Elective in Robotics

Ingenuity dynamic model

(co-axial rotor helicopter)

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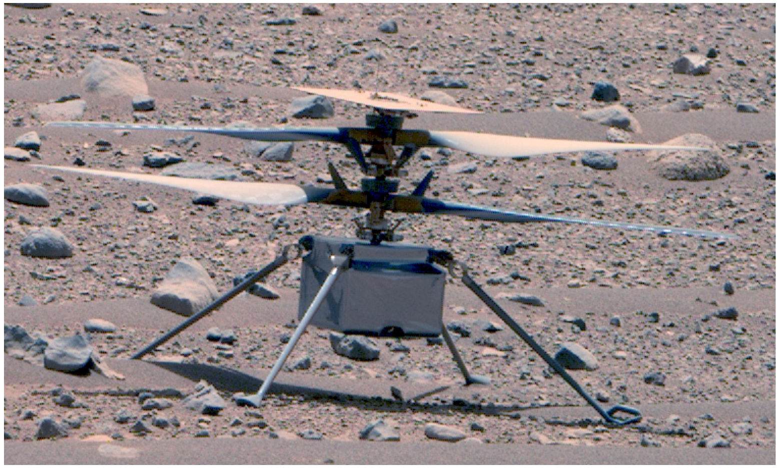
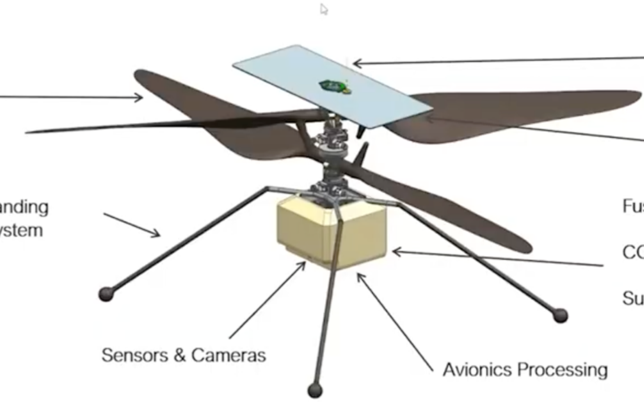
Ingenuity



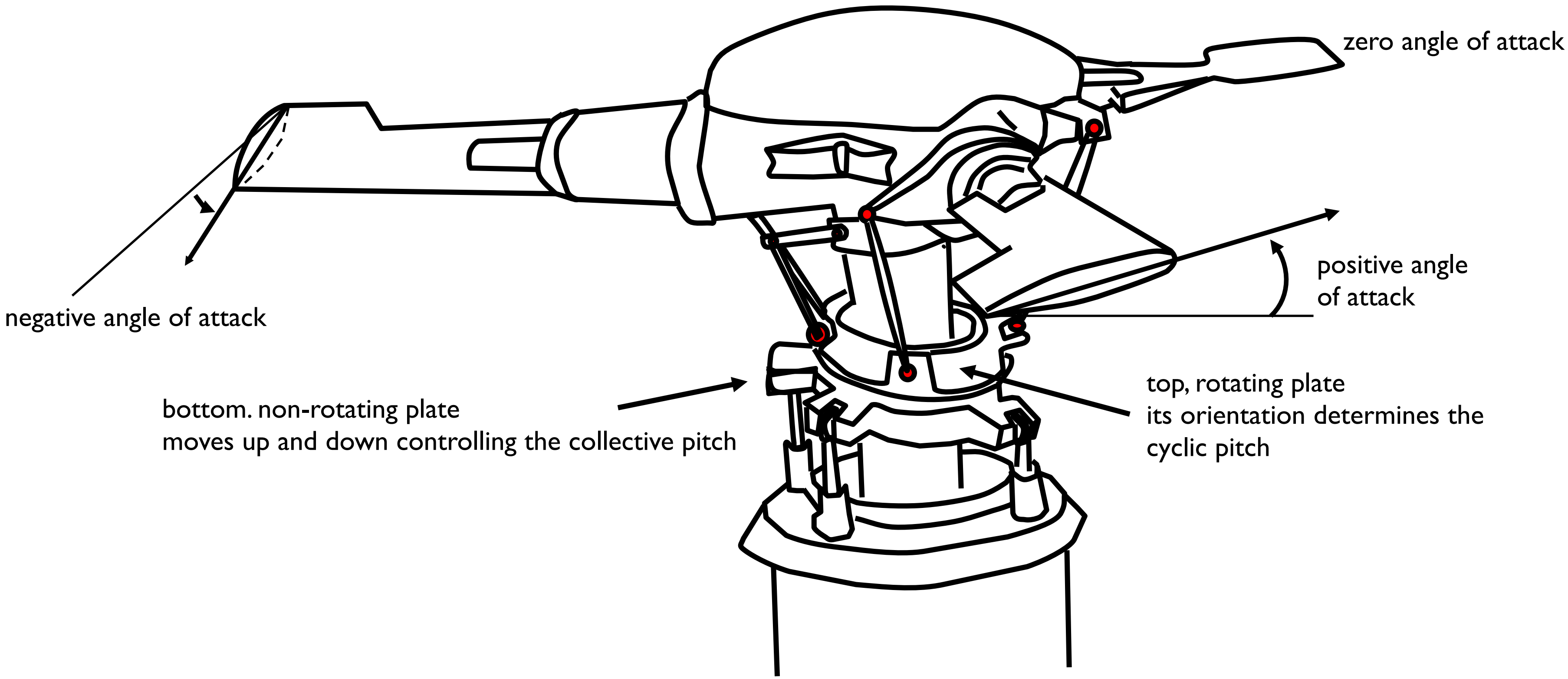
Ingenuity on Mars, April 16 2023



https://youtu.be/ctExpTT0sto?si=mlGGe4_Sf5VCuBbA

- NASA mission Mars 2020 brought the rover Perseverance and the drone Ingenuity on Mars, 65 flights corresponding to 118.4 min, 14.9 Km covered, max altitude 24 m
- Ingenuity is a drone with coaxial rotors and two swashplates
    - it weights 1.8 Kg, the blades span is 1.2 m tip-to-tip
    - efficient thrust generation necessary in an atmosphere with density equal to 1% of the terrestrial with gravity acceleration equal to 3,69 m/sec^2 → high rotor speed is necessary
    - solar panel for energy harvesting, flight autonomy of about 90 min

swashplate mechanism



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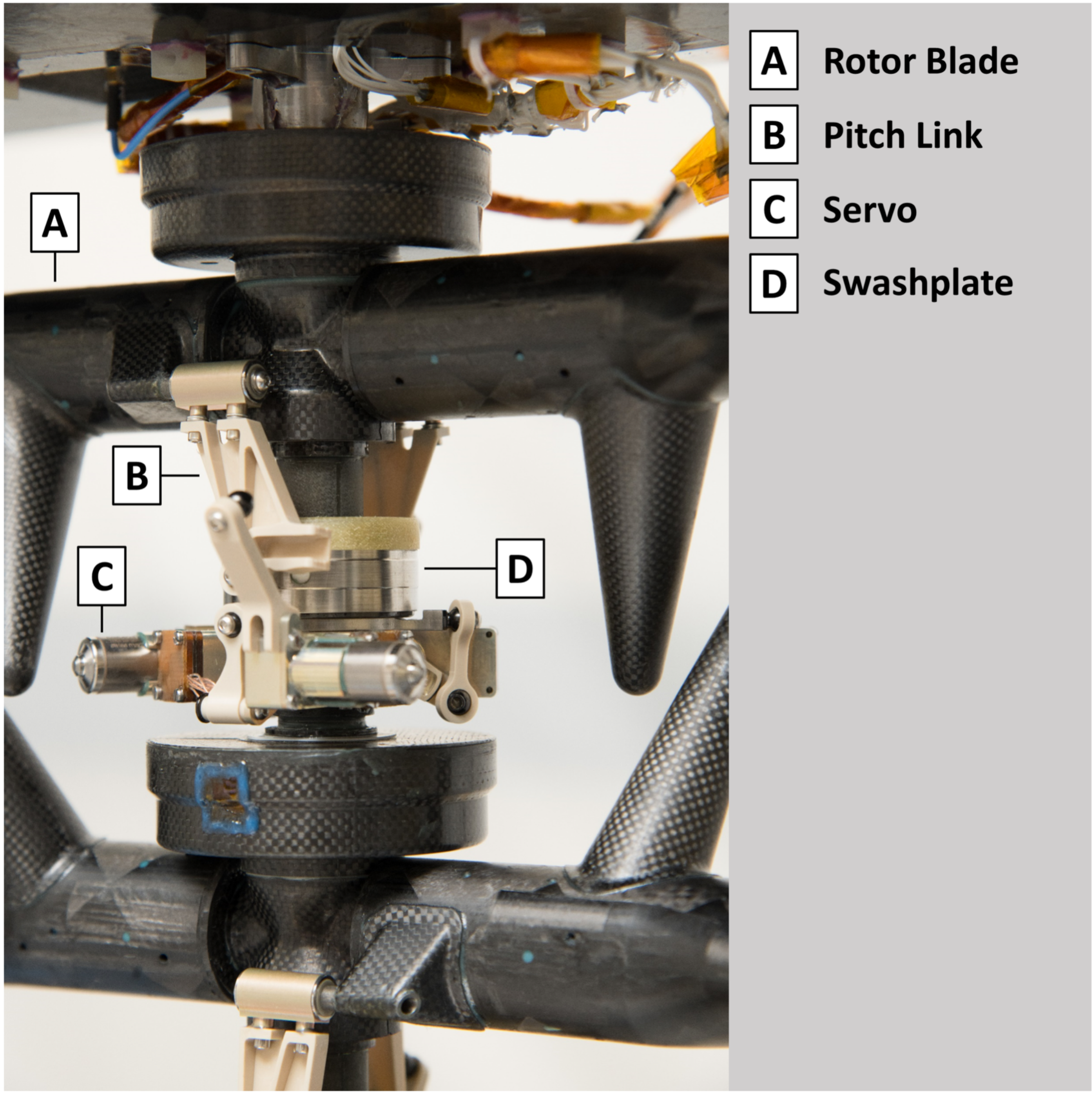
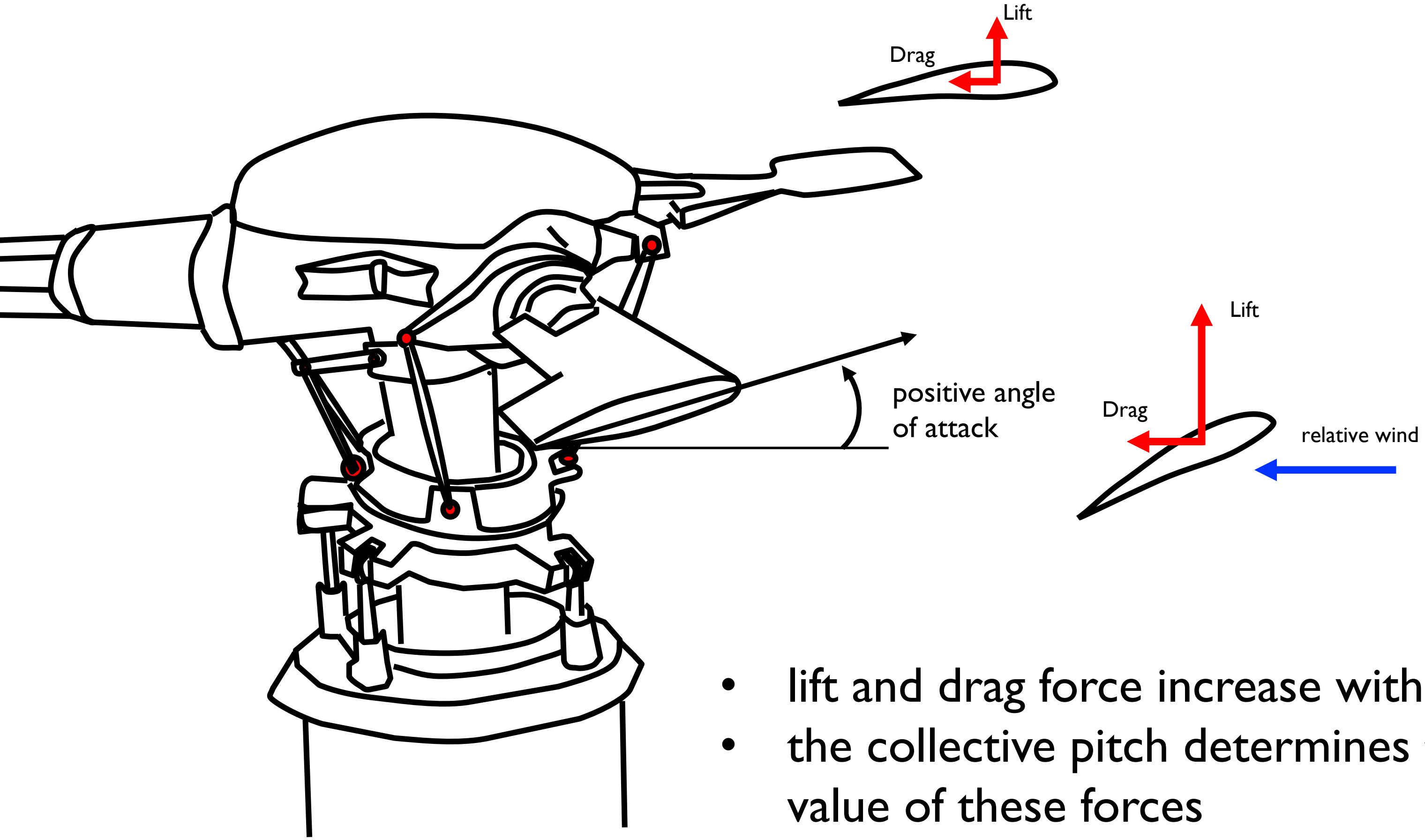
Ingenuity swashplate mechanism



Lift generation



- lift and drag force increase with pitch
- the collective pitch determines the average value of these forces
- the cyclic pitch produces different values on the rotor surface

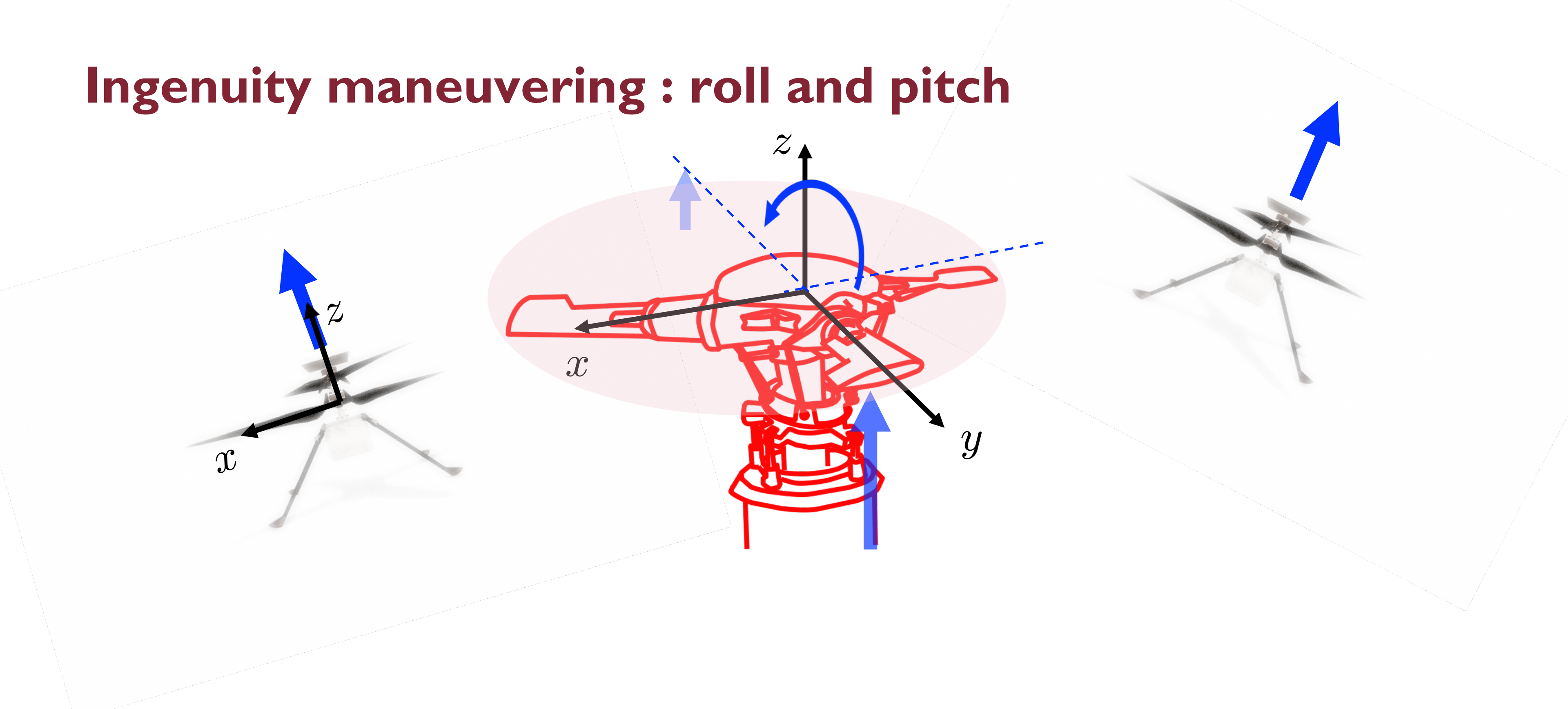
Ingenuity maneuvering: take off and landing

take off

landing

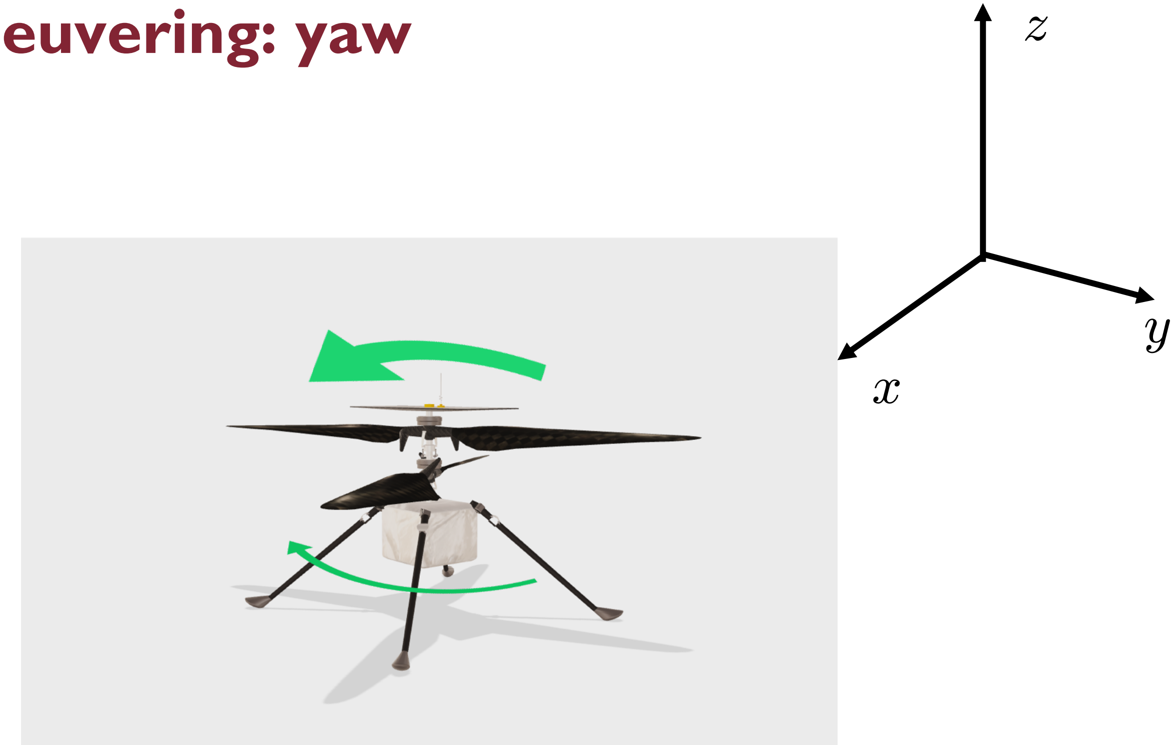
- vertical acceleration is controlled through the rotation velocity and the attack angle of the blades (collective pitch)

Ingenuity maneuvering : roll and pitch



- as for quadrotors roll and pitch motions are generated in an analogous way
- in the example above
  - the cyclic pitch commanded through the swashplate mechanism produces a torque in the direction of x
  - due to gyroscopic precession a torque applied in the direction of x generates a variation of the angular momentum of the rotor in the direction of y, thus generating motion along x

Ingenuity maneuvering: yaw



- the yaw motion is obtained by commanding different collective motion to the two rotors, thus varying the individual reaction torque
- the difference in the reaction torques generates the yaw motion
- in the picture: the arrows illustrate the reaction torques of the upper and lower rotor that would result in a positive yaw motion acceleration

equations of motion

$$
\begin{aligned}
\dot{P} &= RV^b \\
m\dot{V}^b &= F^b_{tot} + R^T F^i_e - \omega \times mV^b \\
I\dot{\omega} &= -\omega \times I\omega + \tau^b_{tot} + R^T \tau^i_e
\end{aligned}
$$

external unknown forces and torques

P: position of the drone's com in the inertial frame
V: position of the drone's com in the inertial frame
R: rotation matrix from inertial to body frame

$$
\begin{aligned}
F^b_{tot} &= F^b_{ac} + R^T F^i_g + F^b_l + F^b_u \\
\tau^b_{tot} &= \tau^b_{ac} + \tau^b_r + \tau^b_l + \tau^b_u
\end{aligned}
$$

total force include actuation coupling, gravity, thrust

total torque include actuation coupling, resistance, thrust-induced

see Chapter 1 of [1] for details on actuation coupling

equations of motion: relevant external forces and torques

$$F_g^i = \begin{pmatrix} 0 \\ 0 \\ 6.642N \end{pmatrix} \qquad F_L = k_L \omega_{rot}^2 \qquad F_D = k_D \omega_{rot}^2$$

l/u: lower/upper rotor
L/D: Lift/Drag force
k_L, K_D: lift and drag coefficient varying with the angle of attack of the blades, include also other constants

$$|F_{m_{l/u}}| = (k_L - k_D)\omega_{rot_{l/u}}^2$$

net thrust determined by the velocity of the rotors and the blades pitch

$$F_{l/u}^b = T(\alpha, \beta)|F_{m_{l/u}}|$$

the direction $T(\alpha, \beta)$ of the thrust vector is controlled through the swashplate

$$\tau_l = d_{cm,l} \times F_l^b \qquad \tau_u = d_{cm,u} \times F_u^b$$

$d_{cm,l/u}$: distance from the com to the lower/upper rotor

$$\tau_r^b = \begin{pmatrix} 0 & 0 & \tau_{r_l} - \tau_{r_u} \end{pmatrix}^T$$

reaction torque: the imbalance in the aerodynamic reaction of upper and lower rotor accelerates the yaw motion

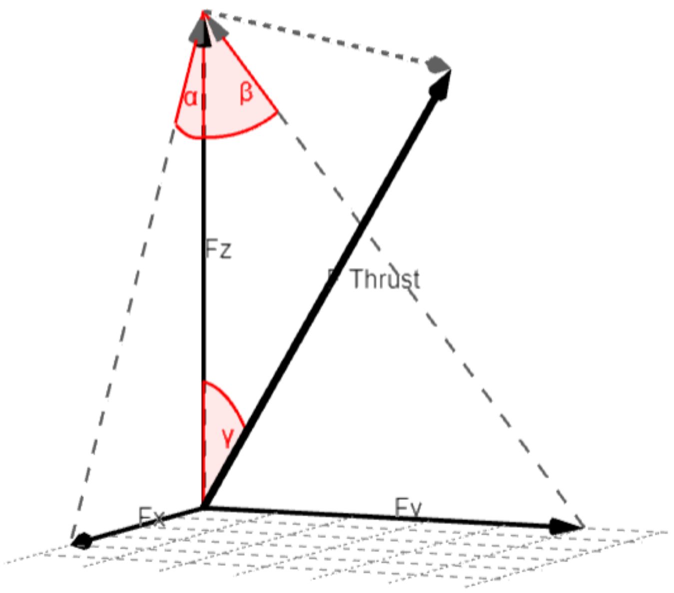
rotor thrust

- thrust direction is determined by the blades inclination which is determined by the cyclic motion controlled through the swashplates

$$F^b_{l/u} = T(\alpha, \beta)|F_{m_{l/u}}|$$

$$T_{(\alpha,\beta)} = \begin{pmatrix} -\tan(\alpha)\cos(\gamma) \\ \tan(\beta)\cos(\gamma) \\ -\cos(\gamma) \end{pmatrix}$$

$$\tan^2(\gamma) = \tan^2(\alpha) + \tan^2(\beta)$$



bibliography

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