Assignment 1
Hardware Design of UAV

Avneesh Mishra
avneesh.mishra@research.iiit.ac.in *

February 23, 2022

Contents

*M.S. by research - CSE, IIIT Hyderabad, Roll No: 2021701032

1 UAV Design for Spraying Fertilizer

The following are the given requirements

$$
\begin{aligned}
\text{Endurance} &= 40\,\text{min} & \text{Range} &= 5\,\text{Km} & \text{Payload weight} &= 10\,\text{Kg} \\
\text{Flying altitude} &= 20\,\text{m} & \text{Climb rate} &= 1\,\text{m/s} & \text{Descent rate} &= 2\,\text{m/s} \\
\text{Cruise speed} &= 5\,\text{m/s}
\end{aligned}
$$

It is assumed that these are the minimum values and with a greater budget these can be extended.

1.1 CONOPS

CONOPS or *Concept of Operations* is the overview of the operations involved in the application of the UAV. The stages of operation are defined as

1. **Takeoff** from ground and **climb** to an altitude of $20\,m$. The climb rate is $1\,m/s$.
2. **Cruise** in straight lines while spraying fertilizer on the field. The equipment to carry out this operation is the payload (maximum $10\,Kg$). The cruise speed is $5\,m/s$. The UAV has the following modes of operation
    - *Manual control*: Giving the UAV velocity commands, directions, and manually controlling the fertilizer equipment.
    - Calibrated *autonomous control*: Calibrate the UAV to the field and configure the fertilizer distribution parameters. Then let the UAV perform the operation.
3. **Descent** after the task of spraying fertilizer is completed. Descent rate is $2\,m/s$ from a height of $20\,m$. After this, the UAV **lands**.

1.2 Requirement specifications

The following can be considered the *requirement specifications* for the starting of the design phase

- *Operating Velocity*: The cruise speed of the UAV is $5\,m/s$.
- *Range*: The total distance the UAV can travel without refuelling/recharging is $5Km$.
- *Endurance*: The total time the UAV can operate without refuelling/recharging is $40\,min$.
- *Payload*: The payload - fertilizer distribution unit and storage - is $10\,Kg$ heavy.
- *Wind* conditions: The UAV will be operated in wind speeds $4\,km/hr$ to $9\,km/hr$ [1]. We can assume the *upper limit of* $10\,km/hr$. Most of the wind flows in the east and west direction.
- *Altitude*: The flight altitude is capped at $20\,m$ from ground. Must operate at a maximum of $1200\,m$ above sea level (ASL) to be used in most of agricultural India.
- *Safety*: The UAV must be certified for safety standards in agriculture and UAV operations. It also must have regulatory compliance with GOI (Government of India) guidelines. The following can be noted [2]
    - The drone falls in the *medium* category (weighing total of $25\,kg$ to $150\,kg$).
    - Drone must have GPS, flight data logging, RTH (Return-to-home), anti-collision light, RFID and SIM with NPNT (No Permission No Takeoff) compliant software, and ID plate.
- *Maneuverability*: No agile maneuvers are needed. The drone will be oriented in the horizontal plane virtually always (no pitch and roll, only yaw).

[1] Weather data of Bangalore from `https://www.weatheronline.in` for Jan 2000 to Dec 2021, see wind speed and direction

[2] Main reference from `https://uavcoach.com/drone-laws-in-india/` and `https://digitalsky.dgca.gov.in/home`

1.3 Market Survey

DJI Agras T30

The DJI Agras T30 UAV is a hexacopter (six propellers) suitable for agricultural applications. The main product can be found at `https://www.dji.com/t30`. Its specifications were obtained from here.

- *Operating Velocity*: The maximum operating velocity is $7\,m/s$, comfortably in the $5\,m/s$ bounds.
- *Range*: The maximum range is around $7\,Km$ (calculated for operating at $6\,m/s$ for $20\,min$ which is comfortably in the operating bounds under $10\,Kg$ payload). However, the range of the remote control is $5\,Km$ to $7\,Km$.
- *Endurance*: The maximum endurance of the drone is $20.5\,min$ on a single battery and the drone has provision for two batteries. Therefore, the total endurance it can get without charging is $41\,min$. This fits in our $40\,min$ requirement.
- *Payload*: The maximum payload is $40\,Kg$, which is beyond our requirement of only $10\,Kg$
- *Wind conditions*: It can operate at wind speeds of up to $8\,m/s$ (or $28.8\,Km/hr$). Our requirement is just $10\,Km/hr$.
- *Altitude*: The maximum flight altitude is $4500\,m$. This is well beyond our requirement of $1200\,m$.
- *Safety*: The UAV has RTH (return-to-home) built-in. Regulatory compliance by GOI will require extra software setup, but it possible.

With the above specifications, the UAV almost exceeds our requirements. Choosing it should give very comfortable bounds, thereby allowing for greater needs in the future. However, the price would be around ₹ 700,000. This drone is shown in figure 1a.

FAE 1115 Octa - Predator

The FAE 1115 Octa Predator is an octacopter (eight propellers) suitable for carrying heavy payloads for agricultural applications. The product can be found at fae-drones.com. Its specifications are as follows

- *Operating velocity*: The mentioned maximum speed is $80\,Km/hr \approx 22\,m/s$. This is much more than our required $5\,m/s$.
- *Range*: The range is mentioned as $20\,Km$. This is much more than our desired $5\,Km$.
- *Endurance*: The flight time is mentioned as $40\,min$ which exactly meets our requirements. However, this reduces to $20\,min$ if the payload increases beyond $10\,Kg$.
- *Payload*: The recommended payload is around $5\,Kg$, but the maximum is $10\,Kg$ with reduced flight time.
- *Wind conditions*: The UAV can operate in wind conditions of up to $50\,Km/hr \approx 13.8\,m/s$. This is within our requirement of $10\,Km/hr$.
- *Altitude*: The maximum flight altitude is $3500\,m$ which is more than our required $1200\,m$.
- *Safety*: The UAV has RTH functionality and will require software modifications to make it compliant with GOI norms.

The UAV above fits our requirements by a narrow margin (even cutting it short sometimes). The price would be around ₹ 500,000. This drone is shown in figure 1b.

(a) DJI Agras T30 (b) FAE 1115 Octa - Predator (c) FAE 1115 Octa - Predator

Figure 1: UAVs identified in market survey
Figure a is from `https://www.dji.com/t30`, figure b is from `https://youtu.be/7wkKQ1ad528`, and figure c is from `https://www.dronestark.com/`

DroneStark Octaglide

The DroneStark Octaglide UAV is a versatile dual quadcopter UAV (eight propellers arranged in the quadcopter configuration - also called *X8* configuration). The main product can be found here. Its specifications are as follows [3]

- *Operating Velocity*: The mentioned maximum speed of the drone is $20\,m/s$. This is much more than our required $5\,m/s$
- *Range*: The range is mentioned as $9\,Km$ during testing. This is above our requirement of $5\,Km$.
- *Endurance*: The flight time is mentioned as $24\,min$ with a $60,000\,mAh$ battery. Extra batteries can be added on board, using which this can be increases to match with our requirement of $40\,min$.
- *Payload*: The drone can carry payloads of upto $20\,Kg$. This is much more than our requirement of $10\,Kg$ payload.
- *Wind conditions*: The UAV can operate in wind conditions of $12\,m/s \approx 43.2\,Km/hr$. This is more than our requirement of $10\,Km/hr$.
- *Altitude*: The UAV can operate at altitudes of $5000\,m$ above sea level with a payload of $10\,Kg$ (it is $3500\,m$ with $20\,Kg$ payload). This is more than our requirement of $1200\,m$.
- *Safety*: The drone has BVLOS (Beyond Visual Line of Sight) RTH (return to home) even *without* radio link or communication. It is compliant with all GOI norms out-of-box as it is manufactured in India.

The UAV fits in our requirement bounds (with very little augmentation out of the box). Unfortunately, a price quote could not be found online, but since it does not have any customs attached, it will probably be the cheapest option (as it is *made in India*). This drone is shown in figure 1c.

1.4 Sizing and Layout

The DroneStark drone presented in the market survey (shown in figure 1c) is explored here. Some parts are not actually those that belong to the drone, but an approximate substitute is chosen.

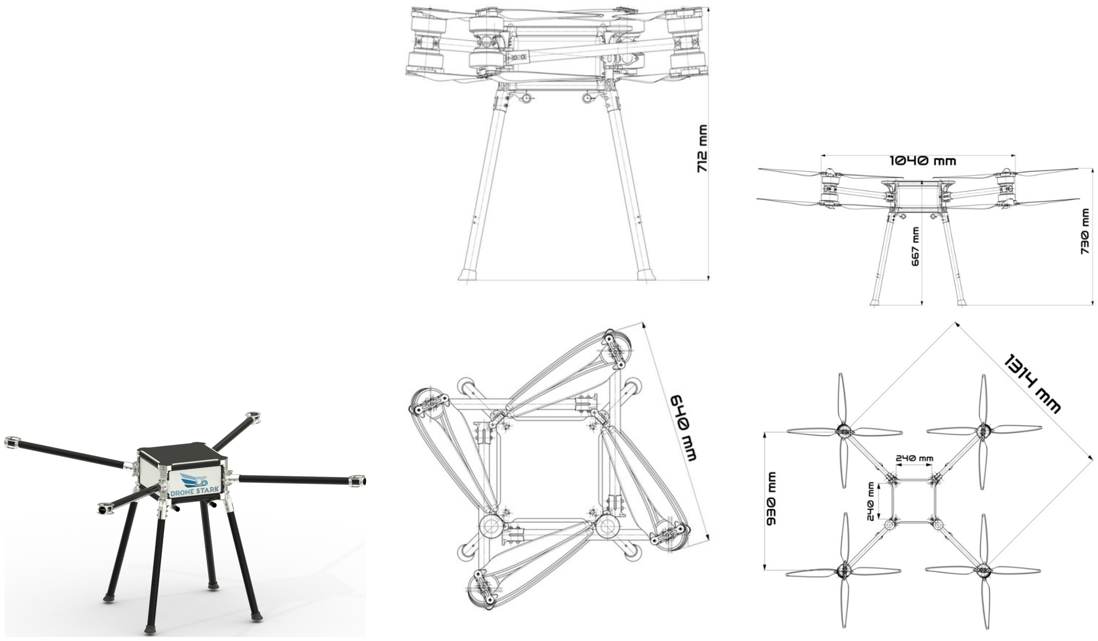
Components

The components that make up the system are described in paragraphs and images below

Body frame The drone needs a body on which everything can rest. This is core mechanical design and has an assembly which can house all components of the drone (described hereon). The frame design of the DroneStark OctaGlide is shown in figure 2a. The body provides a nice $240\,mm$ by $240\,mm$ unit (height of approx. $165\,mm$) where all the electronics and the primary battery is housed.

[3] Obtained from `https://www.dronestark.com/octaglide` and `https://www.dronestark.com/flying-beyond-limits`

Dimensional specifications The drone is foldable, thanks to the body frame allowing it and the propellers themselves folding. The final structure, *when folded* is $712\,mm$ in height, and the length and breadth is $640\,mm$. This makes it easy to transport. When *fully extended* (ready to fly), the drone has $730\,mm$ height, with the total length and breadth being approximately $1688\,mm$. These are box dimensions of the drone. The body frame specifications can be found in figure 2.



(a) Frame (b) Folded (c) Extended

Figure 2: Body and Dimensional Specifications
All figures are from `https://www.dronestark.com/octaglide`. The frame in a is patented by DroneStark.

Propellers and Motors The propellers were identified to have a 30 inch diameter (approximately). They can be assumed to be *foldable* 30×10 propellers made of carbon fiber, shown in figure 3a. The drone motors must be BLDC motors (high speed, power efficient). An approximate model could be something like the YP6215A+ BLDC motor shown in figure 3c. These are selected merely by matching physical dimensions, and are shown in figure 3.

(a) Blades (b) Hub (c) BLDC Motor

Figure 3: Propellers and BLDC Motor
Figure a are of 30×10 propeller blades. They have 30 inch diameter. The figure b shows the hub which connects the two foldable parts of a blade.
Figure c is from crazy-motor. Figures a and b are from indiamart.

1.5 Component Identification

Apart from the hardware components described above (for sizing and layout), the drone has the following components (described in paragraphs).

(a) ESC (b) Battery (c) Controller

Figure 4: ESC, Battery and Controller
Figure a is from hobbywingdirect. Figure b is from MouseWorth on Alibaba. Figure c is from robu.in.

ESC The ESC (Electronic Speed Controller) recommended by the motor manufacturer of the BLDC motor shown in figure 3c is an $80\,A$ HV (high voltage) ESC. A suitable model is `XRotor PRO 80A-HV ESC` shown in figure 4a. Note that we will need eight of these controllers. We can theoretically use four (tap the wiring of the motors in the same branch), but that is not recommended.

Battery The battery capacity listed in the OctaGlide specifications is `32000 mAH / 1420 Watt-Hour`. This is the internal battery. The voltage is $V = {}^{1420\,Wh}/_{32\,Ah} = 44.375\,V \approx 44.4\,V$. A battery with high enough C rating is needed [4]. We can choose the `MoseWorth 44.4V 32000mAh 25C 12S RC LiPo Battery`, as shown in figure 4b. The same battery can be used as an extra battery, mounted externally to extend the range of UAV. The battery size of $215, 134, 130\,mm$ should fit inside the body frame.

Controller We can use the `Holybro Original Pixhawk PX4` Flight Controller. It has a redundant power supply inputs, microSD storage, an abundant power supply, and multiple additional peripherals for controlling IO. The processor is `STM32F76`. This controller is shown in figure 4c.

Additional payloads

The following components are core to agricultural and regulatory compliance. Some sensors are also mentioned here.

Payload: Tank, pump and spray The tank, stored on top of the body, is shown in figure 5a. This tank stores the liquid fertilizer that is to be sprayed on the agricultural field. A pump (also included in figure 5a) pushes the liquid from the tank to the spray nozzle.

GPS and orientation sensors A GPS module is required for mapping (and regulatory compliance). A simple module that can be used is `Ublox NEO-M8N 7M GPS Module`. This is shown in figure 5b. It is a package that contains the NEO-M8 series GNSS module. An IMU (orientation sensors) is required for localizing and control. The `Adafruit 9-DOF IMU` is a good choice with `LSM303DLHC` (3-axis accelerometer and 3-axis magnetometer) and `L3GD20` (3-axis gyroscope) on the same board. This is shown in figure 5c. These sensors have to be connected to the controller shown in figure 4a.

Altimeter The altimeter `Adafruit BMP388 and BMP390` can be used for getting altitude data. This can be found here. A kind of encoder might be needed to connect with the flight controller.

[4]The C Rating gives an estimate of charging and discharging current of a battery $I = C_r \times E_{Ah}$. More here

(a) Payload (b) GPS (c) IMU

Figure 5: Payloads
In a, the component `A` is the storage container for fertilizer. The component `B` is the pump for pumping that liquid fertilizer to the nozzle spray. The component `C` is the spray nozzle which uniformly sprays the fertilizer. Figure a is from dronestark website. Figure b is from Amazon. Figure c is from adafruit.

1.6 Performance Analysis

Propeller selection

We know that the static thrust of a propeller is given by [5]

$$T_h = 0.1606\, n^2 D^{3.5} \sqrt{p_h} \Rightarrow D = \left(\frac{T_h}{0.1606\, n^2 \sqrt{p_h}} \right)^{1/3.5} \tag{1}$$

The hover thrust should *at least* support twice the take-off weight, that is $8T_h = 2mg$ (there are eight propellers). Assuming that the take-off weight is $m = 35\, kg$. This means that $T_h = 85.75\, N$. Assuming that we use the pitch as $p_h = 13\,\text{inches} = 0.3302\, m$. This is to narrow down the propeller selection. Let us assume takeoff at $n = 4000\, RPM = {}^{4000}/_{60}\, RPS$. Substituting all this in equation 1, we get $D = 0.63943\, m = 25.1744\,\text{inches}$. Assuming that we pick from the APC propeller database, we can pick the propeller `APC 27x13 EP` from here and refer the database [6]. So we get $D = 27\,\text{inches} = 0.6858\, m$

Using the propeller mentioned above, the take-off speed (RPM) can be calculated as

$$n = \left(\frac{T_h}{0.1606\, D^{3.5} \sqrt{p_h}} \right)^{1/2} = 58.97995\, RPS = 3538.79\, RPM$$

We select the propeller `APC 27x13 EP`, which will provide lift-off at $3538.79\, RPM$.

Power and Battery

The power needed by the propellers when hovering (that is, $V_a = 0$) is given by

$$P_{out} = \frac{\sqrt{2\, T_h^3}}{\sqrt{\pi \rho D^2}} \tag{2}$$

Assume that $\rho = 1.225\, kg/m^3$. For our case, $P_{out} = 834.69\, W$. To generate this output power, the propellers will have to be given more input power (they're not 100% efficient).

Assuming that the propeller efficiency is 65%, we get $P_{prop\_in} = {}^{P_{out}}/_{\eta_{prop}} = 1284.138\, W$. This is the power the motor will have to output. To generate this output power, the motor will have to be given more input power (they too are not 100% efficient).

[5] Check here for complete formula
[6] The performance data of all APC propellers can be found here

Motor power Assuming that the motor efficiency is 80%, we get $P_{motor\_in} = {}^{P_{prop\_in}}/_{\eta_{motor}} = 1605.172\,W$. This is the power the battery will have to provide (only to the motors for the purpose of hovering).

Assuming that the battery is close to 95% efficient, we get the rated battery power as $P_{bat} = {}^{P_{motor\_in}}/_{\eta_{bat}} = 1689.654\,W$. This is the rated battery power we need. At least a safety margin of 1.2 times should be used (accommodate for other power consuming items on board) when picking a battery.

Battery The battery `44.4V 32000mAh 25C 12S` provides a maximum current [7] of $^{32000}/_{1000} \times 25 = 800\,A$. This means that a power of $44.4 \times 800 = 35.520\,kW$ (maximum peak) can be drawn from the battery. However, at this rate, the battery will last for only $^{(32000/1000)}/_{800} \times 60 = 2.4\,min = 144\,sec$. This is far lesser than our requirement.

Let's see the performance at the current rating. Assuming that we draw $1.2 \times 1689.654 = 2027.585\,W$. We will be drawing a current of $^{2027.585}/_{44.4} = 45.666\,A$. This will last for $^{(32000/1000)}/_{45.666} \times 60 = 42\,min$. This matches our requirement of $45\,min$ exactly (we were generous in assumptions).

Climb performance The climbing thrust can be calculated as follows

$$m\dot{w} + D\text{sign}(w) + n_p T = mg \qquad\qquad D = 0.5 C_D \rho w^2 S \approx 0.1021 w^2$$

Where

- m is the mass, g is the acceleration due to gravity.
- D is the drag force. C_D is the drag coefficient, ρ is the air density, S is the cross sectional area.
- The velocity of the drone is given by $V_B = [u, v, w]^\top$.
- T is the thrust generated by each propeller and n_p is the number of propellers.

$$T_C = \frac{mg - m\dot{w} - D\text{sign}(w)}{n_p} = \frac{mg - m\dot{w} - 0.1021 w^2 \text{sign}(w)}{n_p} \tag{3}$$

Substituting $w = -1\,m/s$ (constant, $\dot{w} = 0$), $m = 35\,kg$, and $n_p = 8$, we get $T_C = 42.8877\,N$

1.7 Maximizing range

The range maximization problem can be converted into an endurance maximization problem by *assuming* that the UAV travels at a constant speed (with same air conditions).

The following assumptions are made

- The propeller is `APC 27x13 EP` (APC performance data here).
- The drone takes off, climbs with a speed of $1\,m/s$, cruises with a speed of $5\,m/s$, and then descents at the speed of $2\,m/s$. These are constants (no acceleration, so $\dot{w} = 0$).
- The take-off mass of the drone is $m = 35\,kg$

Energy requirement

The total energy is given by

$$E_r = P_c t_c + P_{cr} t_{cr} + P_h t_h + P_d t_d$$

Here, P_c, P_{cr}, P_h, and P_d are the power consumed during climb, cruise, hover, and descent phase of the flight (which is the product of thrust and velocity). The time is given by t_*.

[7] Check the C rating for discharge time and maximum current transfer

Climb phase During the climb phase, the power requirement is given as follows

$$T_C = \frac{mg - D\,\mathrm{sign}(w)}{8} = \frac{mg - 0.1021w^2\,\mathrm{sign}(w)}{8} = 42.887\,N$$
$$P_C = T_C\,V_C = 42.887\,W$$

The power during climb phase is $P_C = 42.887\,W$ per propeller.

Cruise phase During the cruise phase, the power requirement is given as follows

$$T = \sum_{i=1}^{n_p} T_i \qquad T\cos(\theta) = mg \qquad T\sin(\theta) = k_d V^2$$
$$\theta = \mathrm{atan}\left(\frac{k_d V^2}{mg}\right) \qquad T = \frac{mg}{\cos(\theta)} = 343.01\,N \qquad P = T\,V = 1715.04\,W$$

The power during the cruise phase is $1715.04\,W$ for all the propellers (T is the sum of all in the above equations).

Descent phase During the descent phase, the power requirement is given as follows

$$T_D = \frac{mg - D\,\mathrm{sign}(w)}{8} = \frac{mg - 0.1021w^2\,\mathrm{sign}(w)}{8} = 42.823\,N$$
$$P_C = T_C\,V_C = 85.6479\,W$$

The power during descent phase is $P_C = 85.6479\,W$ per propeller.

Total power Assuming a $20\,s$ climb, $2400\,s$ cruise, and $10\,s$ descent (flying at a height of $20\,m$ from takeoff). The total power is

$$E_r = 42.887 \times 20 \times 8 + 1715.04 \times 2400 + 85.6479 \times 10 \times 8 = 4129.809\,kJ$$

The drone is expected to consume $4129.809\,kJ$ of energy during its flight. The battery we plan to use is a $32000\,mAh$ battery with $44.4\,V$ voltage. The battery energy is $E_b = 32 \times 3600 \times 44.4 = 5114.880\,kJ$. The battery can comfortably provide for the requirement.

The safety factor is $^{5114.880}/_{4129.809} = 1.23$. Let us put another battery, and add an additional $10\,kg$ to weight. Keeping other things the same, let us calculate the new range, through the endurance which is the cruise time, after this modification.

Modified energy requirements

The weight is now $45\,kg$ (well within the limits of the drone). Rest everything is the same.

Climb phase

$$T_C = \frac{mg - D\,\mathrm{sign}(w)}{8} = \frac{mg - 0.1021w^2\,\mathrm{sign}(w)}{8} = 55.1377\,N$$
$$P_C = T_C\,V_C = 55.1377\,W$$

The climb will require $55.1377\,W$ power per propeller.

Cruise phase

$$\theta = \mathrm{atan}\left(\frac{k_d V^2}{mg}\right) \qquad T = \frac{mg}{\cos(\theta)} = 441.0074\,N \qquad P = T\,V = 2205.0369\,W$$

The cruise phase will require $2205.0369\,W$ power.

Descent phase

$$T_C = \frac{mg - D\,\mathrm{sign}(w)}{8} = \frac{mg - 0.1021w^2\,\mathrm{sign}(w)}{8} = 55.07395\,N$$
$$P_C = T_C\,V_C = 110.1479\,W$$

The climb will require $110.1479\,W$ power per propeller.

Assuming that the battery is 80% efficient, the following can be done to calculate the maximum cruise time allowed

$$0.80 \times 2 \times 32 \times 3600 \times 44.4 = 8 \times 55.1377 \times 20 + 2205.0369\,t_{cr} + 8 \times 110.1479 \times 10 \Rightarrow t_{cr} = 3703.41\,s \approx 61\,min$$

Now that the flight time is $3700\,s$ (approx), the new range (which is maximized) is $d = V_{cr}t_{cr} \approx 18.5\,km$.

Therefore, after one iteration of design change described above, we could maximize the range to $18.5\,km$.

2 Dynamic Thrust Given Propellers

UIUC and APC The UIUC (University of Illinois at Urbana-Champaign) propeller database can be found at [3].
APC is a propeller manufacturer based in California, USA. Propellers are listed here. The APC propellers can be found in UIUC here. All results presented here are summarized in table 1.

Reading Method Say APC 10x4.7 is given. This means a 10-inch diameter propeller with a pitch of 4.7 inch/revolution. The pitch gives an indication of the amount of twist in propeller blades.

Equations The following equations can be found from [1, 2, 4].

$$J = \frac{V}{nD} \qquad C_T = \frac{T}{\rho n^2 D^4} \qquad C_P = \frac{P}{\rho n^3 D^5} \qquad \eta = J\frac{C_T}{C_P} \tag{4}$$

The terms in equation 4 are described below

- J is called the *Advance ratio*.
- V is the *airspeed* (in m/s).
- n is the rotation speed in rev/s. This is also shown as Ω in the plots.
- D is the propeller diameter (in m). This is usually interpreted from the name.
- C_T is the thrust coefficient.
- T is the thrust produced by the propeller (in N).
- ρ is the air density (in kg/m^3).
- C_P is the power coefficient.
- P is the power (in W) which is the product of torque and angular speed. This is the input power.
- η is the efficiency of the propeller in the particular setting. It is same as the ratio of output power $P_{out} = TV$ to input power $P_{in} = P$, that is $\eta = {}^{P_{out}}/_{P_{in}}$.

From equation 4, the thrust of the propeller can be calculated as

$$T = C_T\,\rho n^2 D^4 \tag{5}$$

2.1 APC 8×6

The propeller diameter D is 8 inches ($0.2032\,m$) and the pitch is 6 inches per revolution. Assuming the density of air as $1.29\,Kg/m^3$. Assuming the fight speed to be the air speed, that is $V = 10\,m/s$.

4000 RPM

Here, n is $4000\,RPM$ (or ${}^{200}/_{3}\,rev/s$). First, to calculate J, we know V, D, and n.

$$J = \frac{V}{nD} = \frac{10\,m/s}{{}^{200}/_{3}\,rev/s\;0.2032\,m} = \frac{375}{508} = 0.7381$$

The value of C_T can be found from here (data here). Getting data from line $J = 0.726$. We get $C_T = 0.0496$.

By substituting all this in equation 5, we get the following

$$T = C_T\,\rho n^2 D^4 = 0.0496 \times 1.29 \times ({}^{200}/_{3})^2 \times (0.2032)^4 \approx 0.48482\,N$$

At $4000\,RPM$, the dynamic thrust is $0.48482\,N$.

5000 RPM

Here, n is 5000 RPM (or $^{250}/_{3}\, rev/s$). Substituting in J, we get

$$J = \frac{V}{nD} = \frac{10\, m/s}{^{250}/_{3}\, rev/s\ 0.2032\, m} = \frac{75}{127} = 0.59055$$

The value of C_T can be found from here (data here). Getting data from line $J = 0.609$. We get $C_T = 0.0723$. Substituting all this in equation 5, we get the following

$$T = C_T\, \rho n^2 D^4 = 0.0723 \times 1.29 \times (^{250}/_{3})^2 \times (0.2032)^4 \approx 1.10423\, N$$

At 5000 RPM, the dynamic thrust is 1.10423 N.

6000 RPM

Here, n is 6000 RPM (or 100 rev/s). Substituting in J, we get

$$J = \frac{V}{nD} = \frac{10\, m/s}{100\, rev/s\ 0.2032\, m} = \frac{125}{254} = 0.492125$$

The value of C_T can be found from here (data here). Getting data from line $J = 0.507$. We get $C_T = 0.0970$. Substituting all this in equation 5, we get the following

$$T = C_T\, \rho n^2 D^4 = 0.0970 \times 1.29 \times (100)^2 \times (0.2032)^4 \approx 2.133321\, N$$

At 6000 RPM, the dynamic thrust is 2.133321 N.

2.2 APC 9×6

The propeller diameter D is 9 inches (0.2286 m) and the pitch is 6 inches per revolution. Assuming the density of air as 1.29 Kg/m^3. Assuming the fight speed to be the air speed, that is $V = 10\, m/s$.

4000 RPM

Here, n is 4000 RPM (or $^{200}/_{3}\, rev/s$). Substituting in J, we get

$$J = \frac{V}{nD} = \frac{10\, m/s}{^{200}/_{3}\, rev/s\ 0.2286\, m} = \frac{250}{381} = 0.65616$$

The value of C_T can be found from here (data here). Getting data from line $J = 0.648$. We get $C_T = 0.0515$. Substituting all this in equation 5, we get the following

$$T = C_T\, \rho n^2 D^4 = 0.0515 \times 1.29 \times (^{200}/_{3})^2 \times (0.2286)^4 \approx 0.80634\, N$$

At 4000 RPM, the dynamic thrust is 0.80634 N.

5000 RPM

Here, n is 5000 RPM (or $^{250}/_{3}\, rev/s$). Substituting in J, we get

$$J = \frac{V}{nD} = \frac{10\, m/s}{^{250}/_{3}\, rev/s\ 0.2286\, m} = \frac{200}{381} = 0.524934$$

The value of C_T can be found from here (data here). Getting data from line $J = 0.541$. We get $C_T = 0.0773$. Substituting all this in equation 5, we get the following

$$T = C_T\, \rho n^2 D^4 = 0.0773 \times 1.29 \times (^{250}/_{3})^2 \times (0.2286)^4 \approx 1.89108\, N$$

At 5000 RPM, the dynamic thrust is 1.89108 N.

6000 RPM

Here, n is $6000\,RPM$ (or $100\,rev/s$). Substituting in J, we get

$$J = \frac{V}{nD} = \frac{10\,m/s}{100\,rev/s\;0.2286\,m} = \frac{500}{1143} = 0.437445$$

The value of C_T can be found from here (data here). Getting data from line $J = 0.430$. We get $C_T = 0.1039$. Substituting all this in equation 5, we get the following

$$T = C_T\,\rho n^2 D^4 = 0.1039 \times 1.29 \times (100)^2 \times (0.2286)^4 \approx 3.66024\,N$$

At $6000\,RPM$, the dynamic thrust is $3.66024\,N$.

2.3 APC 10×7

The propeller diameter D is 10 inches ($0.254\,m$) and the pitch is 7 inches per revolution. Assuming the density of air as $1.29\,Kg/m^3$. Assuming the fight speed to be the air speed, that is $V = 10\,m/s$.

4000 RPM

Here, n is $4000\,RPM$ (or $^{200}/_{3}\,rev/s$). Substituting in J, we get

$$J = \frac{V}{nD} = \frac{10\,m/s}{^{200}/_{3}\,rev/s\;0.254\,m} = \frac{75}{127} = 0.59055$$

The value of C_T can be found from here (data here). Getting data from line $J = 0.606$. We get $C_T = 0.0582$. Substituting all this in equation 5, we get the following

$$T = C_T\,\rho n^2 D^4 = 0.0582 \times 1.29 \times (^{200}/_{3})^2 \times (0.254)^4 \approx 1.38888\,N$$

At $4000\,RPM$, the dynamic thrust is $1.38888\,N$.

5000 RPM

Here, n is $5000\,RPM$ (or $^{250}/_{3}\,rev/s$). Substituting in J, we get

$$J = \frac{V}{nD} = \frac{10\,m/s}{^{250}/_{3}\,rev/s\;0.254\,m} = \frac{60}{127} = 0.47244$$

The value of C_T can be found from here (data here). Getting data from line $J = 0.482$. We get $C_T = 0.0872$. Substituting all this in equation 5, we get the following

$$T = C_T\,\rho n^2 D^4 = 0.0872 \times 1.29 \times (^{250}/_{3})^2 \times (0.254)^4 \approx 3.25146\,N$$

At $5000\,RPM$, the dynamic thrust is $3.25146\,N$.

6000 RPM

Here, n is $6000\,RPM$ (or $100\,rev/s$). Substituting in J, we get

$$J = \frac{V}{nD} = \frac{10\,m/s}{100\,rev/s\;0.254\,m} = \frac{50}{127} = 0.39370$$

The value of C_T can be found from here (data here). Getting data from line $J = 0.382$. We get $C_T = 0.1138$. Substituting all this in equation 5, we get the following

$$T = C_T\,\rho n^2 D^4 = 0.1138 \times 1.29 \times (100)^2 \times (0.254)^4 \approx 6.11036\,N$$

At $6000\,RPM$, the dynamic thrust is $6.11036\,N$.

RPM / Model	4000	5000	6000
APC 8×6	0.48482 N	1.10423 N	2.133321 N
APC 9×6	0.80634 N	1.89108 N	3.66024 N
APC 10×7	1.38888 N	3.25146 N	6.11036 N

Table 1: Table of thrust values for different propellers
Dynamic thrust of different APC propellers with $10\,m/s$ flight speed.

References

[1] John Brandt and Michael Selig. "Propeller performance data at low reynolds numbers". In: *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition.* 2011, p. 1255.

[2] Guillaume. *APC propeller data - what's new?* `http://aerotrash.over-blog.com/2015/01/apc-propeller-data-what-s-new.html`. Accessed: 2021-02-16. 2015.

[3] J.B. Brandt et al. *UIUC Propeller Database, Vols 1-3.* `https://m-selig.ae.illinois.edu/props/propDB.html`. Accessed: 2021-02-14.

[4] John B. Brandt et al. *UIUC Propeller Data Site.* `https://m-selig.ae.illinois.edu/props/propDB.html`. Accessed: 2021-02-16.