the quadcopter body within the body frame

## 6.7 Euler Kinematic Equation

Used to determine the rate of change of the Euler angles in the inertial frame. According to the aerospace rotation sequence, the rotation of an aircraft is described as a rotation about the z-axis (yaw) then a rotation about the y-axis (pitch) followed by a rotation about the x-axis (roll). Each rotation is made based on a right-handed system and in a single plane. Using these three rotations a composite rotation matrix can be created which can transform the motion of the aircraft from the body frame to a new reference frame. The resulting rotation matrix transforms rotations from the body frame with respect to the inertial frame and can be found using matrix multiplication.

---


$$C_{b|i} = \begin{bmatrix} c(\theta)c(\phi) & c(\theta)s(\phi) & -s(\theta) \\ -c(\phi)s(\psi) + s(\phi)s(\theta)c(\psi) & c(\phi)c(\psi) + s(\phi)s(\theta)s(\psi) & s(\theta)c(\theta) \\ s(\phi)s(\psi) + c(\phi)s(\theta)c(\psi) & -s(\phi)c(\psi) + c(\phi)s(\theta)s(\psi) & c(\phi)c(\theta) \end{bmatrix}$$

$$C_{i|b} = (C_{b|i})^{-1}$$

$$\dot{\Phi} = \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = C_{i|b} \begin{bmatrix} P \\ Q \\ R \end{bmatrix} = H(\Phi)\omega_{b|i}^b$$

(Euler Kinematic Equation)

### 6.7.1 Velocity State Equation

$${}^b\dot{v}_{CM|i}^b = (1/m)F_{A,T}^b + g^b - \Omega_{b|i}^b\omega_{CM|i}^b = \begin{bmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \end{bmatrix}$$

$$g^b = C_{i|b}g^i$$

$$g^i = 9.8m/s$$

${}^b\dot{v}_{CM|i}^b$  is the linear acceleration of the center of mass in the body frame with respect to the inertial frame.

m is the mass of system

### 6.7.2 Position State Equation

$${}^b\dot{P}_{CM|i}^b = C_{i|b}v_{CM|i}^b = \begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix}$$

${}^b\dot{P}_{CM|i}^b$  is simply the velocity of the quadcopter in the body frame that is rotated into the inertial frame. This state equation allows us to determine the velocity of the quadcopter in the X, Y, and Z directions of the inertial frame.

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## 7 Control System

A control system manages, commands or regulates the behavior of other devices or systems to achieve a desired result. A control system achieves this through control loops, which are a process designed to maintain a process variable at a desired set point.

**The main feature of a control system is that there should be a clear mathematical relationship between the input and output of the system.**

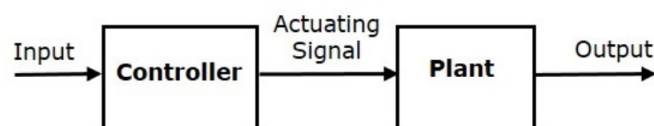
When the relation between input and output of the system can be represented by a linear proportionality, the system is called a linear control system.

And when the relationship between input and output cannot be represented by single linear proportionality, rather the input and output are related by some non-linear relation, the system is referred to as a non-linear control system.

### 7.1 Classification of Control System

#### Open Loop Control System

In open loop control systems, output is not fed-back to the input. So, the control action is independent of the desired output. Open loop systems are easy to design and stable but it can't be used at a place where the accuracy of the output is of high importance. This is because it doesn't count on disturbance.



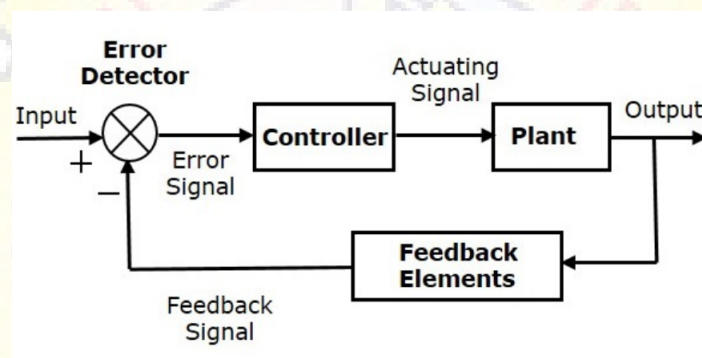


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## Closed Loop Control System

In closed loop control systems, output is fed back to the input. So, the control action is dependent on the desired output. Open loop system can be converted into a closed loop system by adding a feedback element.

Instead of the direct input, the error signal is applied as an input to a controller which is the difference between the input and the feedback signal.



## 7.2 Feedback System

Feedback is the backbone of all control systems. In any control system, the output is affected due to a change in environmental conditions or any kind of disturbance. So one signal is taken from the output and is fed back to the input.

This signal is compared with a reference input and the error signal is generated. This error signal is applied to the controller and the output is corrected. Such a system is called a feedback system.

### Classification of Feedback System

When the feedback signal is positive then the system is called a positive feedback system. For a positive feedback system, the error signal is the addition of a reference input signal and a feedback signal.

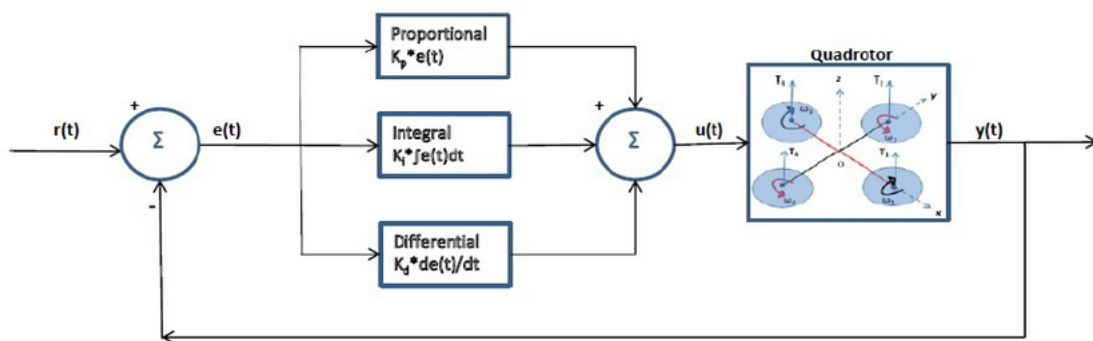
When the feedback signal is negative then the system is called a negative feedback system. For the negative feedback system, the error signal is given

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by the difference between the reference input signal and the feedback signal.

### 7.3 PID Control for UAV

A proportional-integral-derivative controller (PID controller) is a control loop feedback mechanism (controller) widely used in control systems. A PID controller calculates an error value ( $e$ ) as the difference between a measured process variable ( $y$ ) and a desired setpoint ( $r$ ). The controller attempts to minimize the error by adjusting the process through use of a manipulated variable. The output of PID is the control unit ( $u$ ) to the plant.

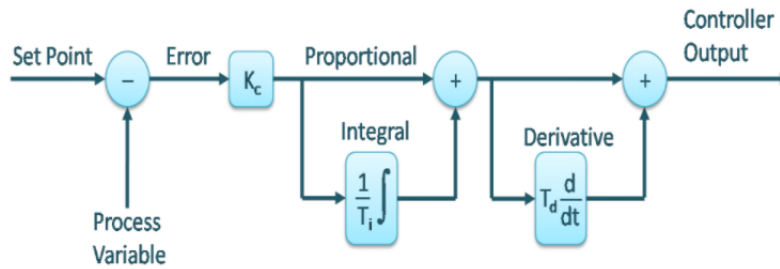


#### 7.3.1 Algorithm

The PID controller algorithm involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted P, I, and D. Simply put, these values can be interpreted in terms of time: P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change.

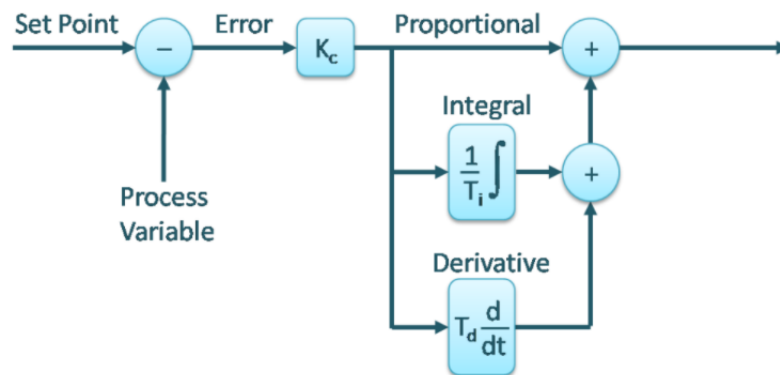
#### Interactive Algorithm

$$u(t) = K_c \left[ e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau \right] \times \left[ 1 + T_d \frac{d}{dt} e(t) \right]$$



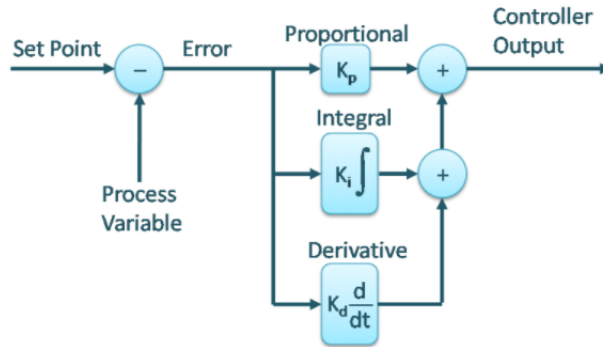
### Non-Interactive Algorithm

$$u(t) = K_c \left[ e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{d}{dt} e(t) \right]$$



### Parallel Algorithm

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t)$$



### 7.3.2 Proportional Term

The proportional term produces an output value that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant  $K_p$ , called the proportional gain constant. The proportional term is given by:  $P_{out} = K_p e(t)$

### 7.3.3 Integral Term

The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. The integral in a PID controller is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously. The accumulated error is then multiplied by the integral gain  $K_i$  and added to the controller output.

### 7.3.4 Derivative Term

The derivative of the process error is calculated by determining the slope of the error over time and multiplying this rate of change by the derivative gain

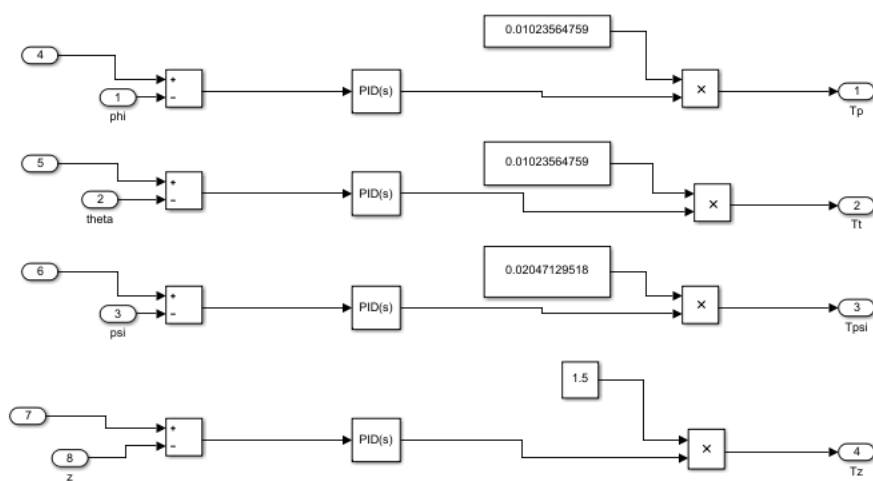
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Kd. The magnitude of the contribution of the derivative term to the overall control action is termed the derivative gain, Kd.

### 7.3.5 Tuning Methods

There are several methods for tuning a PID loop. The most effective methods generally involve the development of some form of process model, then choosing P, I, and D based on the dynamic model parameters. Manual tuning methods can be relatively inefficient, particularly if the loops have response times on the order of minutes or longer.

We have used Software Method(PID Tuning Toolbox in MATLAB) which is an efficient and consistent method and helps in automatically tuning PID control gains to achieve the optimal system design.



An automated PID tuning workflow involves:

- Identifying plant model from input-output test data
- Modeling PID controllers in MATLAB using PID objects or in Simulink using PID Controller blocks

- Automatically tuning PID controller gains and fine-tune your design interactively
- Tuning multiple controllers in batch mode
- Tuning single-input single-output PID controllers as well as multiloop PID controller architectures

### 7.3.6 Overview

CL Response	Rise Time	Overshoot	Settling time	SS Error
Kp	Decrease	Increase	Small Change	Decrease
Ki	Decrease	Increase	Increase	Decrease
Kd	Small Change	Increase	Decrease	No Change

## 7.4 Motor Mixing Algorithm

The motor mixer is the algorithm that transforms the result of the attitude controller into PWM signal for the motors and it does so by redistributing the signal into each motor.

For Example :

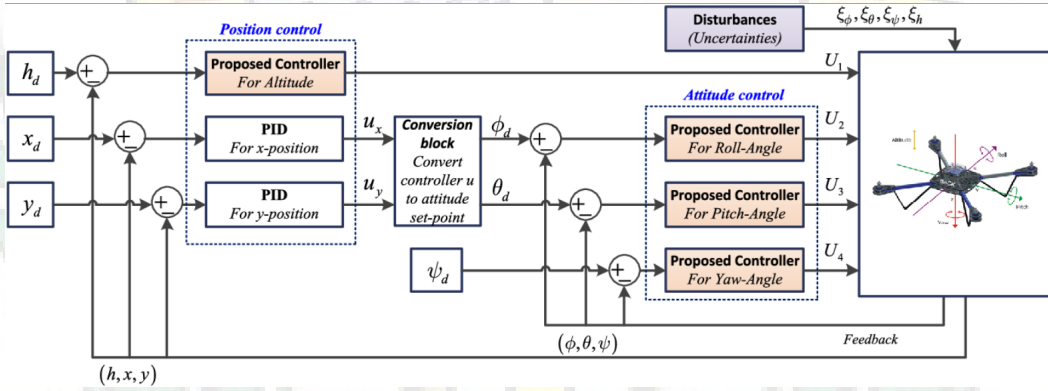
If rolling is required, the signal produce by the PID of the roll rate, shall be distribute so that the motors on the same side should receive the same PWM but this shall be different from the one received by the motors on the other side.

```
function [w12,w22,w32,w42] = fcn(T,t1,t2,t3)
d=0.176777;ct=8.586e-08;cq=4.81e-09;
A=[ct ct ct ct;
  -(d*ct) (d*ct) (d*ct) -(d*ct);
  -d*ct -d*ct d*ct d*ct;
  -cq cq -cq cq];
disp(A);
disp(inv(A));
B=[T t1*1.414 t2*1.414 t3]';
C=inv(A)*B;
disp(C);
w12=C(1,1);
w22=C(2,1);w32=C(3,1);w42=C(4,1);
if(w12<0)
    w12=0;
end
if(w22<0)
    w22=0;
end
if(w32<0)
    w32=0;
end
if(w42<0)
    w42=0;
end
```

**Motor Mixing Algorithm**

$$\begin{aligned} \text{Motor}_{\text{front right}} &= \text{Thrust}_{\text{cmd}} + \text{Yaw}_{\text{cmd}} + \text{Pitch}_{\text{cmd}} + \text{Roll}_{\text{cmd}} \\ \text{Motor}_{\text{front left}} &= \text{Thrust}_{\text{cmd}} - \text{Yaw}_{\text{cmd}} + \text{Pitch}_{\text{cmd}} - \text{Roll}_{\text{cmd}} \\ \text{Motor}_{\text{back right}} &= \text{Thrust}_{\text{cmd}} - \text{Yaw}_{\text{cmd}} - \text{Pitch}_{\text{cmd}} + \text{Roll}_{\text{cmd}} \\ \text{Motor}_{\text{back left}} &= \text{Thrust}_{\text{cmd}} + \text{Yaw}_{\text{cmd}} - \text{Pitch}_{\text{cmd}} - \text{Roll}_{\text{cmd}} \end{aligned}$$

### 7.5 UAV Control System

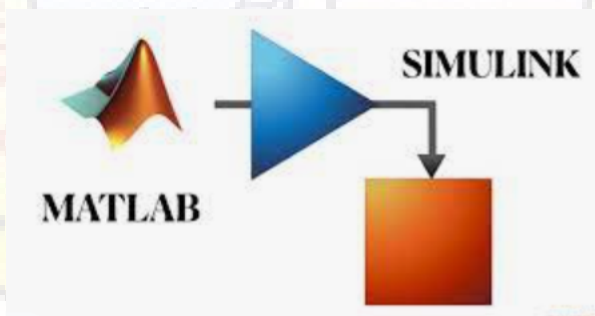


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## 8 MATLAB Simulink

MATLAB (an abbreviation of "matrix laboratory") is a proprietary multi-paradigm programming language and numeric computing environment developed by MathWorks. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages.

Although MATLAB is intended primarily for numeric computing, an optional toolbox uses the MuPAD symbolic engine allowing access to symbolic computing abilities. An additional package, Simulink, adds graphical multi-domain simulation and model-based design for dynamic and embedded systems.

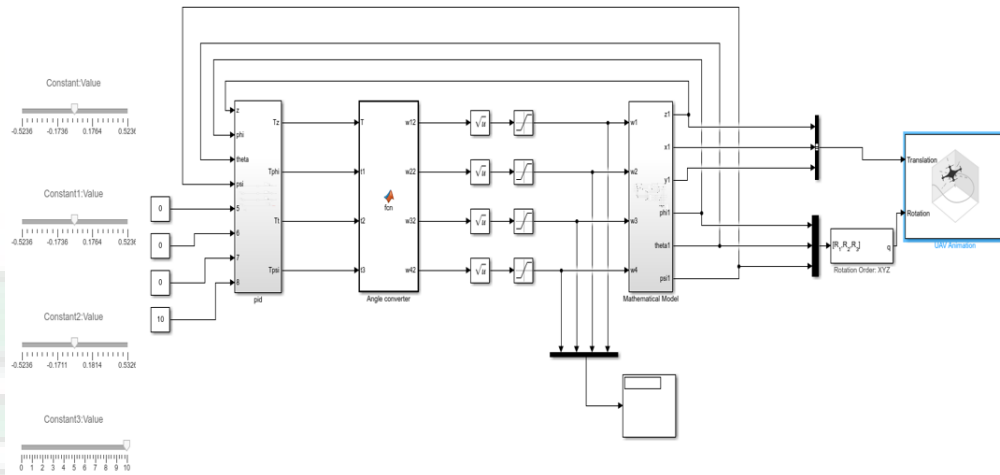


Simulink is a MATLAB-based graphical programming environment for modeling, simulating and analyzing multi domain dynamical systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. We used Simulink as it is graphical and more interactive to the user whereas the Matlab is coding based approach based on the different function available in Matlab.

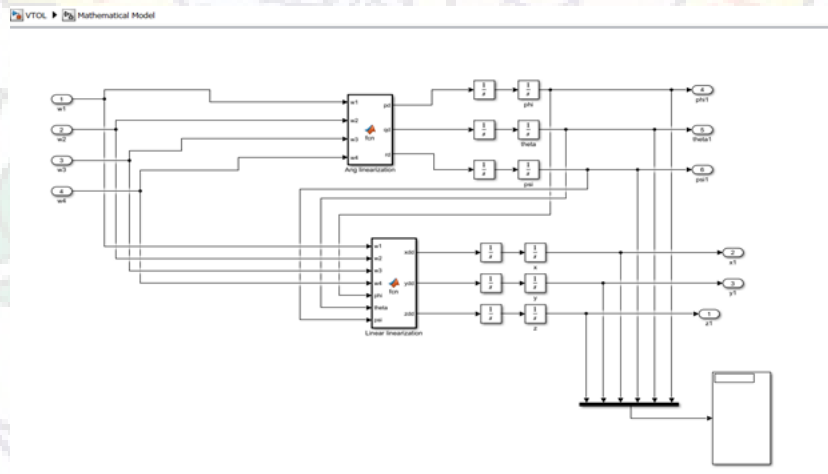


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## 8.1 UAV Subsystems - Simulink



## 8.2 Mathematical model implementation in Simulink



Toolboxes such as CONTROL SYSTEM TOOLBOX, CURVE FITTING TOOLBOX, PID TUNER are used to design the control system of the quadcopter. Whole control system discussed in this documentation is designed and simulated on Simulink.

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## 9 3D Simulation

First, we searched about various 3d simulation software. In which control system and 3d model of quadcopter can be combined and simulation of control system can be simulated with 3d model.

Gone through various libraries and blocks of Simulink MATLAB, where we can simulate 3D CAD model and whole control system. we can Simulate quadcopter 3D model using Simulink 3D Animation library blocks or we can use simmechanics - simscape library blocks.

### 9.1 Simulink 3D Animation

Simulink 3D Animation links Simulink models and MATLAB algorithms to 3D graphics objects in virtual reality scenes. One can animate a virtual world by changing position, rotation, scale, and other object properties during desktop or real-time simulation. One can also sense collisions and other events in the virtual world and feed them back into MATLAB and Simulink algorithms.

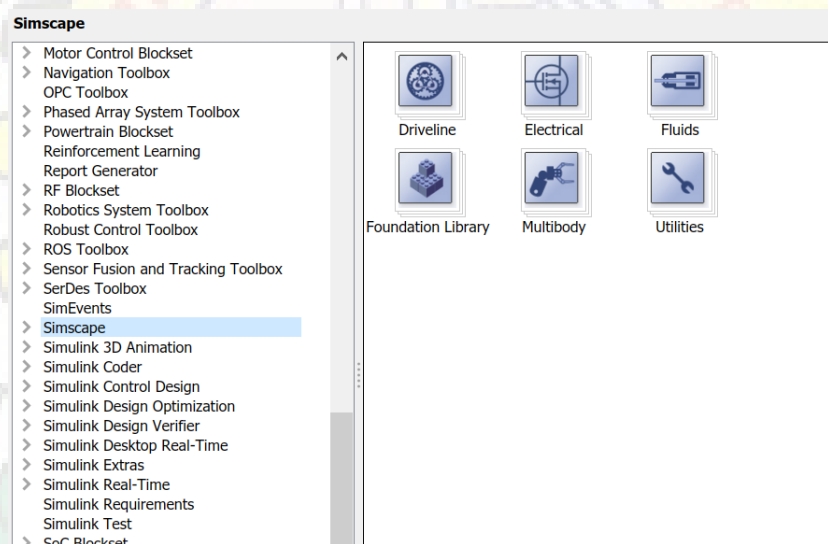
When use the Simulink 3D Animation library, the 3D World Editor is the default editor in that we can create virtual world. First import CAD model file or 3D model files in form of STL, FBX, VRML files. Create a virtual world by opening a new virtual world 3D file and adding a ROOT node with a Transform node that includes other nodes, such as Shape and Geometry nodes. Define properties for the nodes. In 3D world editor after importing 3D model, nodes of different parts and position have to define. It's quite difficult to implement for whole quadcopter model.

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## 9.2 Simmechanics-Simscape library

Simscape enables you to rapidly create models of physical systems within the Simulink environment. With Simscape one can build physical component models based on physical connections that directly integrate with block diagrams and other modeling paradigms. We can model systems by assembling fundamental components into a schematic. Simscape add-on products provide more complex components and analysis capabilities.

### Simscape library blocks



Simscape helps to develop control systems and test system-level performance. Also we can parameterize models using MATLAB variables and expressions, and design control systems for our physical system in Simulink. To deploy models to other simulation environments, including hardware-in-the-loop (HIL) systems, Simscape supports C-code generation. After some research decided to import 3D file of quadcopter model using simscape library block. To import SolidWorks quadcopter model in form of simscape library blocks, have to convert model in .XML file after installing the Simscape Multibody Link Plug-In in CAD software. After that also have to Enable the Simscape Multibody Link Plug-In in to MATLAB.

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### What is Simscape Multibody Link?

Simscape Multibody Link is a plug-in that one install on CAD application to export CAD assembly models. The plug-in generates the files that we need to import the model into the Simscape Multibody environment (using the `smimport` function). we can install the plug-in on three CAD applications:

- SolidWorks
- Autodesk Inventor
- PTC Creo

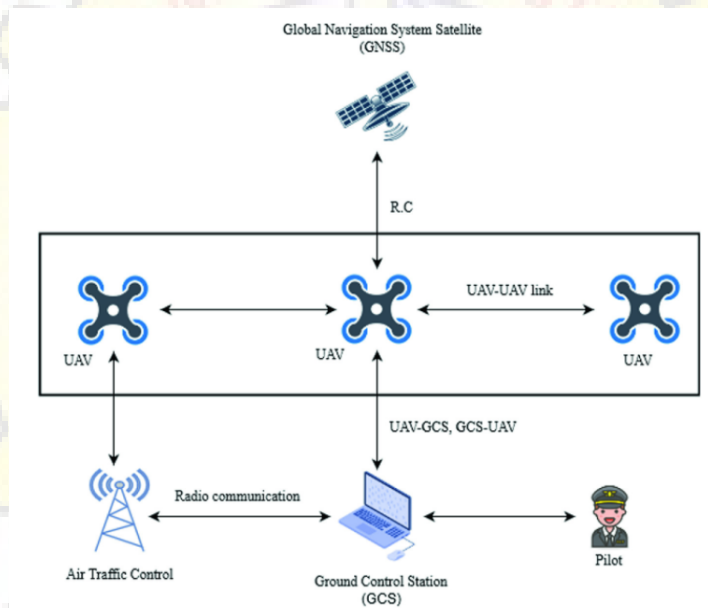
There are steps given into documentation of MATLAB (Install the Simscape Multibody Link Plug-In) to enable plug-in. To import .XML file of model in form of Simscape library blocks write function `smimport(modelsource)` in command window. If model has no missing part then without error model can be imported in Simulink. Imported model contain blocks of Simscape library. Simulating the model, 3D assembly will be imported in SimMechanics space. in SimMechanics space axes, position, view can be changed. By following this steps we can successfully import 3D model in SimMechanics space.

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## 10 Communication

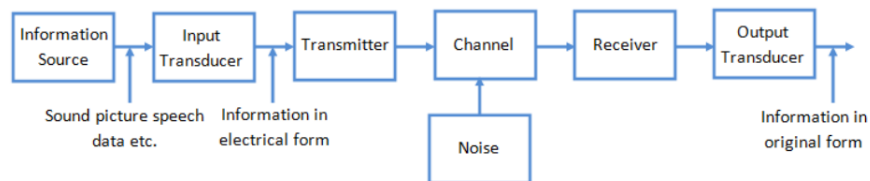
Communication systems are one of the important components in UAV or in VTOL. It helps the operator at the base station(at control station) to know about the exact position, velocity, remaining time of flight of the UAV.

Apart from this it can transmit live video send High resolution images sensor data back to base station.



### 10.1 Working of Communication System

Communication systems consist of 3 main parts i.e. transmitter, receiver channel. In the case of duplex system both ends are capable of receiving transmission, they are known as transceivers.



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The transmitter's function is to process the message signal into a form suitable for transmission over the communication channel. This is called modulation.

Communication channels function is to provide a pathway between the transmitter's output and the receiver's input. The job of the receiver is to process the received signal to recover the appropriate message signal.

Generally S-band (frequency : 2 - 4 GHz ) is used for radio communication. Such higher frequency is used so that wavelength is small as length of antenna is directly proportional to wavelength.

## 10.2 Required Features

- Lightweight, Small in size
- Embedded Encryption
- High Data rate and Full duplex
- Beyond Line-of-sight capabilities
- Low Power Consumption

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## 11 Future Aspects

- Hardware Implementation
- Complete 3D simulation
- Path planning
- Autonomous capabilities

