# STATE OF ART SEMINAR
## Path Planning of Unmanned Aerial Vehicle (UAV) with minimum energy consumption

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25 April, 2022

# Outline

# Introduction

Unmanned Aerial Vehicles (UAVs) or drones over the years have found widespread used in fields like

1. Parcel Delivery
2. Surveillance
3. Precision Agriculture
4. Disaster Management
5. Archaeological Surveys
6. Aerial Photography

- The Civil Aviation Ministry estimates India's drone sector to achieve a total turnover of Rs. 120 -150 billion by 2026. [Online article IBEF]
- To promote the use of UAVs, The Govt. of India has published "The Drone Rules 2021" which has liberalised the drone rules and aims to encourage more applications using UAVs. [GoI, Drone Rules 2021]
- In India, UAVs have immense scope in the field of agriculture and border patrolling. [Online article FICCI]

# Technical drawbacks of using an UAV

- UAV has limited flight time as it can carry a fixed battery pack. *The energy density of LiPo batteries ranges from 140 - 200+ Wh/kg in terms of weight and 250 - 350+ Wh/L for volume [4].*
- Adding a higher capacity battery adds to the weight of the flying vehicle, which in turn reduces the flight time.
- There is no feasible charging scheme mid-flight.
- For a given trip, it is suitable that an UAV picks the right battery pack otherwise, the trip might be inefficient.
- Estimation of energy before a trip is a complicated process and mostly inaccurate.
- Optimal path planning of UAV trips are required for efficient operations.

[4] G. Staff, "A guide to lithium polymer batteries for drones," Dec 2021. [Online].

# Power Consumption Modeling

The major parameters that affect power consumption of an UAV are summarised below [5]

| UAV Design | Environment | Drone dynamics | Delivery operations |
|---|---|---|---|
| UAV weight | Air density | Airspeed (vertical and horizontal) | Payload weight |
| Number of rotors | Gravity | Motion (take-off/landing/ hover/levelled flight) | Size of payload |
| Number of blades per rotor | Wind velocity | Acceleration/ Deacceleration | Drag coefficient of payload |
| Total propeller area | Wind incident angle | Roll/pitch/yaw angle | Fleet size and mix |
| Blade chord length | Weather (rain, snow etc.) | Angular speed of rotors | Single/multi stop trip |
| Angle of attack of propeller disk | Ambient temperature | Flight angle | Delivery mode (tether/landing/ parachute) |
| Advance ratio of propeller | Regulations | Flight altitude | Area of service region |
| Size of rotors | | | |
| UAV body drag co-efficients | | | |
| Battery energy capacity and weight | | | |
| Size of battery | | | |
| Power transfer efficiency | | | |
| Maximum speed | | | |
| Maximum payload | | | |
| Lift-to-drag ratio | | | |
| Avionics | | | |

[5] J. Zhang et. al "Energy consumption models for delivery drones" Transportation Research.

# Power Consumption Modeling: Literature Review [8]

**Power model based on a single parameter**
**Contribution:**

- Combines aerodynamic and drone design aspects to a critical parameter: lift-to-drag ratio $r$ for calculating power.
- For a small sized UAV, $r$ is assumed 3.
- Power is measured as a function of payload weight and velocity.
- Proposes required battery weight for a trip considering LiPo battery has a specific power of 0.35 $kW/kg$.
- A metric is proposed to derive avg. energy cost/km, avg. battery cost/km and maximum range given a payload weight and flight velocity.

[8] R. D'Andrea, "Guest editorial can drones deliver?" IEEE Transactions on Automation Science and Engineering, vol. 11, no. 3, pp. 647–648, 2014.

# Power Consumption Modeling: Literature Review [7]

**Power model based battery and payload weight**
**Contribution:**

- Derives power considering UAV as a multirotor helicopter.
- It is assumed that the power consumed during level flight, takeoff, or landing is approximately equivalent to the power consumed while hovering due to translational lift.
- This power consumption model does not consider the role of UAV speed.
- Field experiments are performed on a 3D Robotics ArduCopter Hexa-B hexacopter and a regression model is developed for power with small payloads.

[7] K. Dorling, J. Heinrichs, G. G. Messier, and S. Magierowski, "Vehicle routing problems for drone delivery," IEEE Transactions on Systems, Man, and Cybernetics:Systems, vol. 47, no. 1, pp. 70–85, 2016.

# Power Consumption Modeling: Literature Review [6]

**Power model from aerodynamic power components**
**Contribution:**

- Power consumed is distributed in to three components, namely induced power, profile power and parasitic power.
- The power equations are derived analytically using aerodynamic principles and then encapsulated with fewer constants and variables.
- The variables are horizontal, vertical velocity and thrust.
- The constants are obtained using field experiments on an IRIS+ UAV.
- A relation for power vs. payload is also obtained. It is shown that ascending takes 9.8% more power than hovering, and descending takes 8.5% less power than hovering.

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[6] Liu et. al. A power consumption model for multi-rotor small unmanned aircraft systems. In 2017 International Conference on Unmanned Aircraft Systems (ICUAS), pages 310–315. IEEE, 2017.

# Power Consumption Modeling: Literature Review [9]

**Power for drone delivery applications**
**Contribution:**

- Power model derived from [6] specifically for a drone delivery application.
- Power equation is derived for different phases namely takeoff and ascend, steady level flight, descent, hovering, and landing.
- Author compares delivery with trucks versus UAVs in Berlin and shows that drone delivery often requires more energy.
- It is concluded that in rural settings with long distances between customers, UAV-based parcel delivery infrastructure has comparable energy considerations to a delivery system with electric trucks.

[9] Kirschstein. Comparison of energy demands of drone-based and ground based parcel delivery services, 2020. [6] Liu et. al. A power consumption model for multi-rotor small unmanned aircraft systems, IEEE, 2017.

# Power Consumption Modeling: Literature Review [10]

**Power model using regression from field experiments**
**Contribution:**

- A black-box modeling approach is used to obtain the power consumption model of an UAV.
- Field experiments are performed considering the impact of various flight scenarios, payload weight and wind.
- Power is modelled with horizontal and vertical velocity, acceleration, payload weight and wind as variables.
- It is also mentioned that power estimations from this model are within 0.4% of that obtained from on-board power sensors.

[10] Chien-Ming Tseng, Chi-Kin Chau, Khaled M Elbassioni, and Majid Khonji. Flight tour planning with recharging optimization for battery-operated autonomous drones. CoRR, abs/1703.10049, 2017.

# Power Consumption Modeling: Literature Review [5]

**Contribution:**

- Few significant power models are studied and compared.
- Field experiments are done and power is calculated with few significant power models. Inspite of identical, setup, hardware and environment, power values obtained are different with each model.
- It is reported that models based on hovering provide good approximation only at low speeds.
- For few power models, authors have obtained optimum value of payload weight and flight speed that would minimise energy consumption per unit distance.

[5] J. Zhang, J. F. Campbell, D. C. Sweeney II, and A. C. Hupman, "Energy consumption models for delivery drones: A comparison and assessment," Transportation Research Part D: Transport and Environment, vol. 90, p. 102668, 2021.

# Power consumption modeling

There are various approaches available in the literature for modeling the power consumed by an UAV. Different approaches to modeling along with a few significant Power Consumption Model(PCM) are

- Component based power modeling
- Power modeling based on aerodynamic aspects
- Power modeling based on Helicopters
- Power modeling based on the extension of Helicopters
- Power Modeling based on flight experiments using Regression

# Component based power modeling

Power consumed by a multi-rotor UAV is distributed into three components

**Induced Power:** The induced power is the power required to keep the UAV afloat. The modeling of induced power is derived from Disk actuator theory [11].

$$P_i = k_1 T \left( \sqrt{\frac{T}{2\rho A} + \left(\frac{V_{vert}}{2}\right)^2} + \frac{V_{vert}}{2} \right) \tag{1}$$

- $T$ : Total thrust applied by the UAV
- $k_1$ : Ratio of actual airflow to idealised uniform airflow
- $\rho$ : Density of air
- $A$ : Total propeller area
- $V_{vert}$ : Vertical velocity of the UAV

[11] W. Johnson, Helicopter Theory. Dover Publications, 1980.

# Component based power modeling

**Profile Power:** The profile power is the power required to overcome the rotational drag encountered by rotating propeller blades. The profile power consumed by a rotating rotor blade is derived from Blade element theory [12]. The profile power for the $i^{th}$ rotor while the UAV is hovering is given by

$$P_{p,hover,i} = \frac{N \times c \times c_d \times \rho \times R^4}{8} {\omega_i}^3 \qquad (2)$$

- $N$ : Total number of blades in a single propeller
- $c$ : Blade chord width
- $c_d$ : Drag coefficient of the blade
- $R$ : Radius of the propeller blade
- $\omega_i$ : Angular speed of $i^{th}$ rotor

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[12] S. Gudmundsson, General Aviation Aircraft Designs - Applied Methods and Procedures. Butterworth-Heinemann, 2013.

# Component based power modeling

In horizontal flight, the profile power becomes

$$P_{p,i} = P_{p,hover,i}\left(1 + {\mu_i}^2\right) \text{ where } \mu_i = \frac{V_{air}cos(\alpha_i)}{\omega_i R} \tag{3}$$

The total power is

$$P_p = \sum_{i=1}^{M}\left(\frac{N \times c \times c_d \times \rho \times R^4}{8}\left({\omega_i}^3 + \left(\frac{V_{air}cos(\alpha_i)}{R}\right)^2 \omega_i\right)\right) \tag{4}$$

- $M$ : Total number of rotors
- $V_{air}$ : Horizontal velocity of the UAV
- $\mu_i$ : Advance ratio for propellers in rotor $i$
- $\alpha_i$ : Angle of attack for propeller disks in rotor $i$

# Component based power modeling

**Parasitic Power:** The parasite power is the power required to resist body drag when there is relative translational motion between the vehicle and wind.
The parasitic power is obtained by assuming that the body drag ($F_{par}$) is proportional to airspeed ($V_{air}$) squared.

$$P_{par} = \frac{1}{2} C_d \times \rho \times A_{quad} \times {V_{air}}^3 \tag{5}$$

- $A_{quad}$ : Cross sectional area of the vehicle when against wind
- $C_d$ : Drag coefficient of vehicle body

# Component based power modeling

**Simplified expressions for power** (derived from [6])

$$P_i(T, V_{vert}) = P_i = \boldsymbol{k_1} T \left( \frac{V_{vert}}{2} + \sqrt{\frac{T}{{k_2}^2} + \left(\frac{V_{vert}}{2}\right)^2} \right) \text{ and } \boldsymbol{k_2} = \sqrt{2\rho A} \tag{6}$$

While hovering, $V_{vert} = 0$ and the induced power is reduced to

$$P_{i,hover}(T, 0) = \frac{k_1}{k_2} T^{\frac{3}{2}} = \boldsymbol{c_1} T^{\frac{3}{2}} \tag{7}$$

Assuming $T_i \propto \omega_i^2$ [13]

$$P_p(T, V_{air}) = \boldsymbol{c_2} T^{\frac{3}{2}} + \boldsymbol{c_3} (V_{air} cos\alpha)^2 T^{\frac{1}{2}} \tag{8}$$

$$P_{par}(V_{air}) = \boldsymbol{c_4} {V_{air}}^3 \tag{9}$$

$$T = mg \tag{10}$$

[13] P. Corke, Robotics, Visions .. . [6] Liu et. al. "A power consumption model..", ICUAS, 2017.

# Component based power modeling

$$P_i = k_1 T \left( \sqrt{\frac{T}{2\rho A} + \left(\frac{V_{vert}}{2}\right)^2} + \frac{V_{vert}}{2} \right)$$

$$P_p = \sum_{i=1}^{M} \left( \frac{N \times c \times c_d \times \rho \times R^4}{8} \left( {\omega_i}^3 + \left( \frac{V_{air} cos(\alpha_i)}{R} \right)^2 \omega_i \right) \right)$$

$$P_{par} = \frac{1}{2} C_d \times \rho \times A_{quad} \times {V_{air}}^3$$

# Component based power modeling

**Model Identification using experiments**

**Experiment 1 - Hover -** The UAV is loaded with different payloads and made to hover. The total power is

$$P_{exp1} = P_{i,hover}(mg, 0) + P_p(mg, 0) = (\boldsymbol{c_1} + \boldsymbol{c_2})(mg)^{\frac{3}{2}} \tag{11}$$

**Experiment 2 - Steady State ascend/descend -** The UAV is commanded to ascend and descend at constant vertical speed between a defined altitude range without payloads.

$$P_{exp2} = P_i(mg, V_{vert}) + P_p(mg, 0) \tag{12}$$

$$P_{exp2} = \boldsymbol{k_1} mg \left( \frac{V_{vert}}{2} + \sqrt{\frac{mg}{\boldsymbol{k_2}^2} + \left(\frac{V_{vert}}{2}\right)^2} \right) + \boldsymbol{c_2}(mg)^{\frac{3}{2}} \tag{13}$$

# Component based power modeling

**Model Identification using experiments**

$$P_{exp1} = (\boldsymbol{c_1} + \boldsymbol{c_2})(mg)^{\frac{3}{2}} \tag{14}$$

$$P_{exp2} = \boldsymbol{k_1} mg \left( \frac{V_{vert}}{2} + \sqrt{\frac{mg}{\boldsymbol{k_2}^2} + \left(\frac{V_{vert}}{2}\right)^2} \right) + \boldsymbol{c_2}(mg)^{\frac{3}{2}} \tag{15}$$

From Experiment 1 and Experiment 2, we have four equations (hover, ascend, descend, and $\boldsymbol{c_1 = k_1/k_2}$), and four unknown parameters $(\boldsymbol{k_1, k_2, c_1, c_2})$.

# Component based power modeling

**Experiment 3 - Cyclical straight lines -** The goal of this experiment is to quantify the effect of parasitic drag.
The parameter $c_3$ is assumed to be 0 to simplify the identification process

$$P_{exp3} = P_i(T, 0) + P_p(T, V_{air}) + P_{par}(V_{air}) \tag{16}$$

$$P_{exp3} = (\boldsymbol{c_1} + \boldsymbol{c_2})T^{\frac{3}{2}} + c_3(V_{air} cos\alpha)^2 T^{\frac{1}{2}} + \boldsymbol{c_4} V_{air}^3 \tag{17}$$

$$P_{exp3} \simeq (\boldsymbol{c_1} + \boldsymbol{c_2})T^{\frac{3}{2}} + \boldsymbol{c_4} V_{air}^3 \tag{18}$$

Parameters identified from the experiments are $\boldsymbol{k_1, k_2, c_1, c_2, c_4}$

# Power modeling based on Helicopters

- The power consumption equations for a multi-rotor UAV are obtained from the power for a single rotor helicopter in hovering as a function of weight [14].
- Power for all stages is considererd an upper bound of power during hovering due to Translational lift. [15]

Using [14], the power $P^*$ is calculated in Watts for a single rotor helicopter in hover, with the thrust $T$ in Newtons, fluid density of air $\rho$ in $kg/m^3$, and the area $\zeta$ of the spinning blade disc in $m^2$ using

$$P^* = \frac{T^{\frac{3}{2}}}{\sqrt{2\rho\zeta}} \tag{19}$$

where the Thrust $T = (W + m)g$ and $W$ is the frame weight in kg, $m$ is the battery and payload weight in kg.

[14] J. Leishman, Principles of Helicopter Aerodynamics. [15] S. Gudmundsson, General Aviation Aircraft Designs - Applied Methods and Procedures.

# Power modeling based on Helicopters

Using eq(19), the power for an n-rotor UAV is derived assuming that each rotor carries a weight of $m' = m/n$ for batteries and payload and $W' = W/n$ for body frame. Therefore, power consumed by a single rotor is

$$P' = (W' + m')^{\frac{3}{2}} \sqrt{\frac{g^3}{2\rho\zeta}} \tag{20}$$

So, the power consumed by all the n rotors is given by

$$P = nP' = (W + m)^{\frac{3}{2}} \sqrt{\frac{g^3}{2\rho\zeta n}} \tag{21}$$

# Power modeling using regression

- This is a class of modeling where the power model is designed designed empirically from field experiments.
- The UAV is subjected to various flight maneuvers and operations and a power/energy expression is captured out of those maneuvers/ operations using regression.
- The authors in [10] have derived a 9 variable power consumption model by performing various experiments on a commercial drone 3DR Solo.

The following factors are considered for obtaining empirical data:

- **Impact of Motion**
- **Impact of Weight**
- **Impact of Wind**

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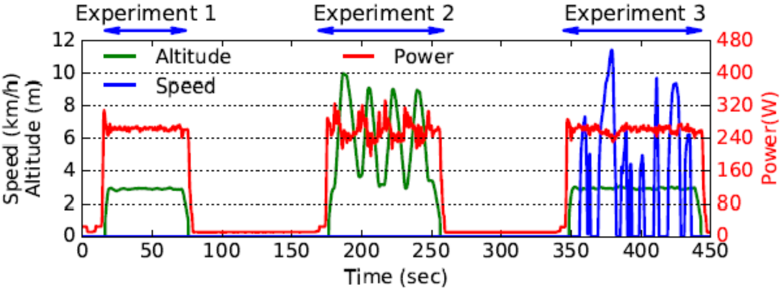
[10] C.-M. Tseng, C.-K. Chau, K. M. Elbassioni, and M. Khonji, “Flight tour planning with recharging optimization for battery-operated autonomous drones,” CoRR, abs/1703.10049, 2017.

# Power modeling using regression

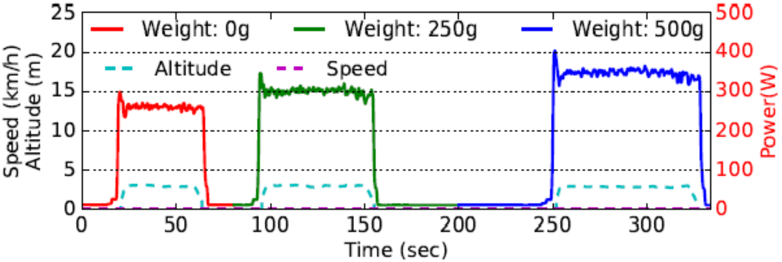
## Experiments to study impact of motion

- **Experiment 1:** The test UAV hovers in the air without any movement in this experiment.
- **Experiment 2:** The test UAV is made to ascend and descend continuously in a repeated fashion in this experiment.
- **Experiment 3:** The test UAV moves horizontally without altering its altitude in this experiment.



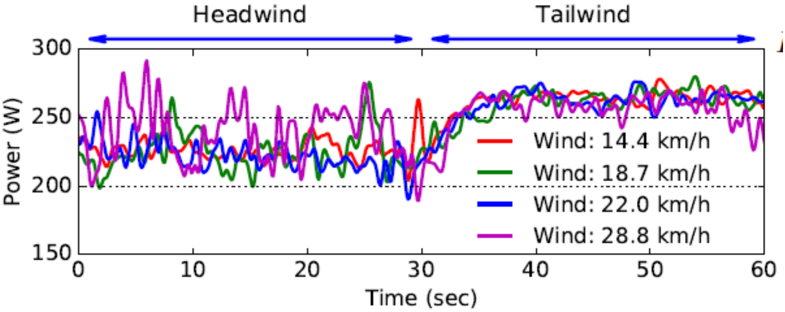
# Power modeling using regression

**Experiments to study impact of weight** The UAV is set to hover with various payloads in the air without any movement power.



## Experiments to study impact of wind

- Several experiments under different wind conditions: headwind as well as tailwind.
- Smaller power consumption is observed when flying into headwind, which is due to the increasing thrust by translational lift.



# Power Consumption Modeling : Research Gap

**On deriving power from hovering**

- An UAV design combines the attributes of airplanes and helicopters. While airplanes are designed to travel long distances efficiently, helicopters are designed to hover efficiently [9].
- In most cases, the power consumption modeling is derived from hovering action in Helicopters [11] as evident from the works done in [8], [16].
- Some works like [16] have extrapolated the dynamics of hovering to capture the power consumption during leveled flight with constant velocity.
- An UAV operation involves different stages of leveled flight, so deriving power from hovering can be a reason for inaccuracy in power calculation.

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[9] Kirschstein, "Comparison of energy demands.." 2020. [11] W. Johnson, Helicopter Theory. [8] D'Andrea, "can drones deliver?",2014. [16] Stolaroff et. al "Energy use and life cycle..", 2018.

# Power Consumption Modeling : Research Gap

**On translational lift**

- There is a consideration where the power consumed during hover is an upper bound to the power consumed for other instances of the flight i.e. take-off/landing/leveled translational motion etc [7] due to translational lift. [15]
- This consideration may not be always true as the UAV is not always in the same attitude.

**On optimum flight velocities**

- None of the power consumption models that are designed analytically gives an optimum horizontal velocity that would minimize the power consumption for an UAV during leveled flight.
- Solution for an optimum vertical velocity during take-off/landing, and an optimum angle for ascend/descend can also be looked for.

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[7] Dorling et. al "Vehicle Routing Problems.." IEEE Transactions on Systems, Man, and Cybernetics:, 2016. [15] S. Gudmundsson General Aviation Aircraft Designs

# Power Consumption Modeling : Research Gap

**On curved paths**

- Almost all power models obtain power formulations for straight line paths. There is a scope to derive power for curved paths considering various flight maneuvers and mapping those maneuvers in a power formulation.
- It can also be checked if curved paths are less expensive than straight line paths.

**On acceleration as a power variable**

- None of the power models derived from aerodynamic principles has acceleration as a power variable. [10] considers acceleration, but it is a black-box modeling.
- UAVs undergo velocity changes at multiple instances, so acceleration can be a factor affecting power.

[10] C.-M. Tseng, C.-K. Chau, K. M. Elbassioni, and M. Khonji, "Flight tour planning with recharging optimization for battery-operated autonomous drones," CoRR, abs/1703.10049, 2017.

# Power Consumption Modeling : Research Gap

**On significant flight variables**

- Different models use a different set of variables for the power consumption modeling. Although different models are based on different philosophies but there is no metric to characterize the crucial variables essential for power consumption modeling.
- The effect of vertical velocity is considered in [6] whereas it is not considered in [16]. In fact, [8] does not consider the effect of velocity at all.

**On consensus in power models**

- Different power models give different power values for experiments with identical setup, hardware and environment as concluded in [5] so power modeling has not reached a consensus in accuracy.

[6] Liu et. al "A power consumption model..", ICUAS, 2017. [16] J. Stolaroff et. al "Energy use..", Nature communications, 2018. [8] R. D'Andrea " Can drones deliver?" 2014. [5] Zhang et. al "Energy consumption..", Transportation Research 2021.

# Research Plan

**Objectives**

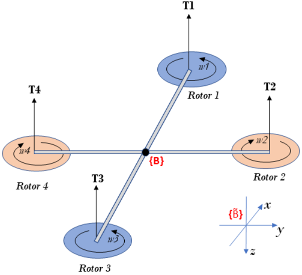
- To derive a power consumption model for an UAV.
- Calculate the endurance (flight time or range) of that UAV.
- Perform optimal path planning such that energy consumption is minimized.
- The power model should be applicable both online and offline.
- The model should be able to capture the role of various flight maneuvers.
- The model should reduce the dependency on multiple parameters.
- The model should also be able to capture the role of disturbances (wind)

**Proposition**: A **dynamic power consumption model** based on

- Thrust
- Angular velocity/speed of rotors
- Torque produced by the rotors

# Research Plan

## Prelimenaries



# Research Plan

**Thrust**

Parameters that affect thrust are

Fixed

1. No. of blades in a single propeller
2. Drag coefficient of blade
3. Blade chord length
4. Angle of attack of propeller blade
5. Propeller blade area

Variable

1. Drone Design
    1. Drone weight (fixed with fixed battery)
    2. Payload weight

# Research Plan

2. Environment
    1. Wind velocity
    2. Wind incident angle
    3. Air density
    4. Gravity

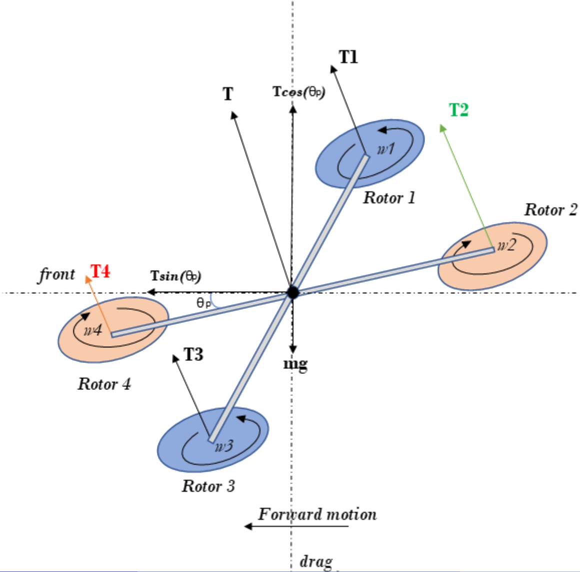
    Note - For wind(external disturbance), the UAV needs to lean against the wind with some roll, pitch and yaw angle depending upon the wind incident angle and prevent it from being deviated from its path/position. Some wind incident angles might also aid in translational motion.

3. Drone dynamics
    1. Climb/Descend (Vertical motion) - All propellers produce the same thrust. Climb/sink rate (vertical velocity) decides the required thrust profile.
    2. Hover - All propellers produce the same thrust.

# Research Plan

3. Roll - Right side and left side propellers produce unequal thrust producing a rolling torque. Roll angle decides the required thrust in respective propellers.
4. Pitch - Front and rear propellers produce unequal thrust resulting in a pitching torque. Pitch angle decides the required thrust in respective propellers.
5. Yaw - Clockwise and counter-clockwise spinning propellers produce unequal torques resulting in a yaw torque. Yaw angle decides the required thrusts in respective propellers.
6. Cruise (Horizontal motion) - Combination of pitch and hover. The thrusts are unequal due to pitch. Due to pitch angle($\theta_p$), the vertical component of thrust is $Tcos(\theta_p)$ and as a result, $T$ required is higher than hover. Also, horizontal velocity depends on the pitch angle.

# Research Plan



# Research Plan

**Drone dynamics with Thrust and angular velocity of rotors**
Ideally [13],

$$\text{Thrust } T = bw^2 \tag{22}$$

where,
$w$ is the angular velocity in number of revolutions per minute(RPM) of the propeller/rotor
$b$ depends upon the fixed parameters $1-5$ and variable parameter air density.
The translational dynamics of the vehicle in world coordinates is given by Newton's second law

$$m\dot{v} = \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} - R_B^0 \begin{bmatrix} 0 \\ 0 \\ T \end{bmatrix} - Bv$$

[13] P. Corke, Robotics, Vision and Control: Fundamental Algorithms in MATLAB.

# Research Plan

$$m\dot{v} = \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} - R_B^0 \begin{bmatrix} 0 \\ 0 \\ T \end{bmatrix} - Bv \qquad (23)$$

where,

- v = velocity of the vehicle's center of mass in world reference frame
- m = total mass of the UAV
- B = aerodynamic friction
- $R_B^0$ = rotation matrix from vehicle frame to world coordinate frame

# Research Plan

Pairwise differences in rotor thrusts cause the vehicle to rotate. The torque about the vehicle's x-axis, the **rolling torque**, is generated by the moments

$$\tau_x = d(T_4 - T_2) \tag{24}$$

where, d is the distance from the rotor axis to the center of mass. We can write this in terms of rotor speeds by substituting eq(22)

$$\tau_x = db(w_4^2 - w_2^2) \tag{25}$$

Similarly, the torque about the vehicle's y-axis, the **pitching torque**, is given by

$$\tau_y = db(w_1^2 - w_3^2) \tag{26}$$

# Research Plan

The torque applied to each propeller by the motor is opposed by aerodynamic drag is given by

$$Q_i = cw_i^2 \text{ and } i \in \{1, 2, 3, 4\} \tag{27}$$

$c$ depends on the same factors as $b$.
This torque exerts a reaction torque on the airframe, which acts to rotate the airframe in the opposite direction to its rotation. The reaction torque about the z-axis is

$$\begin{aligned} \tau_z &= Q_1 - Q_2 + Q_3 - Q_4 \\ &= c(w_1^2 - w_2^2 + w_3^2 - w_4^2) \end{aligned} \tag{28}$$

So, a **yaw torque** is generated simply by appropriate coordinated control of all four rotor speeds.

# Research Plan

The total torque applied to the airframe according to eq(25), eq(26) and eq(28) is $\tau = (\tau_x, \tau_y, \tau_z)^T$.
The rotational acceleration is given by Euler's equation of motion

$$J\dot{w} = -w \times Jw + \tau \tag{29}$$

where, $J$ is the $3 \times 3$ inertia matrix of the UAV and $w$ is the angular velocity vector.
The motion of the quadrotor is obtained by integrating the forward dynamics equations eq(23) and eq(29), where the forces and moments on the airframe are functions of rotor speeds.

$$\begin{bmatrix} T \\ \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = \begin{bmatrix} -b & -b & -b & -b \\ 0 & -db & 0 & -db \\ db & 0 & -db & 0 \\ c & -c & c & -c \end{bmatrix} \begin{bmatrix} w_1^2 \\ w_2^2 \\ w_3^2 \\ w_4^2 \end{bmatrix} = A \begin{bmatrix} w_1^2 \\ w_2^2 \\ w_3^2 \\ w_4^2 \end{bmatrix} \tag{30}$$

The matrix $A$ is constant and full rank if $b, c, d > 0$ and we can obtain the required rotor speeds as

$$\begin{bmatrix} w_1^2 \\ w_2^2 \\ w_3^2 \\ w_4^2 \end{bmatrix} = A^{-1} \begin{bmatrix} T \\ \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} \tag{31}$$

# Research Plan

**Control architecture for translating forward flight to rotor speeds**

A PID control architecture is used to describe the control scheme on the UAV for translational motion. This architecture is based on the work done in[13]. Altitude is controlled by a PD controller

$$T_z = K_p(z^* - z^{\#}) + K_d(\dot{z}^* - \dot{z}^{\#}) + T_0 \tag{32}$$

$T_0 = mg$ is the weight of the vehicle. $z^*$ and $z^{\#}$ are the desired and actual altitudes respectively. Eq(22) and eq(32) determine the average rotor speed. For pitch and x-translational motion, a PD controller is used to compute pitching torque based on the error between desired and actual pitch angle.

$$\tau_y^* = K_{\tau,p}(\theta_p^* - \theta_p^{\#}) + K_{\tau,d}(\dot{\theta_p}^* - \dot{\theta_p}^{\#}) \tag{33}$$

where, $K_{\tau,p}$ and $K_{\tau,d}$ are controller gains, $\theta_p^*$ and $\theta_p^{\#}$ are the desired and actual pitch angles respectively.

[13] P. Corke, Robotics, Vision and Control: Fundamental Algorithms in MATLAB.

## Research Plan

The world coordinate frame is designated by $\tilde{B}$ attached to the vehicle and with the same origin as $B$ but with its x and y axes in the horizontal plane and parallel to the ground.
The thrust vector is parallel to the z-axis of frame $B$ and pitching the nose down, rotating about the y-axis by $\theta_p$, generates a force

$$^{\tilde{B}}f = \mathscr{R}_y(\theta_p). \begin{bmatrix} 0 \\ 0 \\ T \end{bmatrix} = \begin{bmatrix} Tsin(\theta_p) \\ 0 \\ Tcos(\theta_p) \end{bmatrix}$$

The component $^{\tilde{B}}f_x$ accelerates the vehicle in the $^{\tilde{B}}x$-direction, and we have assumed that $\theta_p$ is small.

$$^{\tilde{B}}f_x = Tsin(\theta_p) \approx T\theta_p \tag{34}$$

We can control the velocity in this direction with a proportional control law

$$^{\tilde{B}}f_x{}^* = m \times K_f(^{\tilde{B}}v_x{}^* - {}^{\tilde{B}}v_x{}^{\#}) \tag{35}$$

where, $K_f$ is the controller gain, $^{\tilde{B}}v_x{}^*$, $^{\tilde{B}}v_x{}^{\#}$ are the desired and actual velocities in world reference frame

Combining eq(34) and eq(35), we obtain the desired pitch angle required to achieve the desired forward velocity.

$$\theta_p^* \approx \frac{m}{T} K_f(^{\tilde{B}}v_x{}^* - {}^{\tilde{B}}v_x{}^{\#}) \tag{36}$$

Using eq(33), we compute the required pitching torque, and then using eq(31), the required rotor speeds.

# Research Plan

**Summary**

- Desired velocity is given in world coordinates.
- The velocity controller implements eq(36) and outputs the desired pitch angle based on desired velocity.
- The attitude (pitch) controller determines the appropriate pitch torque to achieve these angles based on the feedback of current pitch and pitch rate.
- The three torques (assuming roll and yaw torque to be 0) and $T_z$ as gives the required rotor speeds using eq(31).
- Similar philosophy can be applied in 2D motion, which will involve roll, pitch and yaw torque.

# Research Plan

**Power Calculation**

The shaft power for a DC motor drive in Watts is given by

$$P = \frac{2\pi \times w \times T_{or}}{60}$$

where $w$ is the angular speed of the motor in $RPM$ and $T_{or}$ is the torque in $N-m$.

According to Disk actuator theory [11], the torque produced by a rotor is given by

$$T_{or} = \frac{1}{2} T_q \rho A w^2 R^3 \tag{37}$$

where $T_q$ is the torque coefficient which is fixed for a given propeller.$\rho$ is air density, $A$ is propeller disk area and $R$ is blade chord length.

[11] W. Johnson, Helicopter Theory. Dover Publications, 1980.

# Research Plan

$$P = \frac{2\pi \times w \times T_{or}}{60} \quad (38)$$

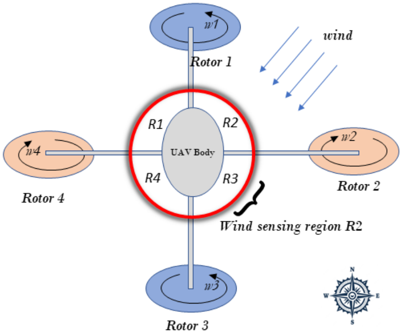
From eq(38) and eq(37),

$$P \propto w^3$$

Here $\rho$ is assumed constant for an operation while remaining parameters are constant by mechanical construction of the UAV. So, every dynamics and every parameter are mapped to a single variable for obtaining power.

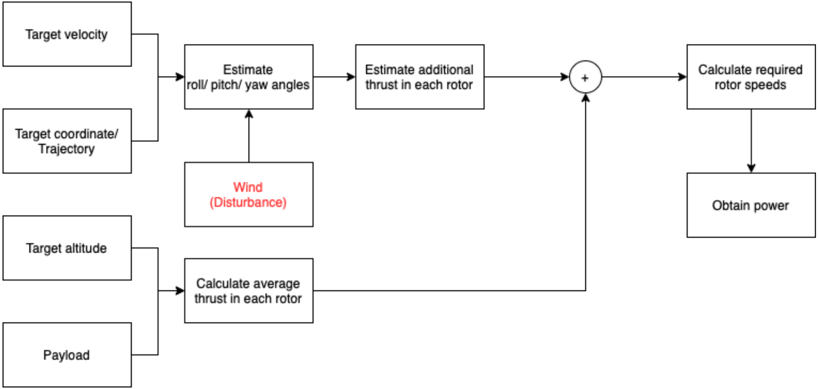
# Research Plan

To capture additional power due to wind, we need to detect wind velocity and wind incident angle on the UAV body.



# Research Plan

## Snapshot of the power calculation

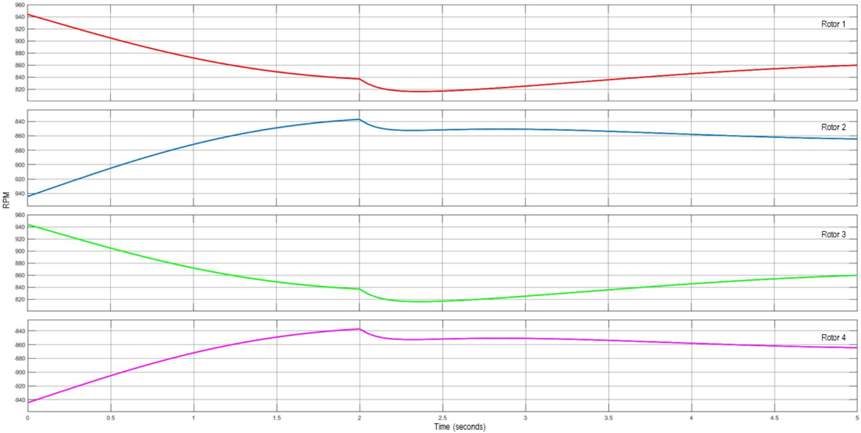


**MATLAB Simulations**
using Robotics Toolbox (RTB10.x)

The simulations are performed using a quadcopter model avaiabe in the Robotics Toolbox (RTB10.x) of MATLAB R2021a. This toolbox is designed by Peter Corke. The experiments were carried out on an Intel Core i5 computer at 3.50 GHz with 8 GB RAM using Windows 10 operating system.

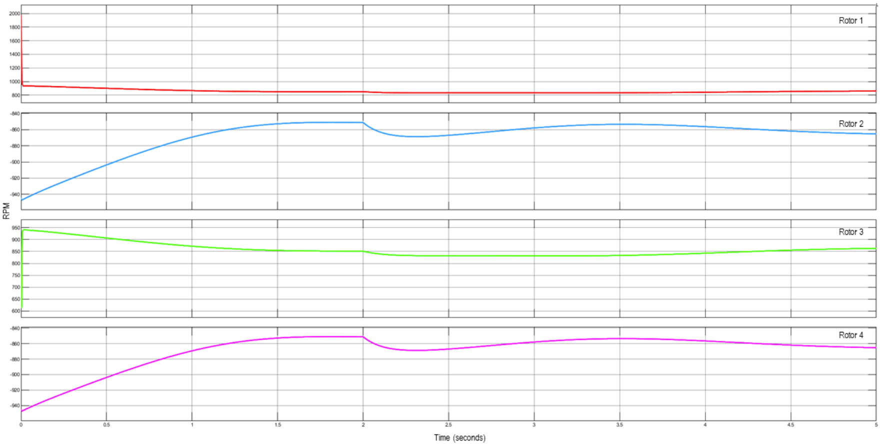
# Research Plan

**Simulation 1 :**
Initial position = (0,0,0), Target Position = (0,0,2)
Simulation time = 5 seconds.

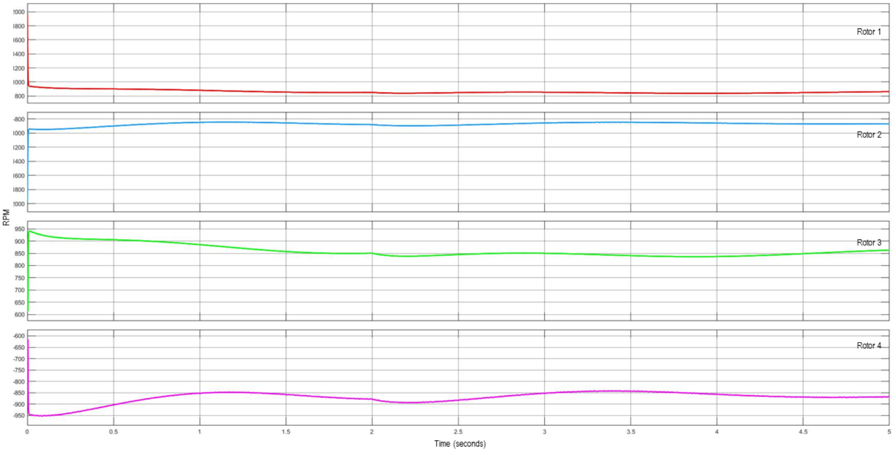


# Research Plan

**Simulation 2 :**
Initial position = (0,0,0), Target Position = (4,0,2)
Simulation time = 5 seconds.

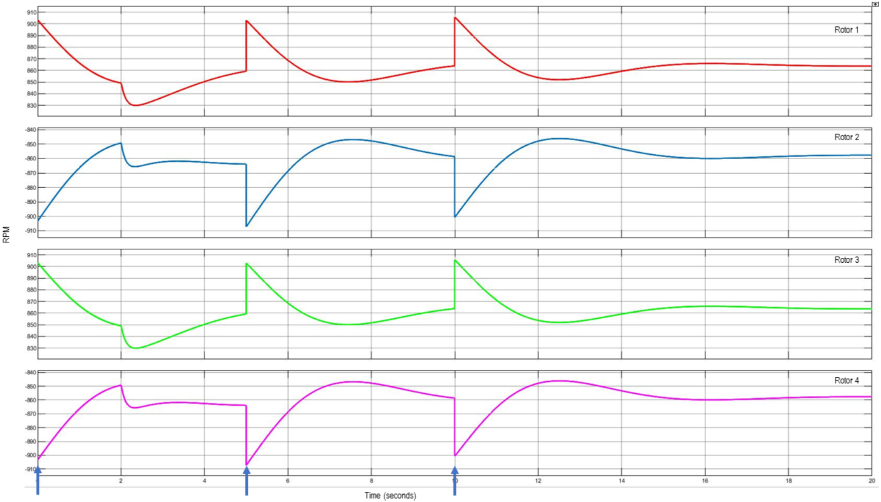


**Simulation 3 :**
Initial position = (0,0,0), Target Position = (4,4,2)
Simulation time = 5 seconds.



# Research Plan

**Simulation 4 :**
Initial position = (0,0,0), Target Position = (0,0,1) at time $t$ = 0s, (0,0,2) at time $t$ = 5s, (0,0,3) at time $t$ = 10s
Simulation time = 20 seconds



# Path Planning

# Path Planning: Introduction

**Path planning**: Generation of a set of waypoints between an initial location and a desired destination with an optimal or near-optimal performance under constraints.

Path planning is performed to ensure the following attributes [18]

- Stealth
- Physical Feasibility
  - Flying time
  - Payload weight
  - Communication range
  - Maximum translational velocity
  - Maximum climb/sink rate
  - On-board computational power
- Performance of Mission
- Cooperation
- Real-Time Implementation

[18] Zheng et. al "Evolutionary route planner for unmanned air vehicles," IEEE Transactions

# Path Planning: Literature Review [7]

**Problem:** Multi-objective Vehicle Routing Problem (VRP) to minimise the time and cost of an operation

**Contribution:**

- Solved VRP as multi-trip VRP.
- An energy consumption model is developed where energy consumed is shown identical irrespective of hover or levelled flight.
- They have also concluded that energy consumption varies linearly with weight.
- They have addressed a VRP where the number of UAVs, the routes they fly, battery weight and payload weight are optimized.
- It is shown that minimum time has an inverse exponential relationship with minimum cost.

[7] K. Dorling, J. Heinrichs, G. G. Messier, and S. Magierowski, "Vehicle routing problems for drone delivery," IEEE Transactions on Systems, Man, and Cybernetics:Systems, vol. 47, no. 1, pp. 70–85, 2016.

# Path Planning: Literature Review [19]

**Problem:** A multi-modal path planning problem for UAVs under a low altitude dynamic urban environment.

**Contribution:**

- A Multi-objective path planning (MOPP) framework concerning travel time and safety level has been proposed.
- A static and a dynamic SIM is established offline to indicate the main static obstacles in the geography and unexpected obstacles during flight.
- A joint offline and online search method has been developed to address the MOPP problem.
- The performance of the MOPP is evaluated using average/max runtime, trajectory, travel time and total safety index.
- A travel time and safety index trade-off curve is provided for the operator.

[19] C. Yin, Z. Xiao, "Offline and online search: UAV multiobjective path planning under dynamic urban environment," IEEE Internet of Things Journal, vol. 5, no. 2, pp. 546–558, 2017.

# Path Planning: Literature Review [20]

**Problem:** Four-dimensional multi-objective path planning of an UAV in a large dynamic environment

**Contribution:**

- The multiple objectives addressed are safety, flying rules, delivery time and fuel consumption.
- The constraints considered in flight are cruise velocity, altitude, rate of climb, turn radius, vehicle separation, storm cell avoidance and population risk criterion.
- A multi-step A* search algorithm is proposed which employs a variable successor operator and finds a cost-optimal path.
- It is concluded that the computational time of MSA* is four times better than A* while the total cost is only marginally improved.

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[20]P. P.-Y. Wu et. al, "Multi-objective four-dimensional vehicle motion planning in large dynamic environments," IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics), vol. 41, no. 3, pp. 621–634, 2010.

# Path Planning: Literature Review [21]

**Problem:** Real-time path planning problem of an UAV in a complex 3D environment

**Contribution:**

- Compared two evolutionary algorithms GA and PSO for path planning.
- The cost function includes optimality criteria like the length of the path, altitude and danger zones and feasible criteria like power availability, and collision avoidance.
- It is concluded that GA produces superior path planning results than PSO.
- A parallel computing paradigm is developed between these two algorithms in a single program and execution time is improved.

[21] V. Roberge, M. Tarbouchi, and G. Labont´e, "Comparison of parallel genetic algorithm and particle swarm optimization for real-time UAV path planning," IEEE Transactions on industrial informatics, vol. 9, no. 1, pp. 132–141, 2012.

# Types of path planning

There are two major classes of path planning

**1. Offline path planning**

Offline path planning is also known as global path planning.
Under this situation, the environment is static, and its global information is known a priori.
Offline path planning is applied in scenarios like -

- To check feasibility of whether an UAV can perform an operation in fixed time or with a fixed energy budget.
- To derive vehicle routing solutions in multi-agent scenarios.
- To plan multi-vehicle scenerios, like truck-drone delivery operations.

# Online path planning

**2. Online path planning**

Offline path planning also known as local path planning is a scheme, where the path is generated by taking data from the sensors/cooperative agents during the movement of the UAV.

An UAV can generate a new path in response to a new environment/objective.

Online path planning is applied in the following scenarios -

- The UAV comes in proximity of an unforseen object/topography.
- The UAV gets dissuaded from its path due to unknown environmental factors.
- In a cooperative operation, the objective of an UAV changes.
- There is an updation of the global information map.

# Path Planning : Research Gap

- On a multi-objective path planning scheme, the objective of minimizing energy consumption is avoided in most cases. The cases that consider energy consumption as an objective are grid-based path planning, where the path is assumed as a straight line from one point to the other [23]. The power consumption modeling can be tested against various types of trajectories and accordingly an optimal/quasi-optimal trajectory can be obtained.
- To the best of our knowledge, optimal online path planning is not formulated in the literature when an UAV gets dissuaded from its path due to environmental factors like wind. Consider a case where a UAV is dissuaded from its preplanned path due to external stimuli. The path planning algorithm should be able to replan a trajectory from that instant such that energy is minimized for the rest of the journey.

[23] Wai et. al, “Adaptive neural network control and optimal path planning of UAV” IEEE Access, 2019.

# Path Planning : Research Gap

- To the best of our knowledge, weather data is not taken into consideration during the path planning of an UAV. In civil aviation, a flight plan is designed based on the current weather, which may include waypoints that are placed according to the wind directions of the region[24]. Such flight plans aid the flight with minimum fuel burnt against the flow of wind. Similarly in UAV path planning, wind data can be considered for an efficient flight.

[24] W.-X. Lim and Z.-W. Zhong, "Re-planning of flight routes avoiding convective weather and the "three areas"," IEEE Transactions on Intelligent Transportation Systems, vol. 19, no. 3, pp. 868–877, 2017.

# Conclusion

- Two aspects of an Unmanned Aerial Vehicle (UAV) are addressed, power consumption modeling and path planning. A literature survey is carried out for both these aspects.
- An attempt is made to derive a dynamic power consumption model using the angular speeds of rotors. The model however needs to be defined with proper units. The model also needs to be tested against practical power consumption using voltage and current measurements on a real UAV setup.
- The future prospect of the work is to derive a path planning algorithm that will be formulated using our power consumption model. We aim to address the research gaps mentioned above.
- Finally, we wish to apply path planning with minimal energy consumption in a multi-agent setup.

# Questions?

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