Adaptive and Autonomous Aerospace Systems

School of Industrial and Information Engineering - Aeronautical Engineering

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Part 2: Adaptive Control

Lab experience on adaptive control

POLITECNICO
MILANO 1863

ASCL
AEROSPACE SYSTEMS & CONTROL LABORATORY

Fundamental system and control research

DIPARTIMENTO DI SCIENZE E TECNOLOGIE AEROSPAZIALI

ASCL
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Applied aerospace systems and control research:

Guidance, navigation and control (GNC) for aircraft/spacecraft

Experimental activities:

UAV design, prototyping and integration

Research topics

Fundamental system and control research

- Model identification
- Data-driven controller design
- Nonlinear attitude determination
- Nonlinear and geometric control for multibody systems
- Anti-windup design
- Adaptive control

Research topics

Applied aerospace systems and control research

- Rotorcraft and tiltrotor attitude control
- Helicopter vibration and noise – identification and control
- UAV guidance, navigation and control
- Attitude dynamics and control of spacecraft
- Combined spacecraft control

Research topics

Experimental activities

- Study of estimation and control problems for multirotor UAVs
- Experimental validation of new modelling, identification and control technologies
- Development of innovative multirotor platforms

Introduction to UAVs:
Main configurations and capabilities

Unmanned Aerial Vehicles

Emergence of Unmanned Aerial Vehicles (UAVs) capable of agile autonomous maneuvering in possibly unknown or cluttered environments (*Advanced Air Mobility & Delivery*).

Fixed wings UAVs

- high endurance (long time of flight)
- high payload capabilities (advanced sensors and high computational power).
- a runway is needed to take off and land (small models can be launched/caught).
- non-zero forward velocity is needed to fly (due to aerodynamic constraints)

MQ-4C Triton (Northrop Grumman)

AirSTAR (NASA)

Rotary wings UAVs

- high maneuverability
- Vertical Take Off and Landing (can land on very small areas)
- stationary/slow flight (useful to perform long time tasks in the same position).
- can easily fly in small and cluttered environment (e.g., by performing hovering and slow motion).

ROG-1 (ANT-X)

V-150 (UMS SKELDAR)

Mixed configurations

Fixed-wing tiltrotor (Bell Eagle Eye)

VTOL + fixed wing (Wing (Google))

Unconventional configurations:
Tilt-arm/rotor UAVs

propellers + servo-actuators

The thrust vectoring capability increases significantly the operation range:

- Improved maneuverability (partial or full decoupling of tracking objectives)
- Augmented disturbance rejection capabilities

Tilt-X (ASCL)

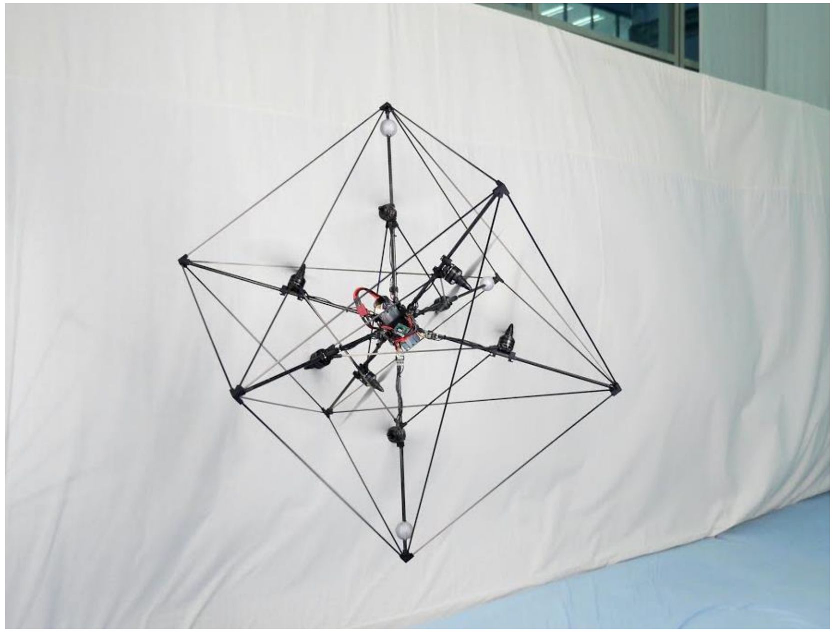
Unmanned Aerial Vehicles

Unconventional configurations:

Fixed-tilted multirotor UAVs

6+ propellers inclined with respect to the airframe

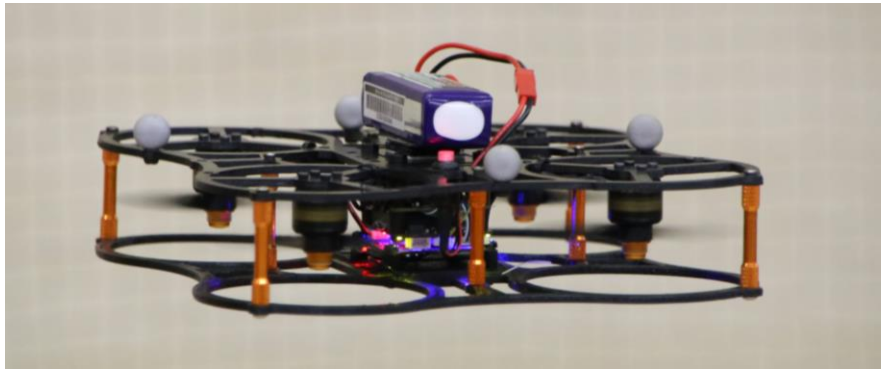
Partial or full thrust-vectoring capabilities



Omnicopter (ETH Zurich)

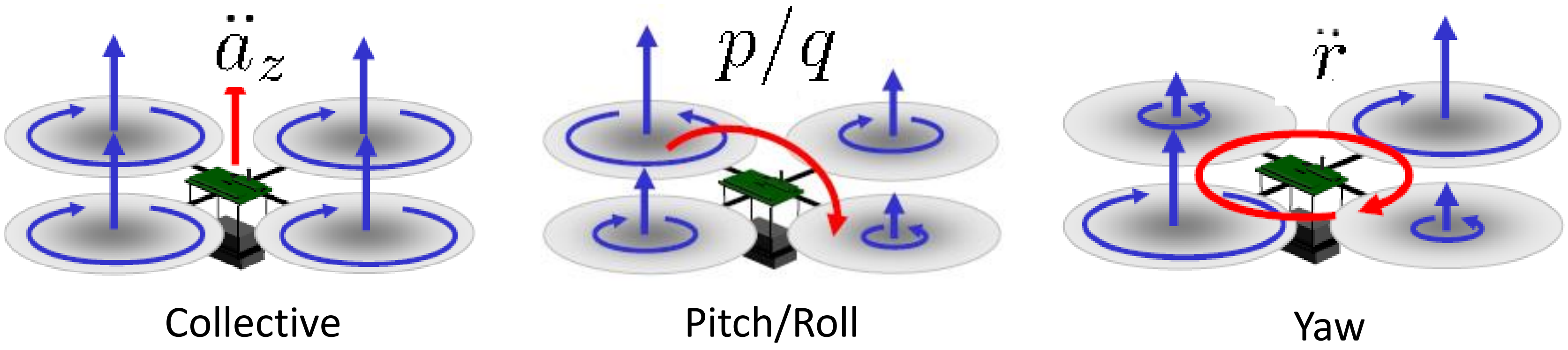
Multirotor UAVs

- Quadrotor (and in general multirotor) UAVs are the most flexible and adaptable platforms for undertaking aerial research.
- Small and safe (well operated in an indoor laboratory environment).
- Can carry sensor and computer payload to function autonomously.
- Capable of hover flight or forward flight.
- Sensing and control problems are ubiquitous in aerial flight control systems.



ANT-X quadrotor

A quadrotor consists of 4 individual rotors attached to a rigid cross airframe in a coplanar fashion.



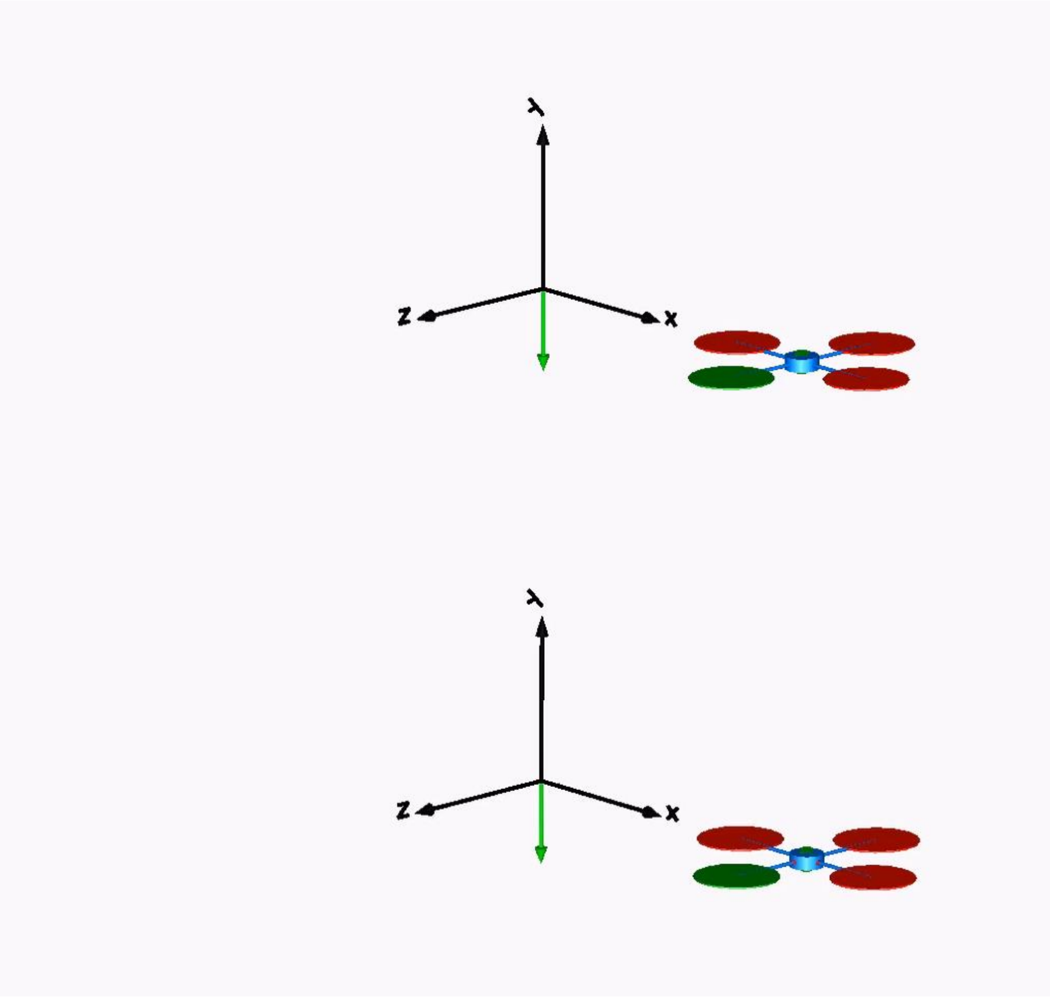
Motion control in quadrotors is achieved by differential control of the thrust generated by each rotor:

- the force component (along the vertical axis of the airframe) is generated by the sum of the thrust of the individual rotors.
- pitch and roll torques are obtained by differential thrust along the NS axis or EW axis.
- yaw torque is obtained by differential control of the NS rotors compared to the EW rotors such that the total thrust is constant.

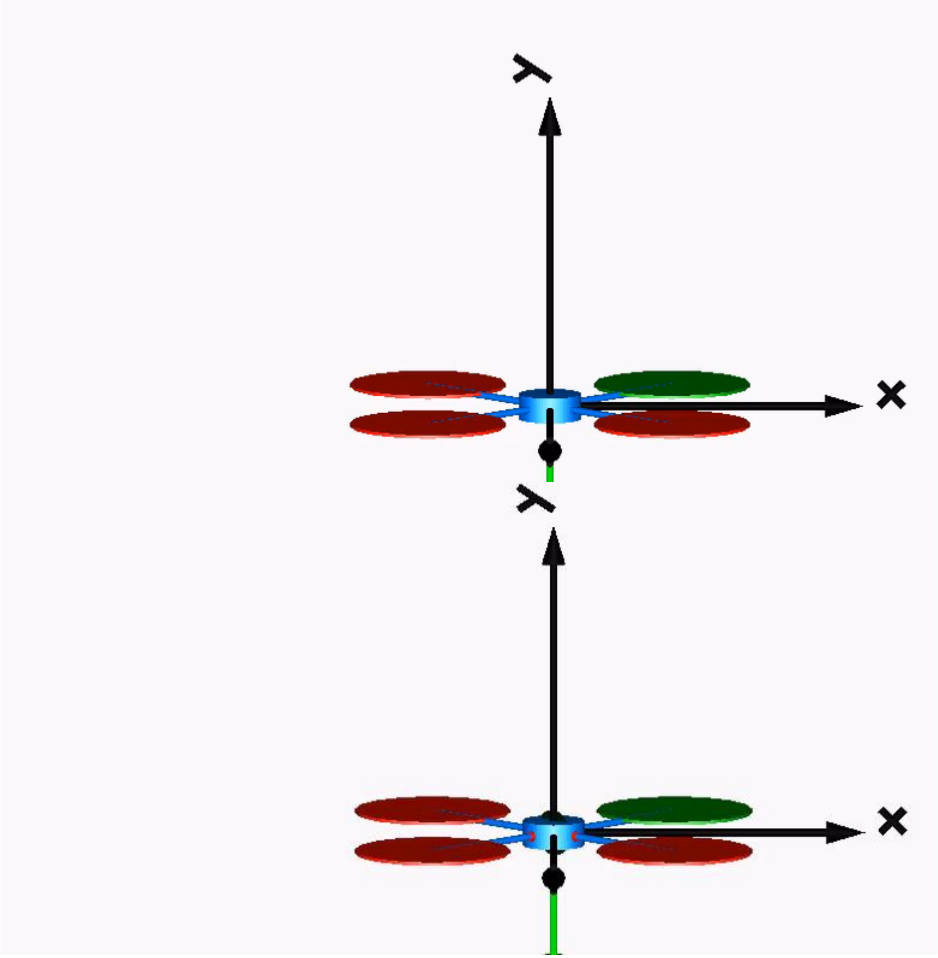
A quadrotor is an underactuated platform

- 4 inputs – 6 degrees of freedom (attitude and position)
- No force component can be actively generated in the plane of the rotors.
- Translational degrees of freedom in the horizontal plane can be controlled through the attitude dynamics.

Maneuverability limitations



Disturbance rejection capabilities



Mathematical model of quadrotor UAVs

To develop a mathematical model suitable for flight control system design, the following is needed:

- a model for the «bare aircraft»: for multirotor UAVs the equations of motion for a rigid body suffice;
- a model for the actuators, i.e., the ESC + motor + propeller groups;
- a model for the sensors, i.e., the devices through which we can sense the vehicle’s motion.

In this presentation we will focus on the first bullet.

Rigid body modeling: attitude dynamics

The model describing the attitude dynamics is given by Euler's equation

$$J\,\dot{\omega} + \omega \times J\omega = \tau_c + \tau_e.$$

- $J = J^\top \in R^{3\times3}$ is the inertia matrix referred to the Center of Mass (CoM) of the quadrotor
- $\omega = [p \quad q \quad r]^\top \in R^3$ is the vector of the body components of the angular velocity;
- $\tau_c = [L_c \quad M_c \quad N_c]^\top \in R^3$ is the control torque acting at the CoM of the quadrotor delivered by the propellers.
- $\tau_e = [L_e \quad M_e \quad N_e]^\top \in R^3$ is an exogenous torque acting at the CoM of the quadrotor collecting the effect of exogenous forces and torques (gravity, aerodynamics,...)

Modeling the dynamics of quadrotors

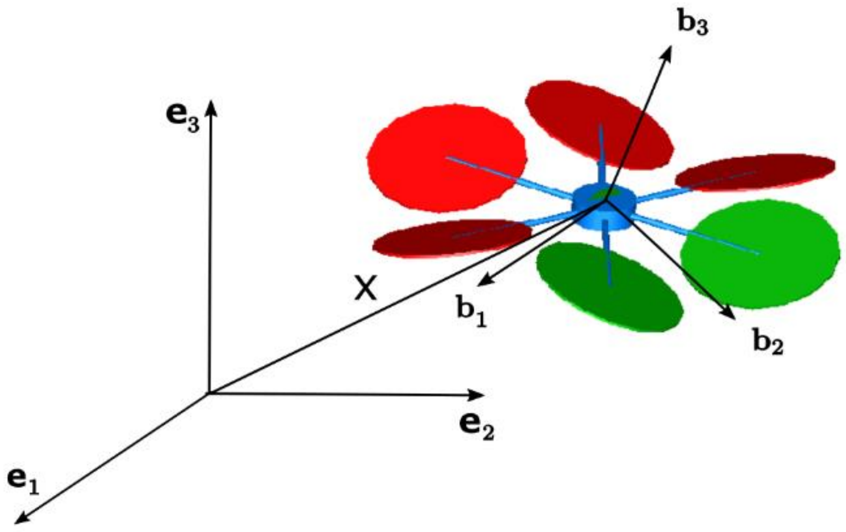
The attitude motion of the quadrotor is fully characterized by Euler's equation and the kinematic equation

$$\dot{R} = RS(\omega)$$

where $R = [b_1\ b_2\ b_3]$ is the rotation matrix describing the orientation of the body fixed frame w.r.t. to the inertial frame.

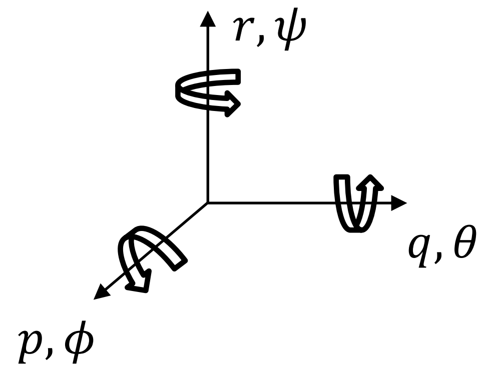
$$S(\omega) = \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix}$$

is a skew symmetric matrix such that $S(\omega)y = \omega \times y\ \forall \omega, y \in R^3$.



By parametrizing the rotation matrix with roll-pitch-yaw angles (ψ, θ, ϕ), the previous equation becomes

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin(\phi)\tan(\theta) & \cos(\phi)\tan(\theta) \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \dfrac{\sin(\phi)}{\cos(\theta)} & \dfrac{\cos(\phi)}{\cos(\theta)} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix},$$



The kinematics in terms of Euler angles suffers from singularity issues.

- other representations are often employed for (nonlinear) control purposes (e.g., quaternions, rotation matrix).

Modeling the dynamics of quadrotors

The model describing the position kinematics and dynamics of a quadrotor is described by:

$$\dot{p} = v$$
$$m\dot{v} = mge_3 - T_c b_3(\phi, \theta, \psi) + f_e$$

- $p = [x\ y\ z]^\mathsf{T}$ is the position of the quadrotor CoM with respect to the inertial frame origin (North-East-Down convection);
- $v = \left[v_x\ v_y\ v_z\right]^\mathsf{T}$ is the velocity of the quadrotor centre of mass (resolved in the inertial frame);
- $mge_3 = mg[0 \quad 0 \quad 1]^\mathsf{T}$ is the force associated with gravity (resolved in the inertial frame);
- $f_e = \left[f_{e_x} \quad f_{e_y} \quad f_{e_z}\right]^\mathsf{T}$ is a disturbance force (aerodynamic drag);
- T_c is the total thrust delivered by the propellers, which is directed along the negative direction of the vertical axis of the quadrotor frame, represented in the inertial frame by the unit vector b_3.

Modeling the dynamics of quadrotors

The most common operating scenario of quadrotors corresponds to the so-called «hovering» condition, in which the quadrotor is moving at low speed with small deviations with respect to a fixed position $\bar{p}$:

$$p = \bar{p} + \Delta\mathrm{p}$$
$$v = \Delta v$$
$$\omega = \Delta\omega$$
$$(\phi, \theta, \psi) = (\Delta\phi, \Delta\theta, \Delta\psi)$$

where the Δ terms represent small deviations.

The thrust in hovering conditions is the sum of the weight of the drone plus a small deviation ΔT_c:

$$T_c = mg + \Delta T_c$$

Linearizing the equations of motion presented in the previous slides with respect to such an equilibrium point, one obtains:

$$
\begin{aligned}
\Delta\dot{\phi} &= \Delta p \\
\Delta\dot{\theta} &= \Delta q \\
\Delta\dot{\psi} &= \Delta r \\
J_\phi \Delta\dot{p} &= L_c + L_e \\
J_\theta \Delta\dot{q} &= M_c + M_e \\
J_\psi \Delta\dot{r} &= N_c + N_e
\end{aligned}
$$

(attitude)

$$
\begin{aligned}
\Delta\dot{x} &= \Delta v_x \\
\Delta\dot{y} &= \Delta v_y \\
\Delta\dot{z} &= \Delta v_z \\
m\Delta\dot{v}_x &= -mg\Delta\theta + f_{xe} \\
m\Delta\dot{v}_y &= mg\Delta\phi + f_{ye} \\
m\Delta\dot{v}_z &= -\Delta T_c + f_{ze}
\end{aligned}
$$

(translation)

Modeling the dynamics of quadrotors

- The linearized attitude dynamics is described by three sets of independent equations, one for each axis, *e.g.*, for the pitch axis:

$$\Delta\dot{\theta} = \Delta q$$
$$J_\theta \Delta\dot{q} = M_c + M_e$$

- The in-plane linearized translational dynamics is influenced by the attitude dynamics. For instance, the translation along the x-axis is affected by the pitch rotation:

$$\Delta\dot{x} = \Delta v_x$$
$$m\Delta\dot{v}_x = -mg\Delta\theta + f_{e_x}$$

➢ By properly controlling the pitch and roll dynamics one can indirectly control the position dynamics.

Thrust-torque generation mechanism

- The control force T_c and the three torque components L_c, M_c, N_c are the resultant of the forces and torques delivered by the propellers.

- While T_c, L_c, N_c, M_c are typically considered as variables for control design, they are obtained through a mixing of the thrusts T_i $(i = 1,2,3,4)$ of the propellers (cross configuration):

$$\begin{bmatrix} T_c \\ L_c \\ M_c \\ N_c \end{bmatrix} = \underbrace{\begin{bmatrix} -1 & -1 & -1 & -1 \\ -\frac{b}{\sqrt{2}} & +\frac{b}{\sqrt{2}} & +\frac{b}{\sqrt{2}} & -\frac{b}{\sqrt{2}} \\ +\frac{b}{\sqrt{2}} & -\frac{b}{\sqrt{2}} & +\frac{b}{\sqrt{2}} & -\frac{b}{\sqrt{2}} \\ +\sigma & +\sigma & -\sigma & -\sigma \end{bmatrix}}_{\text{input matrix W}} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix}$$

where σ is an aerodynamic coefficient relating torque and thrust and b is the arm length.

The thrust-mixing model presented in the previous slide is based on a simplified (quadratic) model of the rotor aerodynamics.

Thrust:

$$T_i = c_T \Omega_i^2$$

Torque:

$$\tau_{p_i} = -\sigma \xi_i T_i$$

According to the simplified model, no force is generated in the plane of the rotors.

- This is true only for hovering conditions.

Secondary aerodynamics effects are typically neglected for control design purposes (dominated with high gain control) but they might become important for high-speed flight.

Drag is that frictional force that opposes the relative motion of an object in air.

At typical speeds for quadrotors

- parasitic drag associated with the airframe is almost negligible;
- the drag force models to be considered are primarily based on rotor aerodynamic effects.

Several sources of drag in rotors:

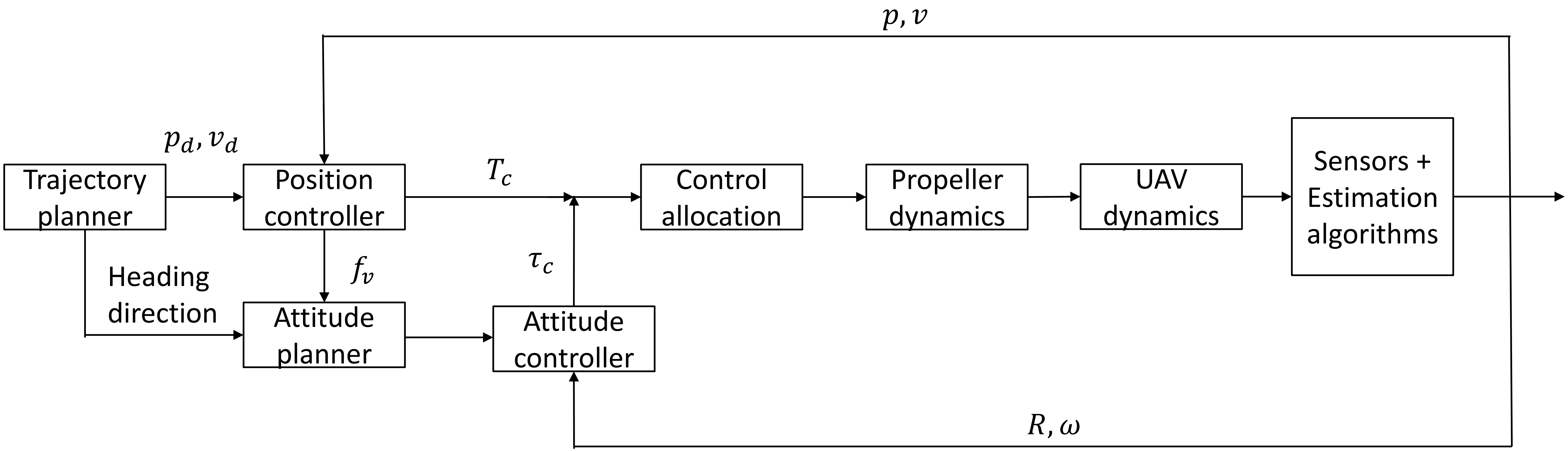
- Blade flapping
- Induced drag
- Translational drag
- Profile drag

Typically neglected or modeled using a lumped approach for control design.

(A quick introduction to) hierarchical control for quadrotors

Hierarchical control design for quadrotors

Almost all control systems for small scale aerial robotics use a hierarchical control architecture for position-heading control according to the following scheme:



Position control

For position control the quadrotor dynamics is rewritten as follows:

$$m\dot{v} = mge_3 - T_c b_3 + f_e = mge_3 + f_d + (f_a - f_d) + f_e$$

where $f_a := T_c b_3$ is the actual delivered force while f_d is a “virtual” force input to be designed to achieve position control.

The term $\Delta f := (f_a - f_d)$ represents the mismatch between the delivered and desired force

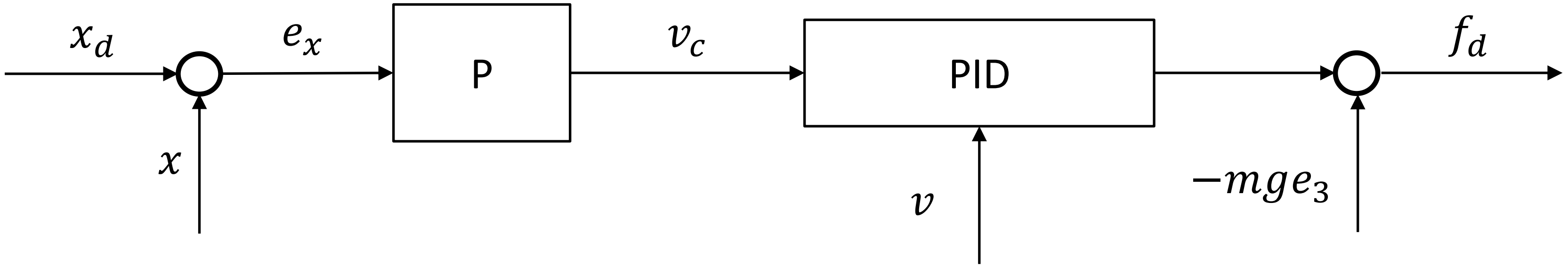
This mismatch can be regulated to zero by properly modulating the thrust T_c and by controlling the thrust-axis direction (hierarchical design idea).

Assuming that $\Delta f = 0$ can be achieved almost instantaneously by high-gain attitude control, one can work with the simplified model

$$m\dot{v} = mge_3 + f_d + f_e$$

to control the position dynamics, using f_d as an input variable.

A popular control architecture for f_d is based on PID loops (P/PID cascade) + gravity compensation

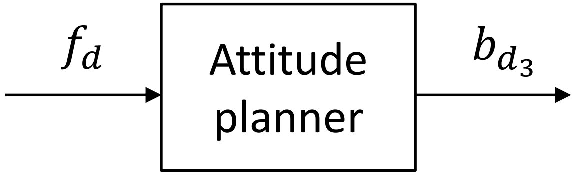


Attitude planner

The objective is to specify a reference attitude trajectory to make the term $\Delta f = (f_d + T_c b_3)$ converge to zero, namely, to have

$$T_c b_3 \rightarrow -f_d$$

The above objective can be achieved by selecting



$$T_c = |f_d|$$
$$b_{d_3} = -\frac{f_d}{|f_d|}$$

where b_{d_3} defines the desired direction of the third body-axis (the thrust-axis) to be tracked by the attitude controller.

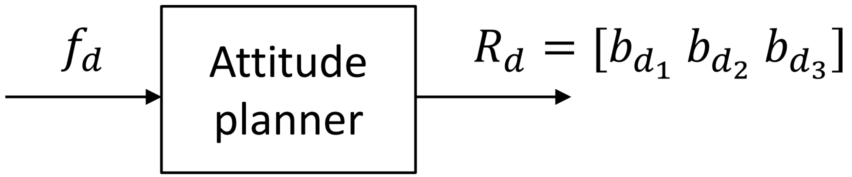
To fully specify the desired attitude, the desired heading direction

$$h_d = [\cos(\psi_d)\ \ \sin(\psi_d)\ \ 0]^\top$$

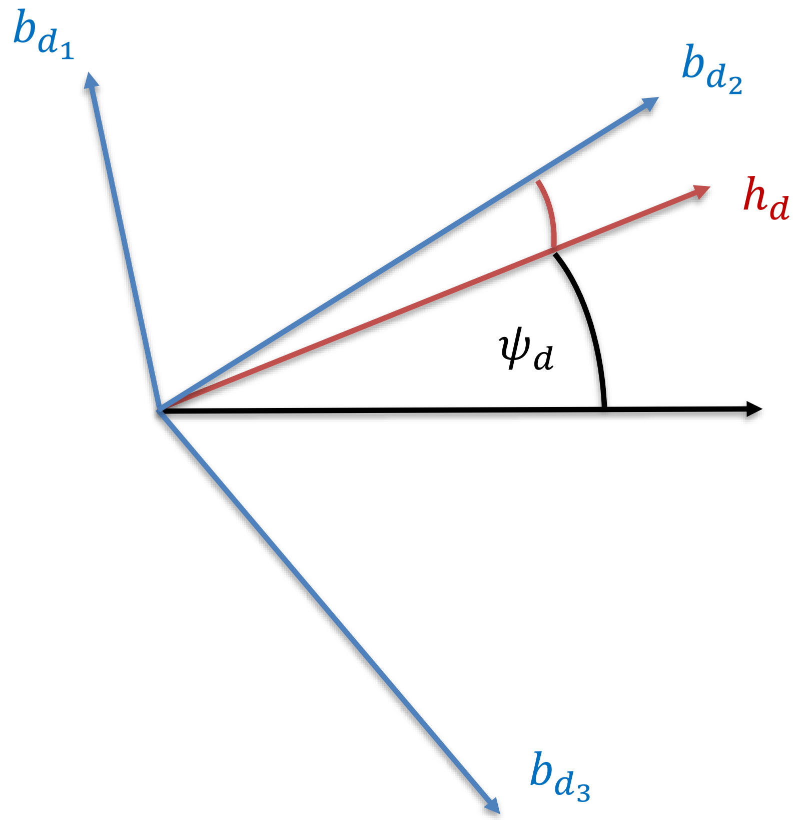
is merged together with the desired thrust-axis direction b_{d_3} to obtain

$$b_{d_1} = b_{d_2} \times b_{d_3}, \qquad\qquad b_{d_2} = \frac{b_{d_3} \times h_d}{|b_{d_3} \times h_d|}$$

The output of the attitude planner is the corresponding rotation matrix (or quaternion)



Construction of the reference attitude



$$b_{d_1} = b_{d_2} \times b_{d_3}$$

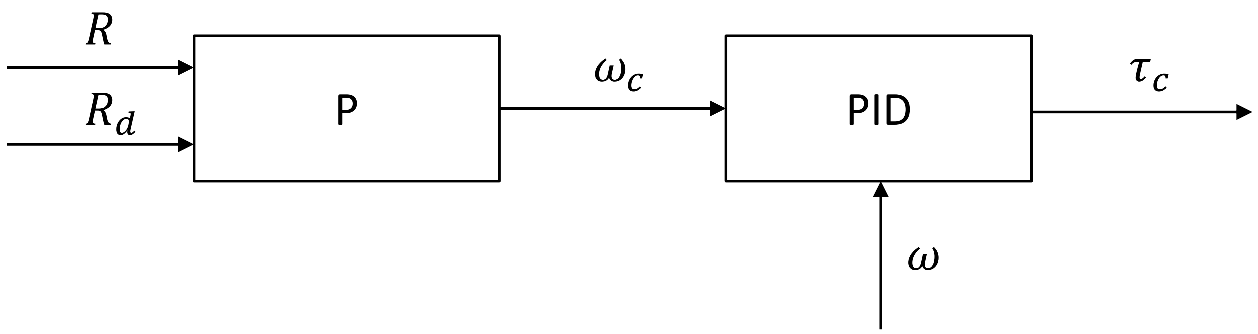
$$b_{d_2} = \frac{b_{d_3} \times h_d}{|b_{d_3} \times h_d|}$$

Thrust-axis direction

Attitude control

The attitude subsystem is fully-actuated by the torque τ_c, which can be used to track (ideally) any desired attitude trajectory.

Popular schemes used in autopilots are based on (nonlinear) PID loops (P/PID cascade)



Attitude error computation

- $R_e = R_d^\top R$
- $q_e = q_d^\top \otimes q^*$ ($\otimes$ quaternion product, *conjugate quaternion)

Control allocation

Since the input map W is invertible, the relationship between the rotor thrusts (T_i) and the control variables (T_c, L_c, N_c, M_c) can be inverted:

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} = W^{-1} \begin{bmatrix} T_c \\ L_c \\ M_c \\ N_c \end{bmatrix}.$$

The obtained rotor thrust commands are then converted into percentage throttles commands and sent to the ESC.