Autonomous Mobile Robot Design

Topic: Propulsion Systems for Robotics

Dr. Kostas Alexis (CSE)

Propulsion Systems for Robotics

How do I move?

Understanding propulsion systems is about knowing how a mobile robot can actuate it, how it generates the required forces for its motion.

Propulsion Systems for Robotics

- Different propulsion systems designs are employed for different robotic configurations.
- Miniaturization of propulsion systems –in combination with good efficiency– is among the reasons for the success of small robotics.
- Within this course we will focus on:
  - DC Motors
  - DC Brushless Motors
  - Propelled-systems
  - Wheeled-systems

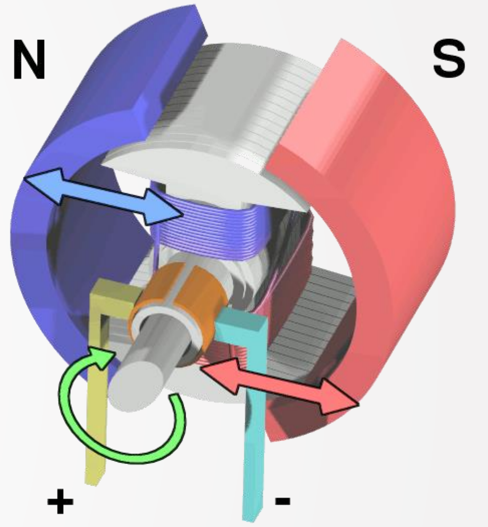
Our focus

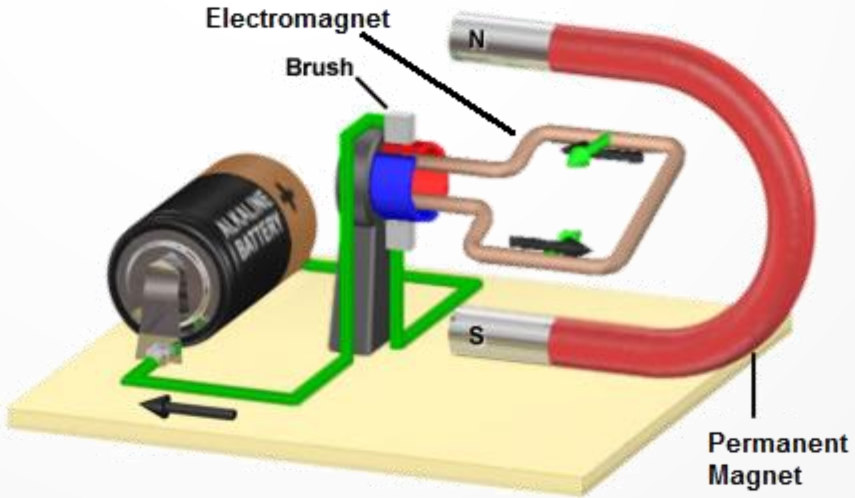
Design of Propelled Aerial Robots and Wheeled Ground Robots

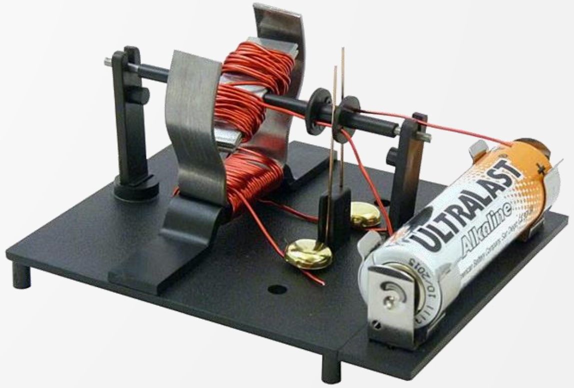
Many other interesting robot configurations also exist!

DC Motors

- Stationary permanent magnet
- Electromagnet on axis induces torque
- Split ring + brushes switch direction of current
- If you have never built one – do so!

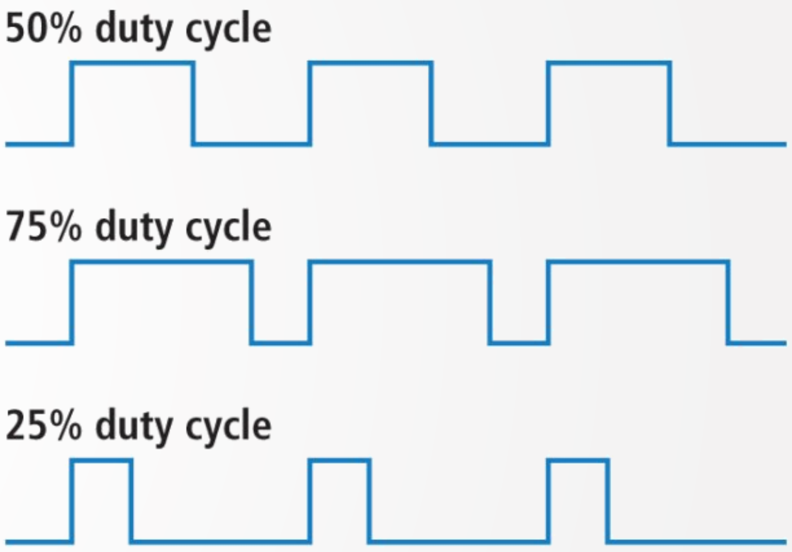






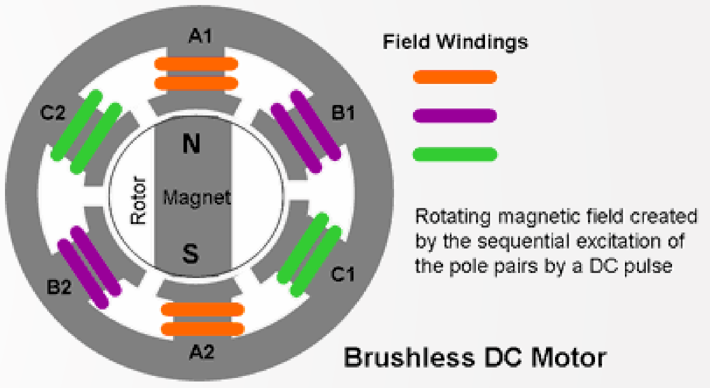
Control of DC Motors

- More power means faster rotation
- How to modulate power using a digital signal? What is the digital equivalent function to directly control power at the input?
  - Fixed voltage with pulse modulation – specifically:
- Pulse Width Modulation (PWM)
- Duty cycle is the proportion of “ON” time vs. period



Brushless Motors

- Electromagnets are stationary
- Permanent magnets on the axis (either inside or outside)
- Three coils (or more)
- No brushes (less maintenance, higher efficiency)
- Brushless motors come with high torque, mostly eliminating the need for gearboxes in case of multirotor aerial robots therefore maximizing endurance

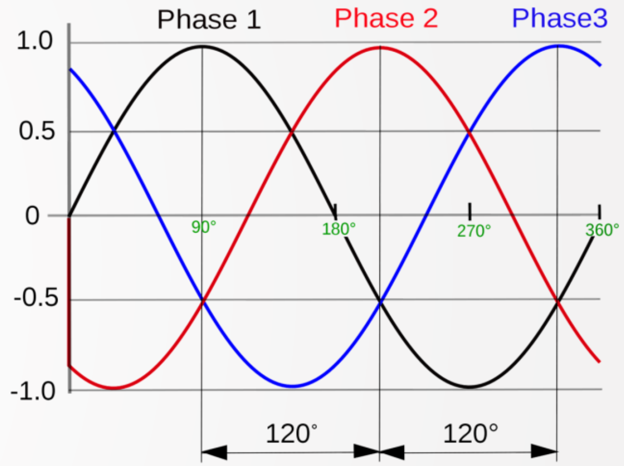


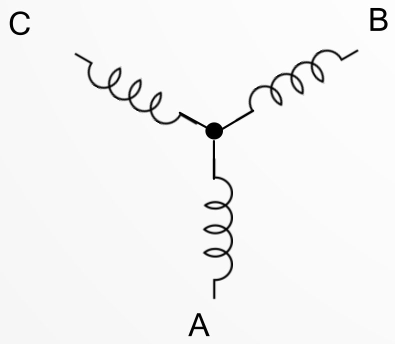
www.mpoweruk.com

https://www.hobbyking.com/hobbyking/store/__25556__AX_2810Q_750KV_Brushless_Quadcopter_Motor.html

Brushless Electronic Speed Controllers

- Typically one microcontroller per motor
  - Called Electronic Speed Controller (ESC)
- Generates PWM signal for the three motor phases
- AC signal converter (MOSFET) to convert PWM to analogue output
- Measure motor position/speed using back-EMF

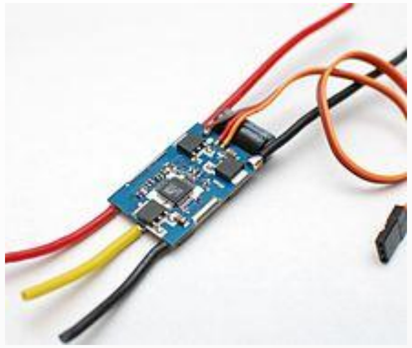




A-B

B-C

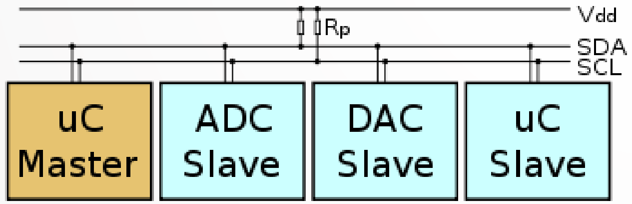
C-A



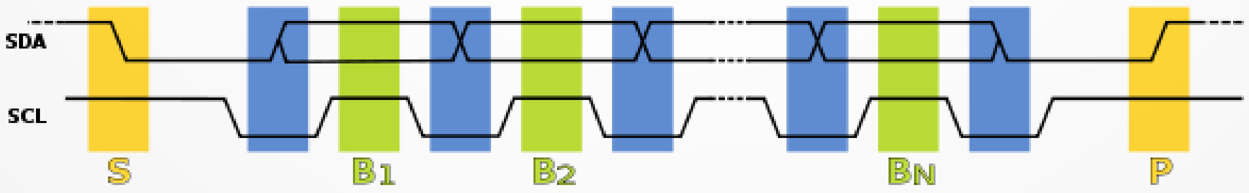
http://en.wikipedia.org/wiki/File:ESC_35A.jpg

I2C Protocol

- Often digital protocol to command the ESC
- Serial data line (SDA) + serial clock line (SCL)
- All devices connected in parallel
- 7-10 bit address, 100-3400 kbit/s speed
- Communication between motor controller and autopilot



http://en.wikipedia.org/wiki/File:I2C.svg

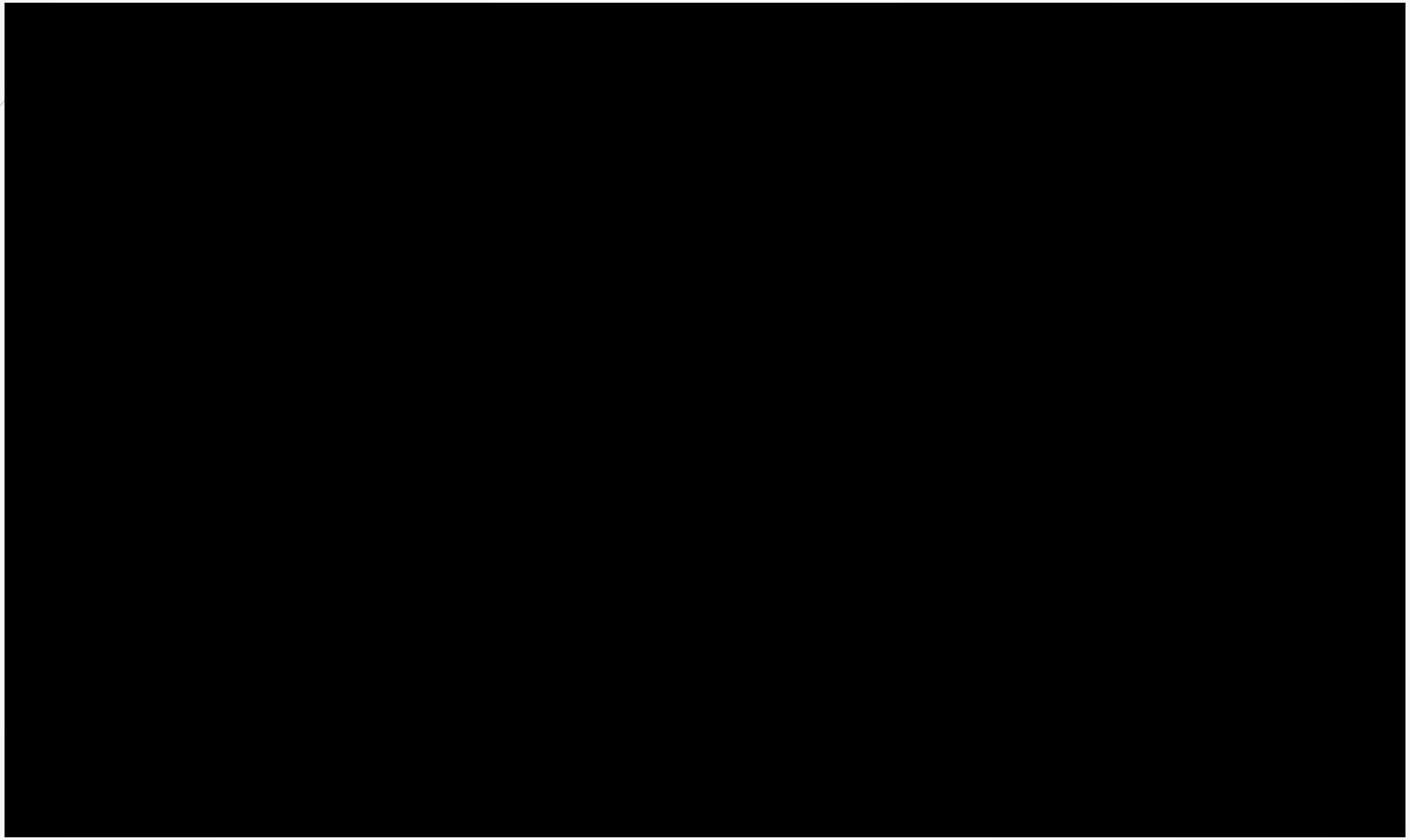


http://en.wikipedia.org/wiki/File:I2C_data_transfer.svg

The Micro Aerial Vehicle propeller

- **Is something much simpler than a helicopter rotor**

The Micro Aerial Vehicle propeller



- Video of airflow and vortex patterns with propellers. These tests were conducted at NACA, now NASA Langley Research Center. The interior tests were probably at the Propeller Research Tunnel. The exterior tests at the end of the film were at the Helicopter Test Tower. Langley Film #L-118

The Micro Aerial Vehicle propeller

- Rotor modeling is a very complicated process.
- **A Rotor is different than a propeller.** It is not-rigid and contains degrees of freedom. Among them blade flapping allows the control of the rotor tip path plane and therefore control the helicopter.

- Used to produce thrust.
- Propeller plane perpendicular to shaft.
- Rigid blade. No flapping.
- Fixed blade pitch angle or collective changes only.

- Used to produce lift and directional control.
- Elastic element between blade and shaft.
- Blade flapping used to change tip path plane.
- Blade pitch angle controlled by swashplate.

The Micro Aerial Vehicle propeller

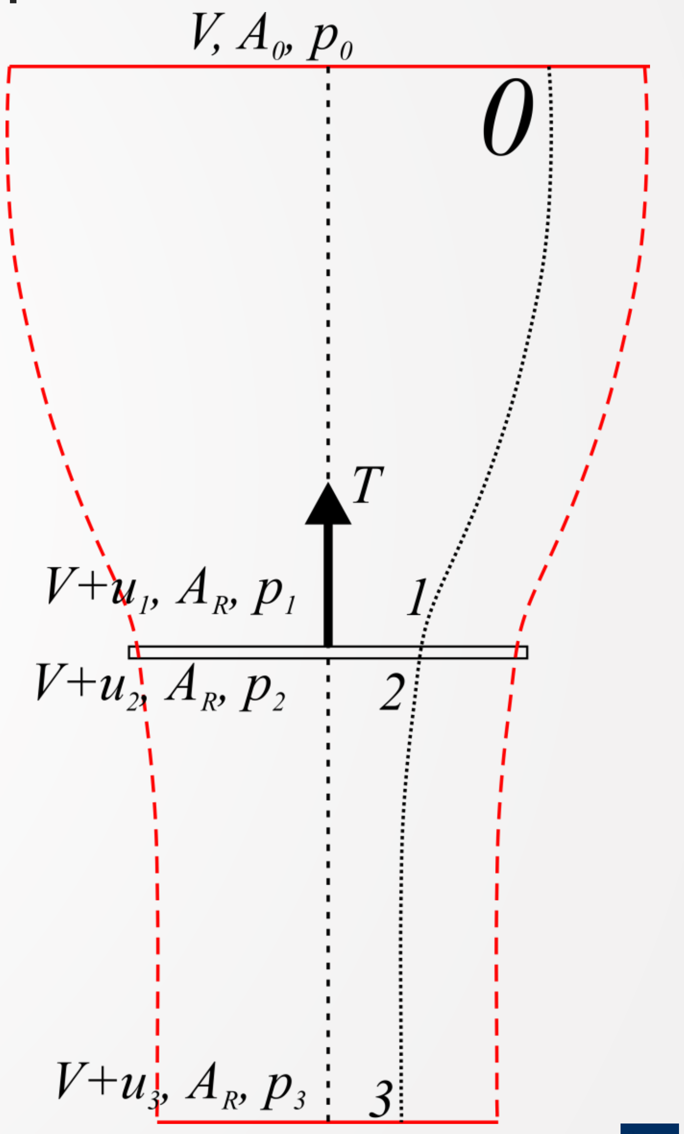
- In a simplified assumption, a propeller is considered to present no blade flapping.
- It is approximated as a rotor disc producing thrust and drag forces.
- Thrust & Power Equations

$$F_{Thrust} = \frac{1}{2}\rho A v^2$$

$$P = \frac{1}{2}A v^2$$

- Hover case (ideal power):

$$P = \frac{F_{Thrust}^{3/2}}{\sqrt{2\rho A_R}} = \frac{(mg)^{3/2}}{\sqrt{2\rho A_R}}$$



The Micro Aerial Vehicle propeller

- Thrust & Power Equations

$$F_{Thrust} = \frac{1}{2}\rho A v^2$$

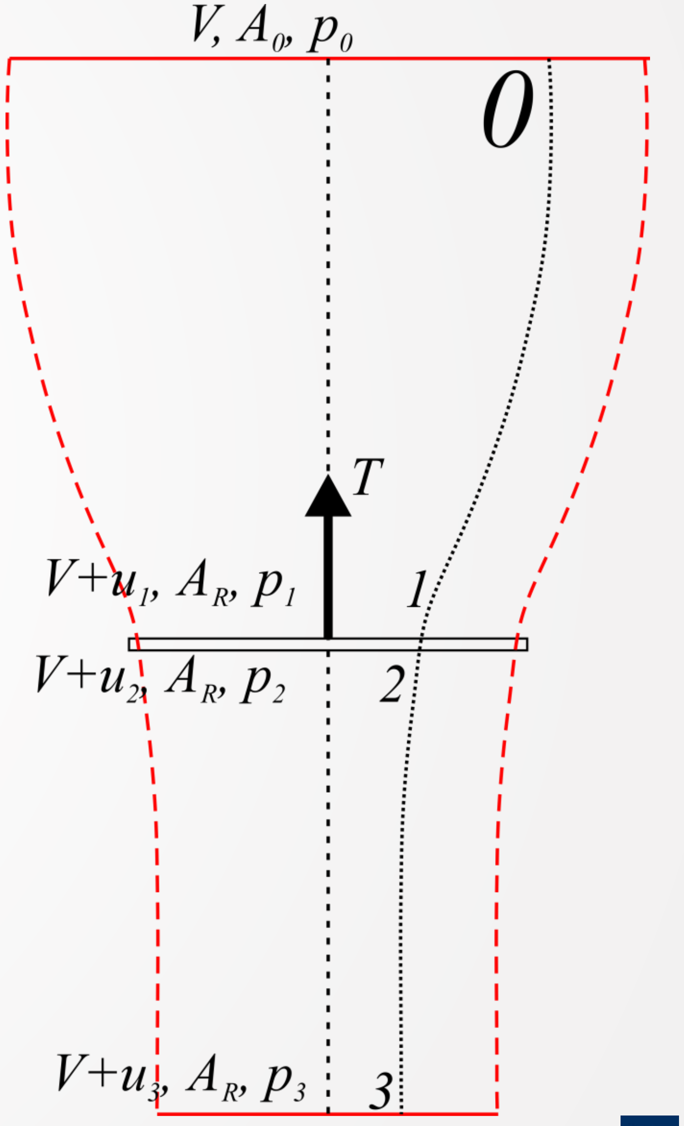
$$P = \frac{1}{2}A v^2$$

- Hover case (ideal power):

$$P = \frac{F_{Thrust}^{3/2}}{\sqrt{2\rho A_R}} = \frac{(mg)^{3/2}}{\sqrt{2\rho A_R}}$$

- Figure of Merit:

$$FM = \frac{Ideal\ Power\ to\ Hover}{Real\ Power\ to\ Hover}$$



The Micro Aerial Vehicle propeller

- Lift & Drag at Blade Element:

$$dL = \frac{\rho}{2} C_L c dr V^2 \qquad dD = \frac{\rho}{2} C_L c dr V^2$$

$$dT = N_b (dL \cos\phi - dD \sin\phi)$$

$$dQ = N_b (dL \sin\phi - dD \cos\phi) r$$

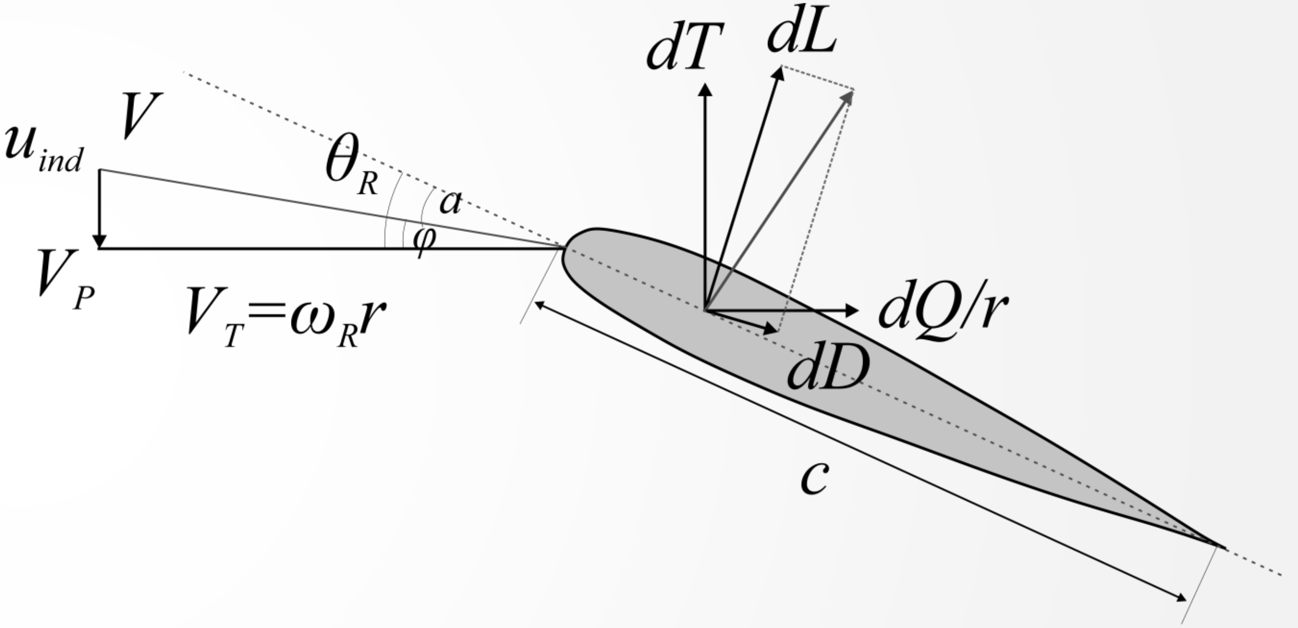
$$V \approx V_T \qquad \phi \approx \frac{V_P'}{V_T}$$

$$dT \approx N_b dL$$

$$C_L = C_{L\alpha}(\alpha - \alpha_0)$$

$$C_{L\alpha} = 2\pi$$

$$C_{L\alpha} = 5.7$$



- A0: zero lift angle of attack.
- Linearize polar for Reynolds number at 2/3 R

$$dT_{be} = N_b \frac{\rho}{2} C_{L\alpha} \left(\theta_R - \frac{V_P'}{V_T} - \alpha_0\right) c dr V_T^2$$

The Micro Aerial Vehicle propeller

- Simplified model forces and moments:
  - **Thrust Force:** the resultant of the vertical forces acting on all the blade elements.

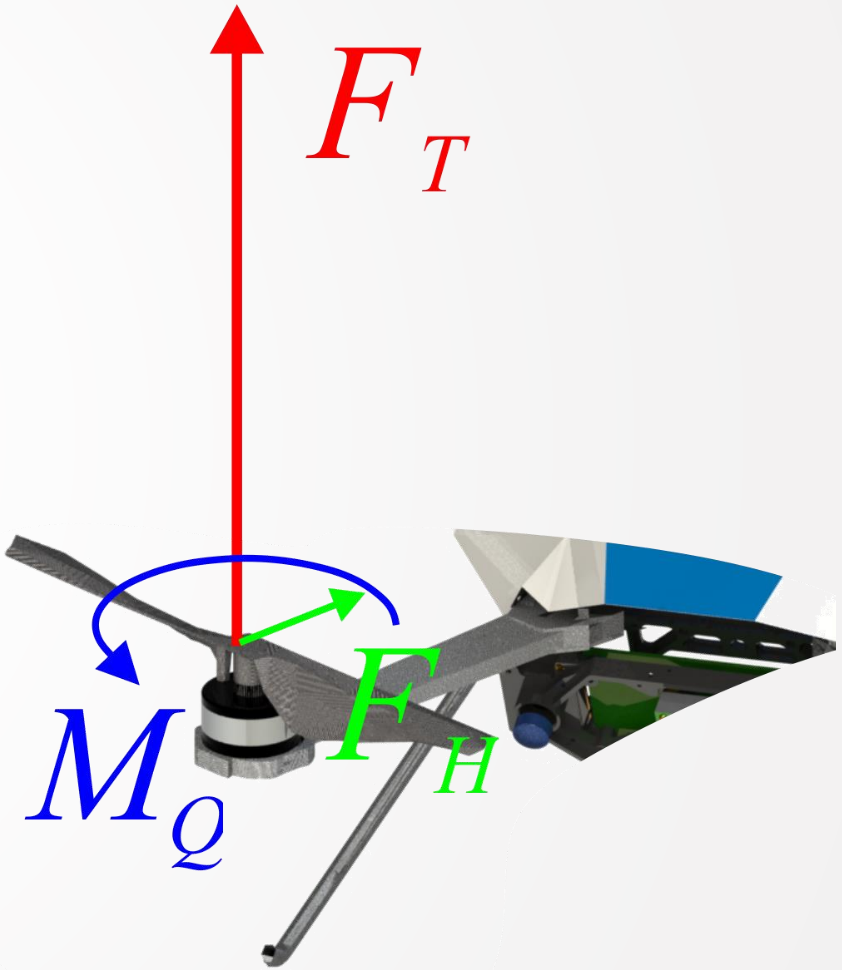
$$F_T = T = C_T \rho A (\Omega R)^2$$

  - **Hub Force:** the resultant of all the horizontal forces acting on all the blade elements.

$$F_H = H = C_H \rho A (\Omega R)^2$$

  - **Drag Moment:** This moment about the rotor shaft is caused by the aerodynamic forces acting on the blade elements. The horizontal forces acting on the rotor are multiplied by the moment arm and integrated over the rotor. Drag moment determines the power required to spin the rotor.

$$M_Q = Q = C_Q \rho A (\Omega R)^2 R$$



The wheel of a small ground robot

- **Circular Motion – Rotational Formulas**
  - Angular Velocity

    $$\omega = \theta / t \qquad v = \omega r$$

  - Angular Velocity and Acceleration

    $$\omega = \omega_0 + at$$

  - Angular Displacement

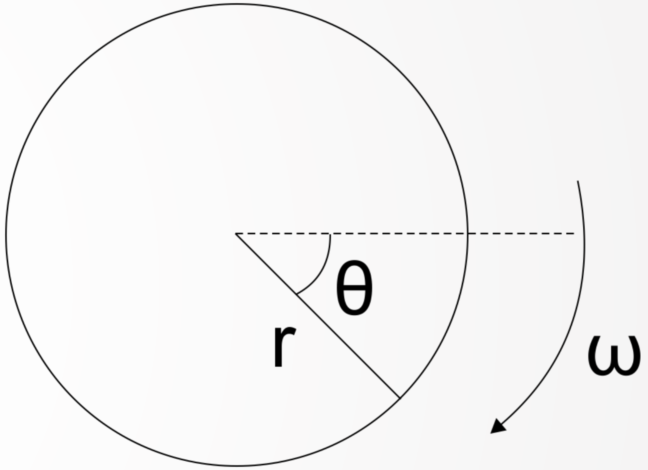
    $$\theta = \omega_0 t + \frac{1}{2} a t^2$$

  - Angular Acceleration

    $$a = \frac{d^2\theta}{dt} = \frac{d\omega}{dt}$$

  - Angular Momentum or Torque

    $$T = aJ_w$$



- ω = angular velocity
- θ = angular position
- r = radius of the wheel
- a = angular acceleration
- J_w = moment inertia
- T = angular momentum

Code Example

- MATLAB DC Motor Control Example
  - https://github.com/unr-arl/autonomous_mobile_robot_design_course/tree/master/matlab/propulsion-systems/motor-control
  - MATLAB 2016 Live note

Code Example

- Indicative in-class run

How does this apply to my project?

- DC Brushless Motors with Electronic Speed Controllers are used for the actuation of the multirotor UAVs, the fixed-wing UAV and the remote-controlled boat of the course projects.
- DC brushed motors are used for the actuation of the ground robot of the course projects.
- What do I have to do about it?
  - Not much. The on-board autopilot you are integrating is handling such basic functionalities.

Thank you!

Please ask your question!