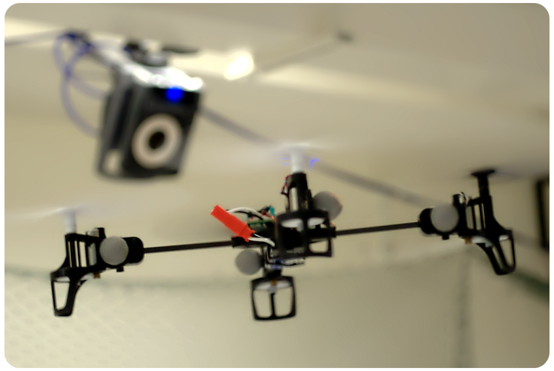
Dynamic modeling and motion control of quadrotor vehicles





Rita Cunha

Lisboa, March, 2021

TÉCNICO LISBOA
PÓLO DO IST
DSOR dynamical systems and ocean robotics LAB
LARSyS Robotics and Systems in Engineering and Science

Why are unmanned aerial vehicles (drones) on the spotlight?

Inspection, Precision Agriculture, Recreation

Drones on the news

BBC News, Oct. 2020

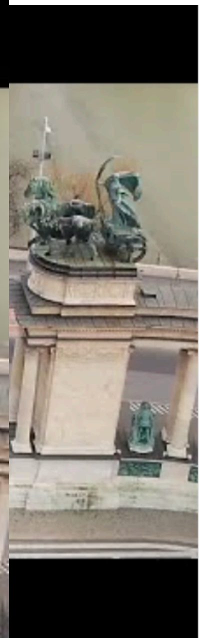
Covid-19: NHS trial

tests and equipmen

A hybrid drone is being trial

typical drone and the wings

good at flying long distances



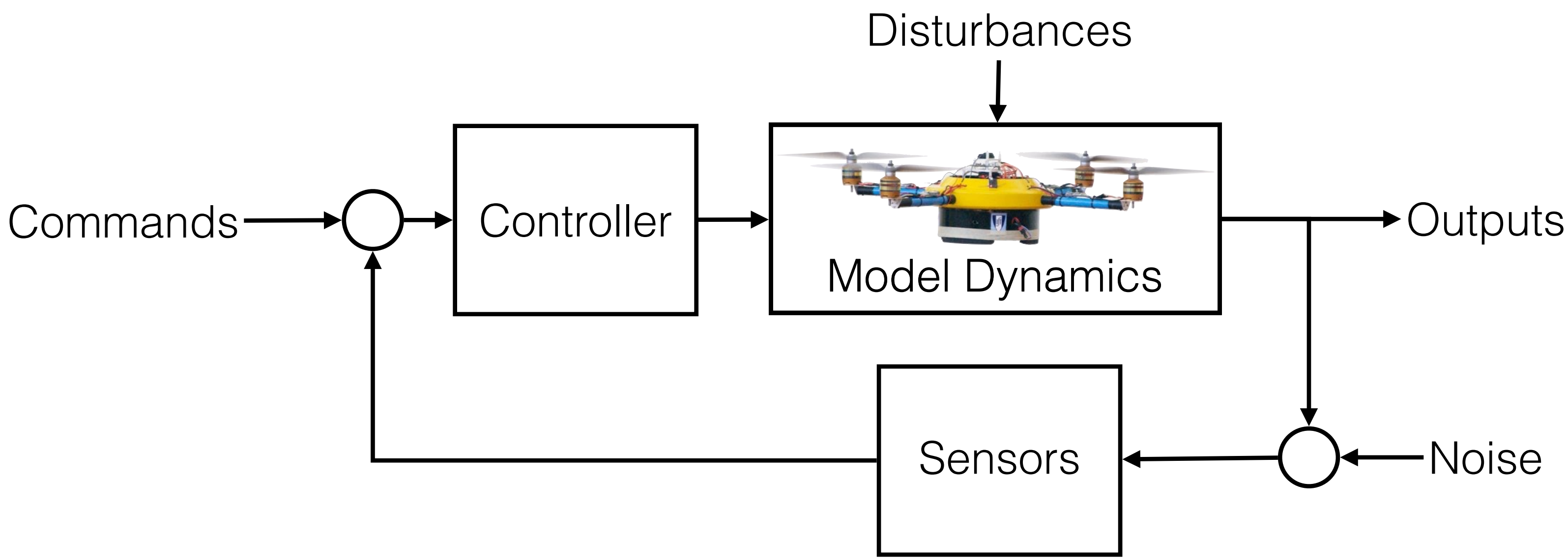
sto

Motion Control of Aerial Vehicles

Trajectory Tracking - Control Objectives

- Track a trajectory
- Realistic model
- Robustness to disturbances
- Actuation bounds
- Large basin of attraction

The quadrotor as a control system



Let's start with the model

The quadrotor as a rigid body

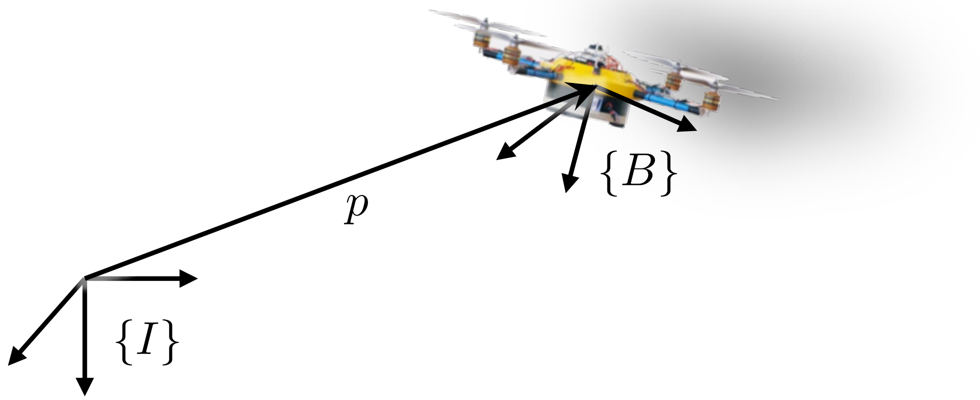
Kinematics

$$\begin{cases} \dot{p} = v \\ \dot{R} = RS(\omega) \end{cases}$$

Dynamics

$$\begin{cases} m\dot{v} = f \\ J\dot{\omega} = -S(\omega)J\omega + n \end{cases}$$

$S(\omega)a = \omega \times a$, for $\omega, a \in \mathbb{R}^3$



$m \in \mathbb{R}$ – mass

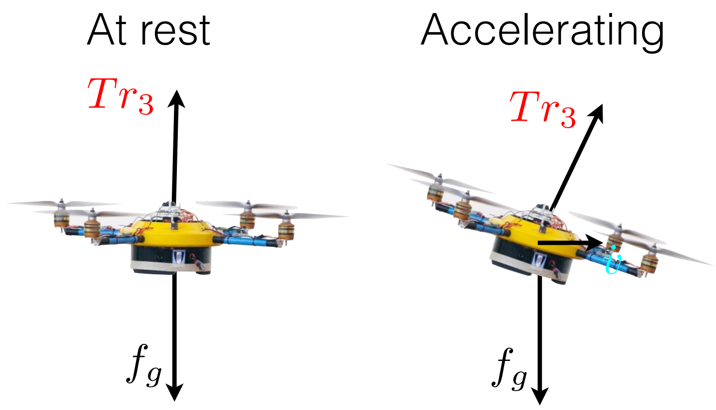
$J \in \mathbb{R}^{3\times 3}$ – Tensor of inertia expressed in$\{B\}$

$f \in \mathbb{R}^3$ – External forces expressed in $\{I\}$

$n \in \mathbb{R}^3$ – External moments expressed in $\{B\}$

Quadrotor forces

Underactuated system: 12 states, 4 inputs



$$v = 0$$
$$Tr_3 = f_g$$

$$\dot{v} \neq 0$$
$$Tr_3 = f_g - m\dot{v}$$

Control objective:

Steer the position to a desired trajectory

$$p(t) \to p_d(t)$$

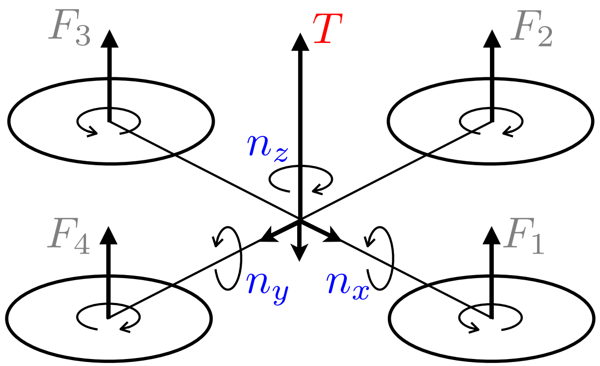
using (T, n) as inputs.

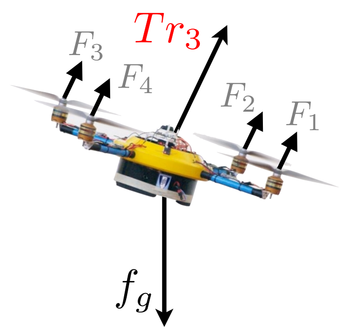
Can only prescribe 4 states:
e.g. 3D position and rotation about z-axis

Desired output (p_d, ψ_d)

Quadrotor forces and moments

Two pairs of counter-rotating rotors



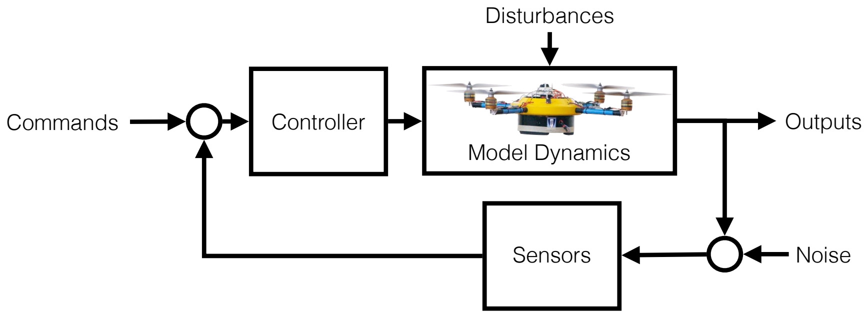


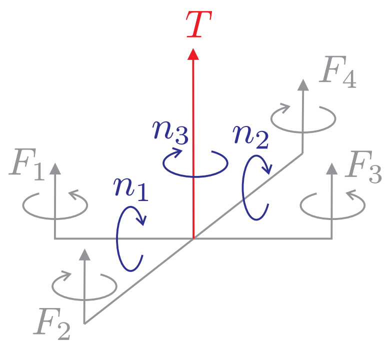
$$\begin{bmatrix} T \\ n_x \\ n_y \\ n_z \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & b & 0 & -b \\ -b & 0 & b & 0 \\ c & -c & c & -c \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix}$$

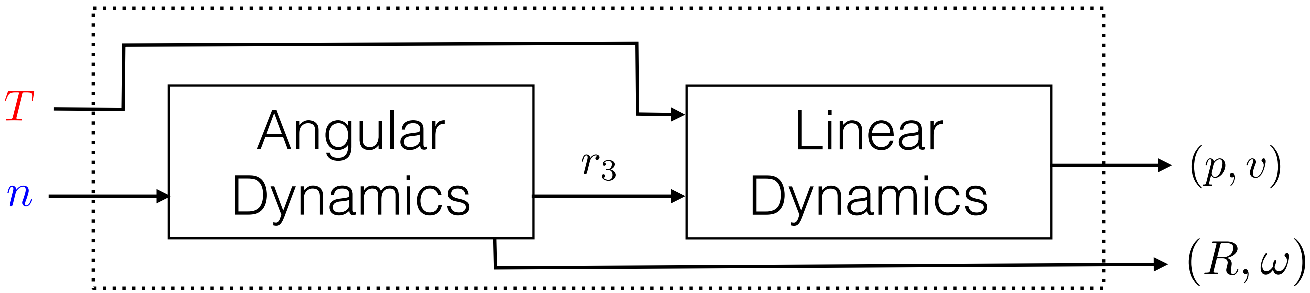
$$r_3 = Re_3 = R \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$f_g = mge_3$$

Quadrotor dynamic model







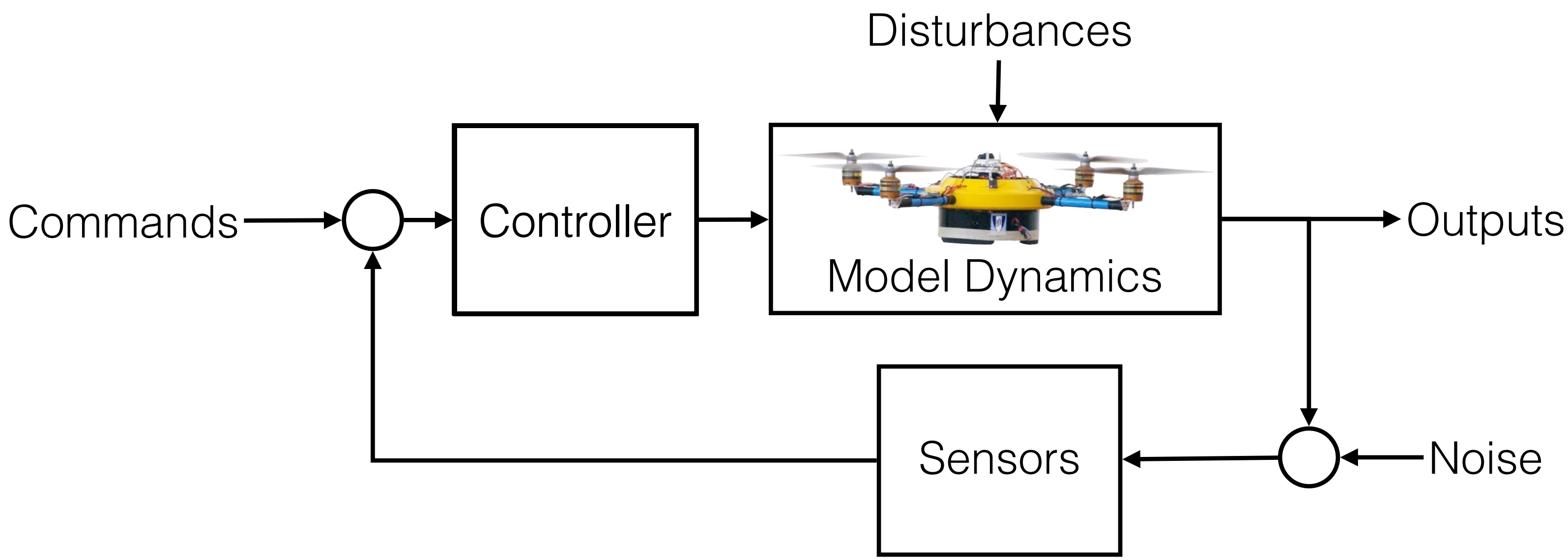
State (p, v, R, ω)

Input (T, n)

Underactuated system: 12 states, 4 inputs

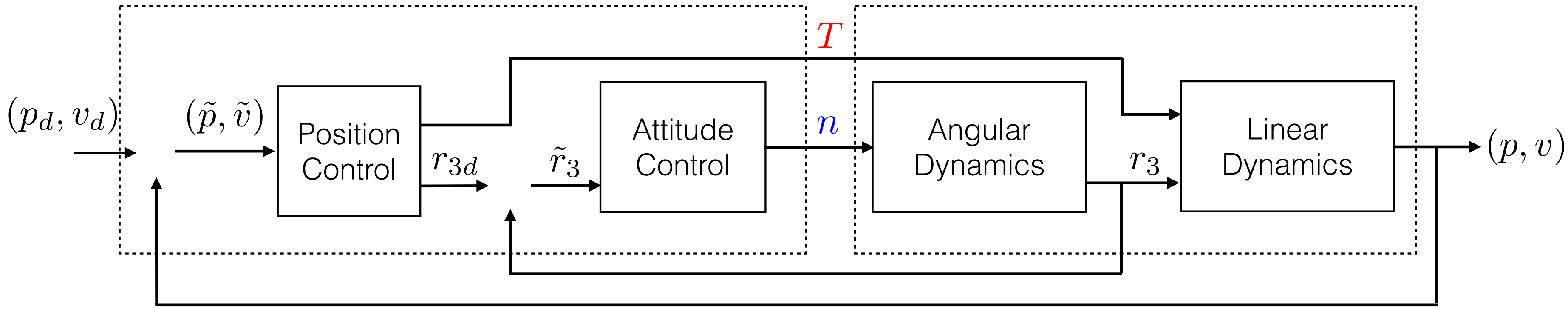
Can prescribe $(p,\ \psi) \in \mathbb{R}^4$

The quadrotor as a control system



Now the controller

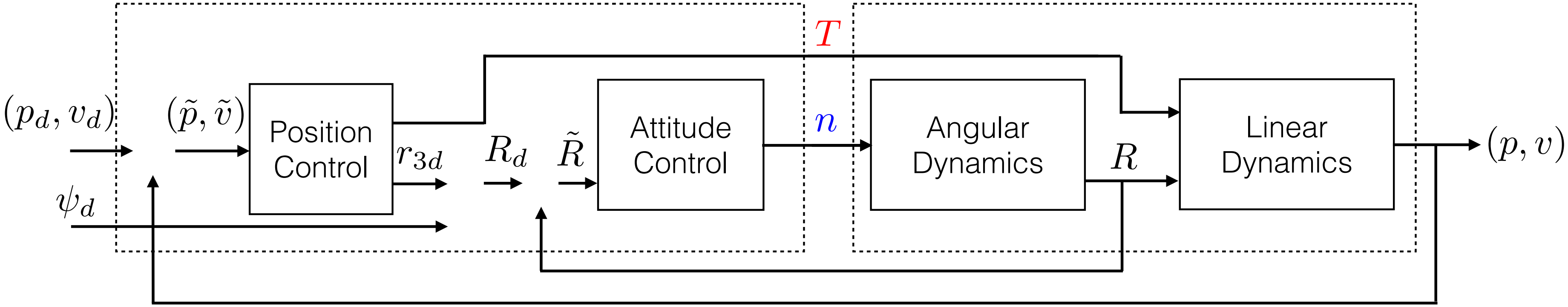
Trajectory Tracking Control



Simplest Position Controller yields a mass-spring-damper system

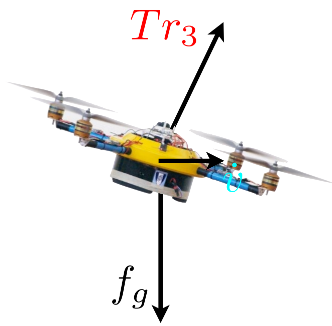
$$m\dot{\tilde{v}} = -k_1\tilde{p} - k_2\tilde{v}$$

Trajectory Tracking Control

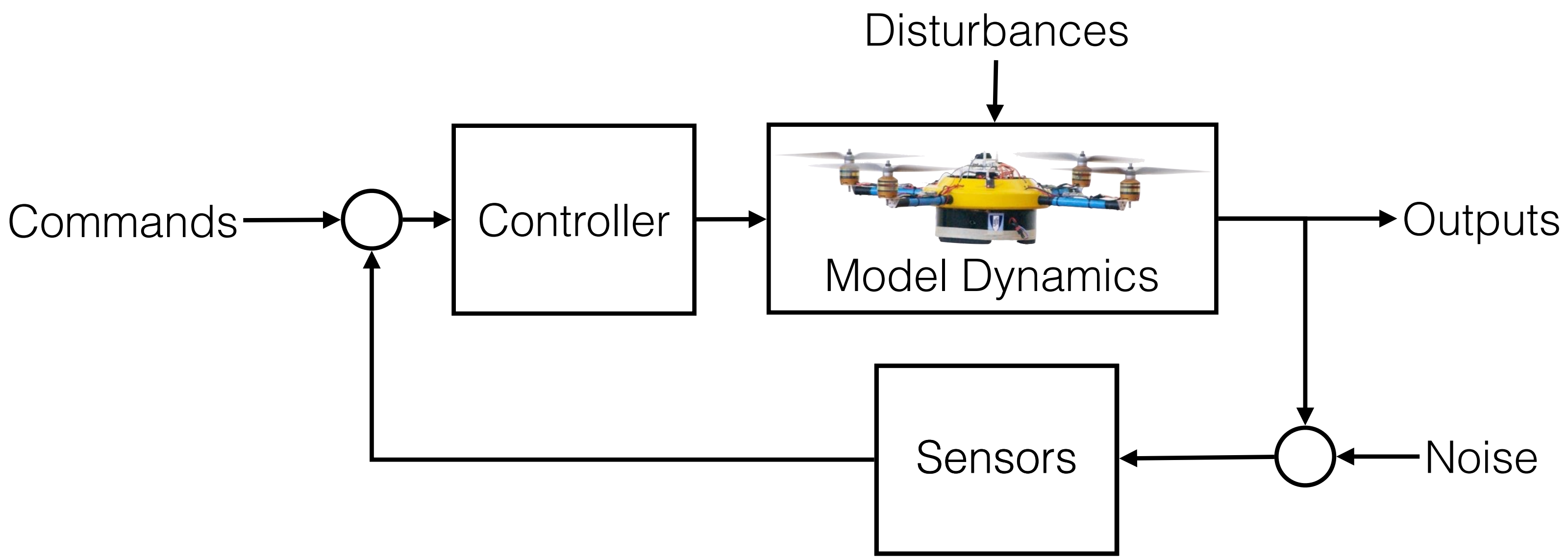


Desired position and yaw angle

(p_d, ψ_d)



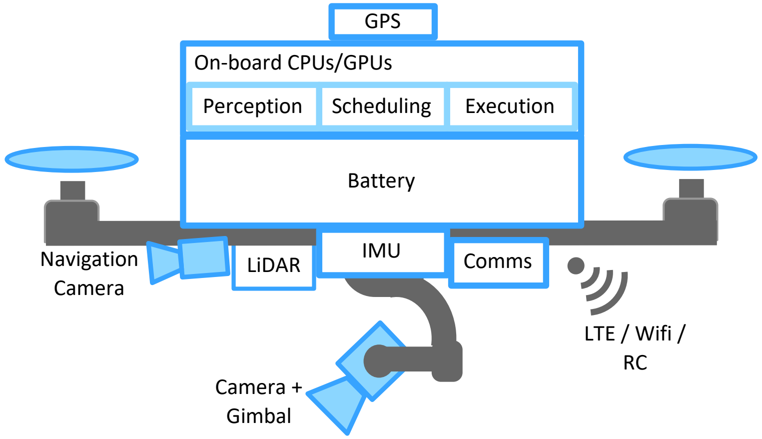
The quadrotor as a control system



Now the sensors

Sensors and Onboard Architecture

- Sensors
  - GPS - position estimates
  - IMU (accelerometers, gyroscopes, magnetometers) - attitude estimates
  - Cameras and LiDARs - mainly used for obstacle avoidance and task execution (surveying, inspection, …)
- Onboard Computers
- Communication Systems
- Batteries



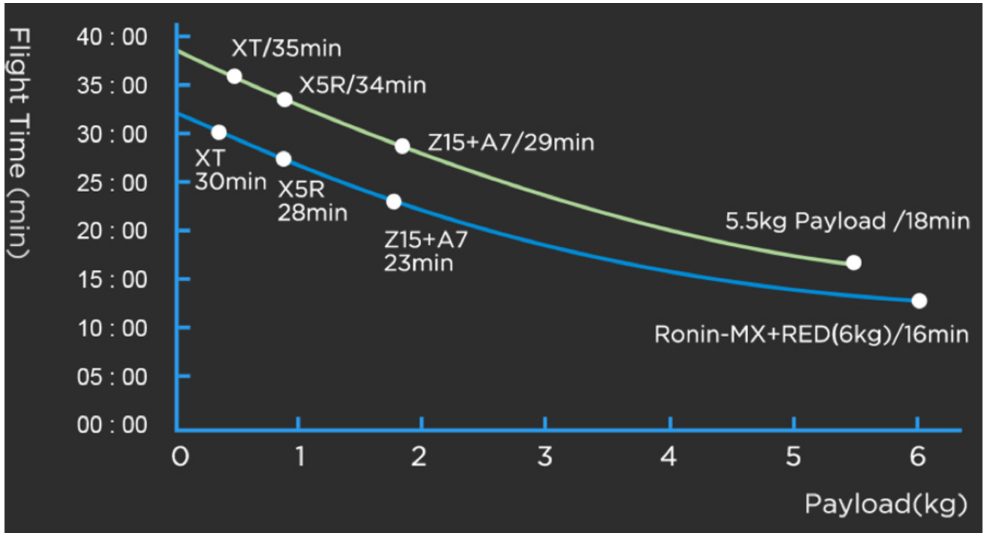
Biggest limitation to enhanced autonomy

- Flight time *vs.* available payload

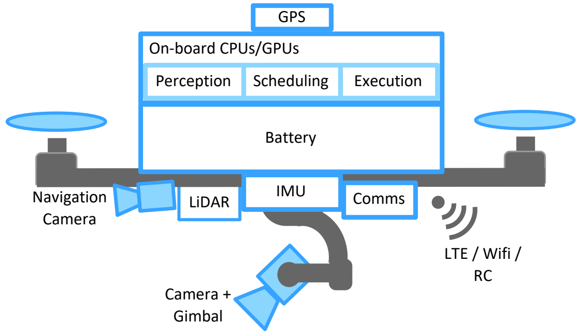
Onboard Architecture

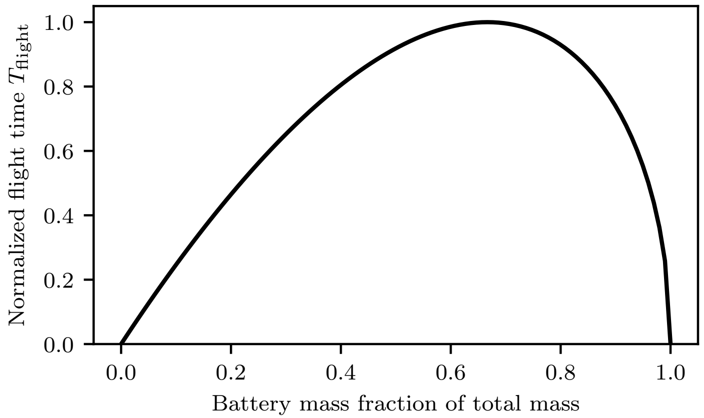
Biggest limitation to enhanced autonomy

- Flight duration *vs.* available payload



Source: https://www.dji.com/pt/matrice600-pro

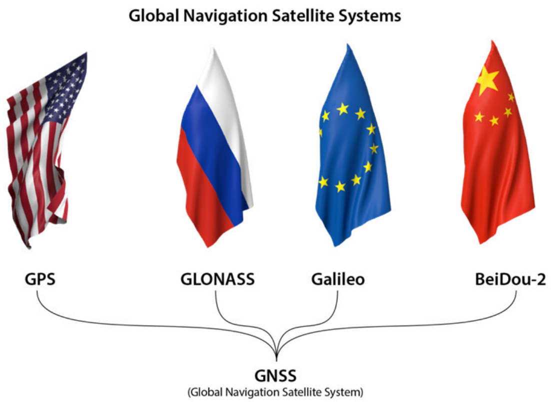


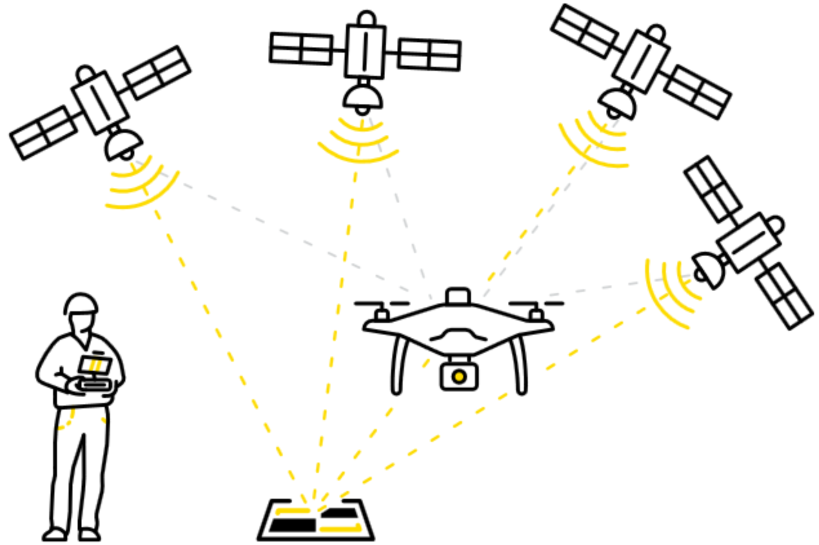


Source: https://spectrum.ieee.org/automaton/robotics/drones/swappable-flying-batteries-keep-drones-aloft-almost-forever

GNSS - Global Navigation Satellite System

- Used to estimate **position** based on time and known position of dedicated satellites.



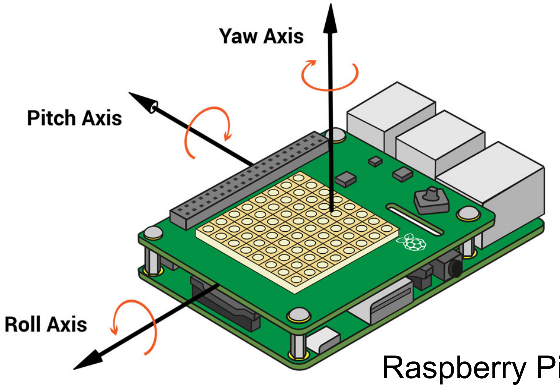


IMU - Inertial Measurement Unit

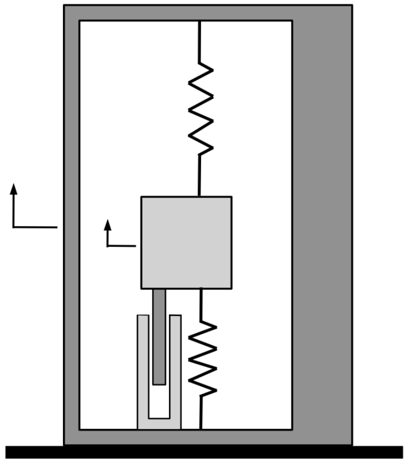
- Three-axis accelerometers, gyroscopes, and magnetometers
- Used to estimate the orientation of the vehicle

How a Smartphone Knows Up from Down (accelerometer)

https://www.youtube.com/watch?v=KZVgKu6v808

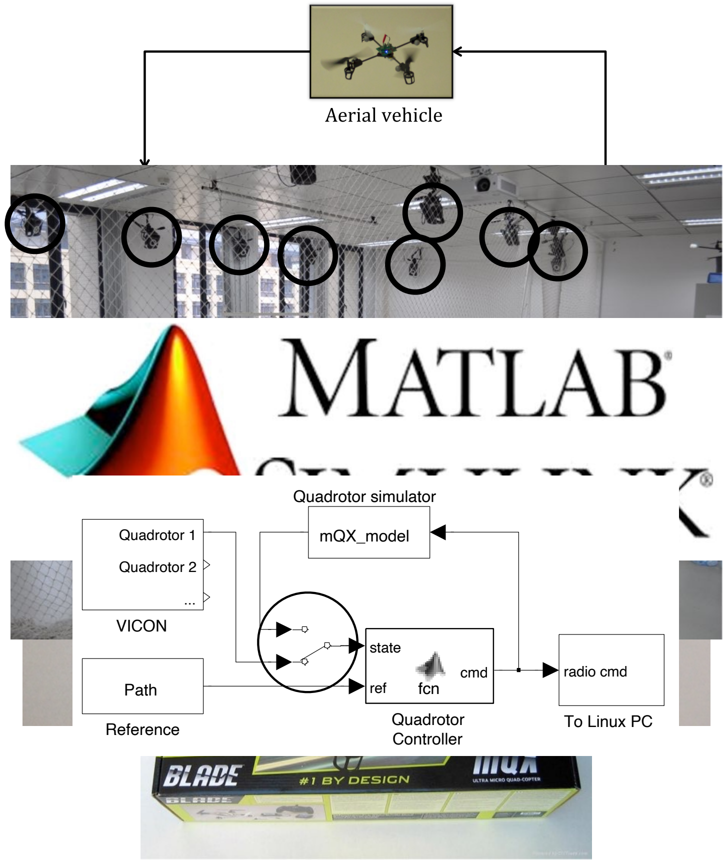


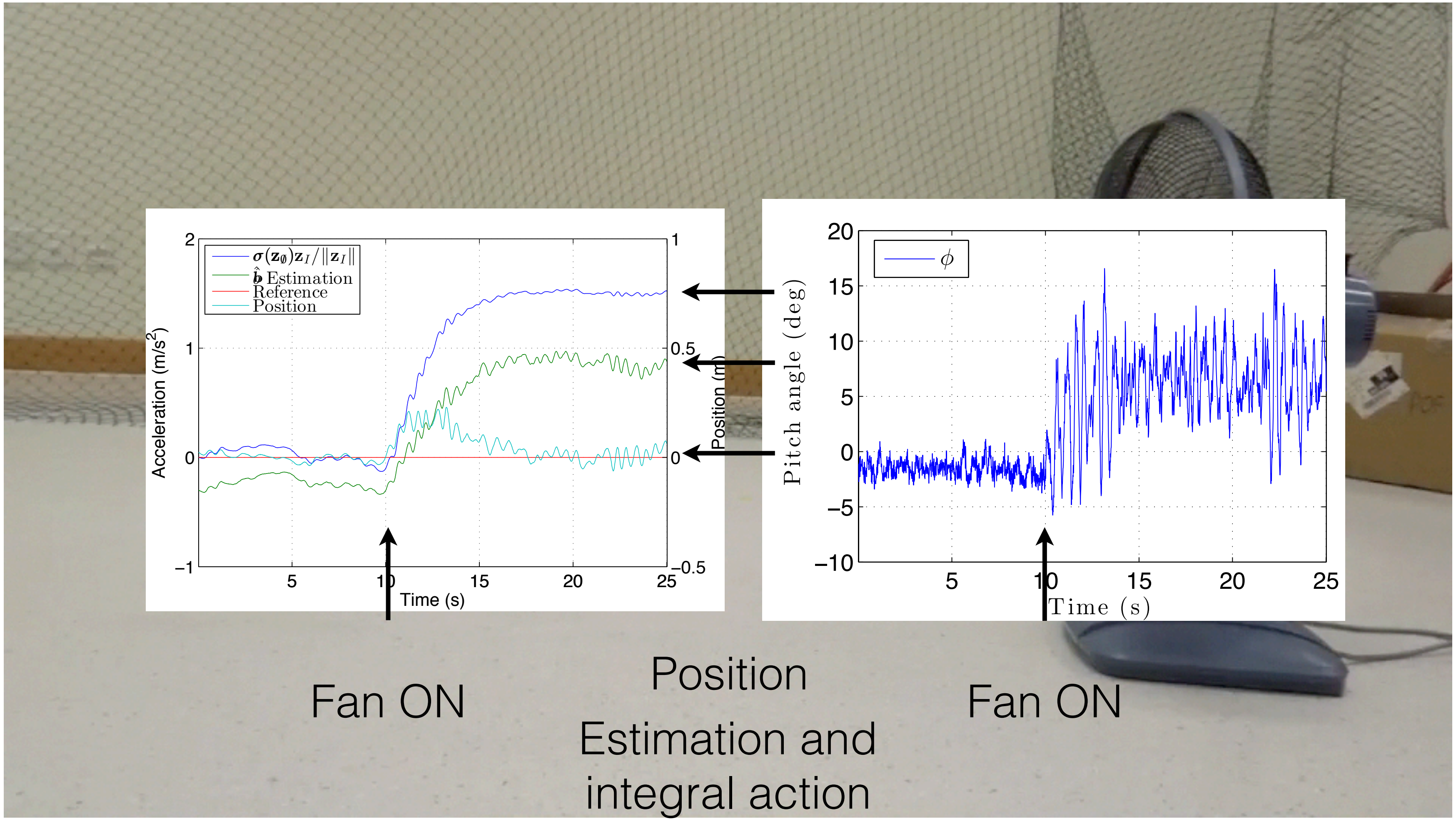
Raspberry Pi™ Sense HAT



Indoors - Experimental Setup

- Readily available quadrotor solution
- Computer controlled radio transmitters
- Motion Capture system for state measurements
- Integrated system
- Rapid prototyping and experimental testing of controllers





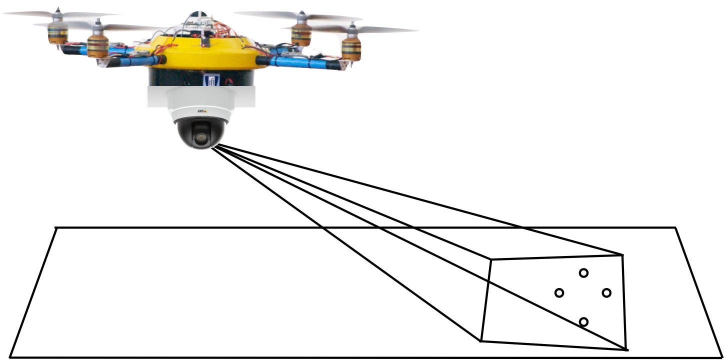
http://users.isr.ist.utl.pt/~rmac/videos/freeflight.mp4

http://users.isr.ist.utl.pt/~rmac/videos/aggressive.mp4

Landing on a moving platform using vision-based control

Landing on a moving platform

- Quadrotor
- IMU
- Wide-angle camera
- *Goal:* land on a target

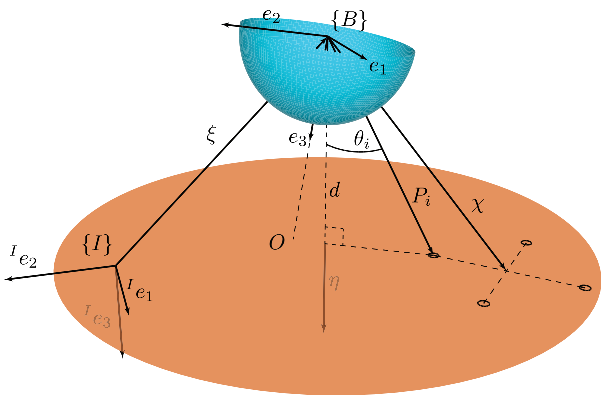


Assumptions

- Planar target
- Moving platform
  - Translation
- Non-agressive maneuvers

Vision-based controller

Control objective: $\chi \to 0$

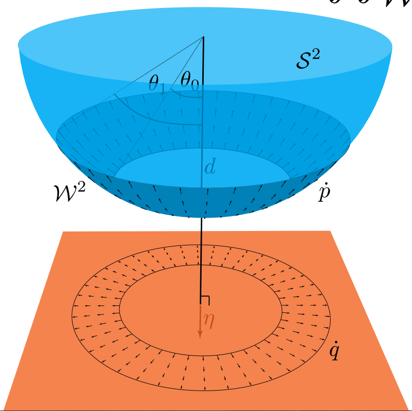


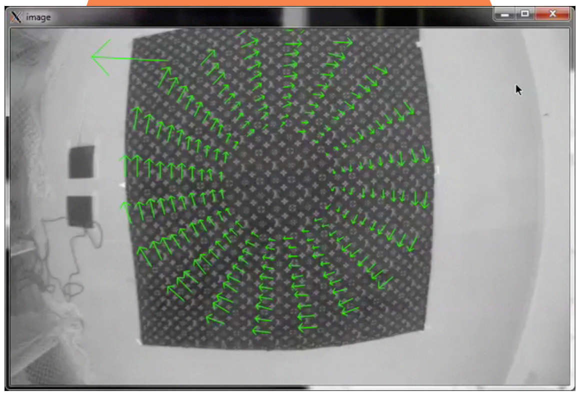
Available measurements:

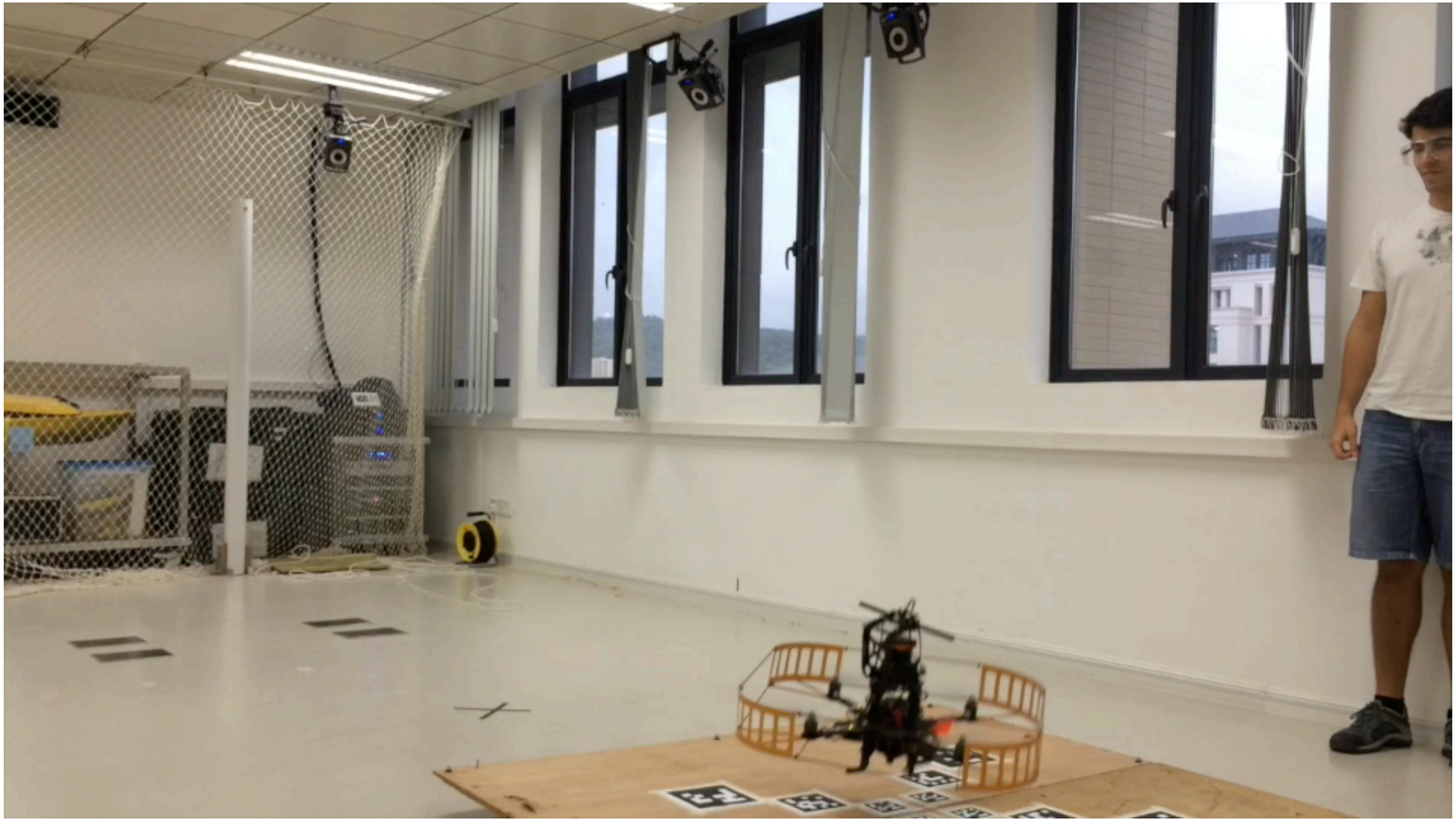
- Images of target points

$$p_i = \frac{P_i}{\|P_i\|} \qquad \frac{P_i}{d} \qquad \frac{\chi}{d}$$

- Optical flow field $\phi = \iint_{\mathcal{W}^2} \dot{p} \; \mathrm{d}p$ $\qquad \frac{\dot{\chi}}{d}$





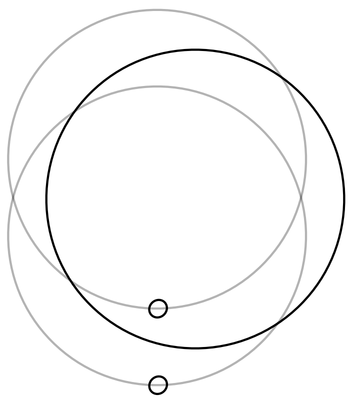


http://users.isr.ist.utl.pt/~rmac/videos/interaction_2.mp4

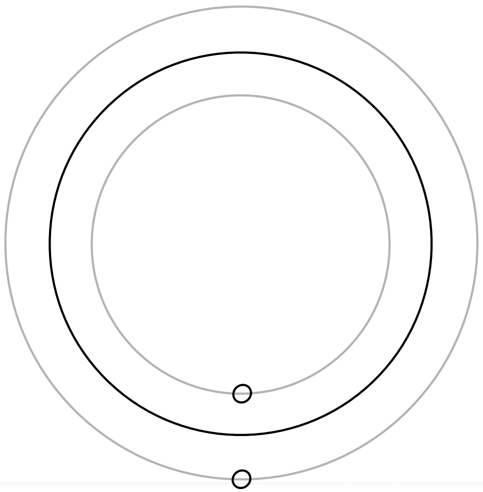
Leader-following for formation control

Leader-following for formation control

- Main idea:
  Trailer-like behavior for the followers.

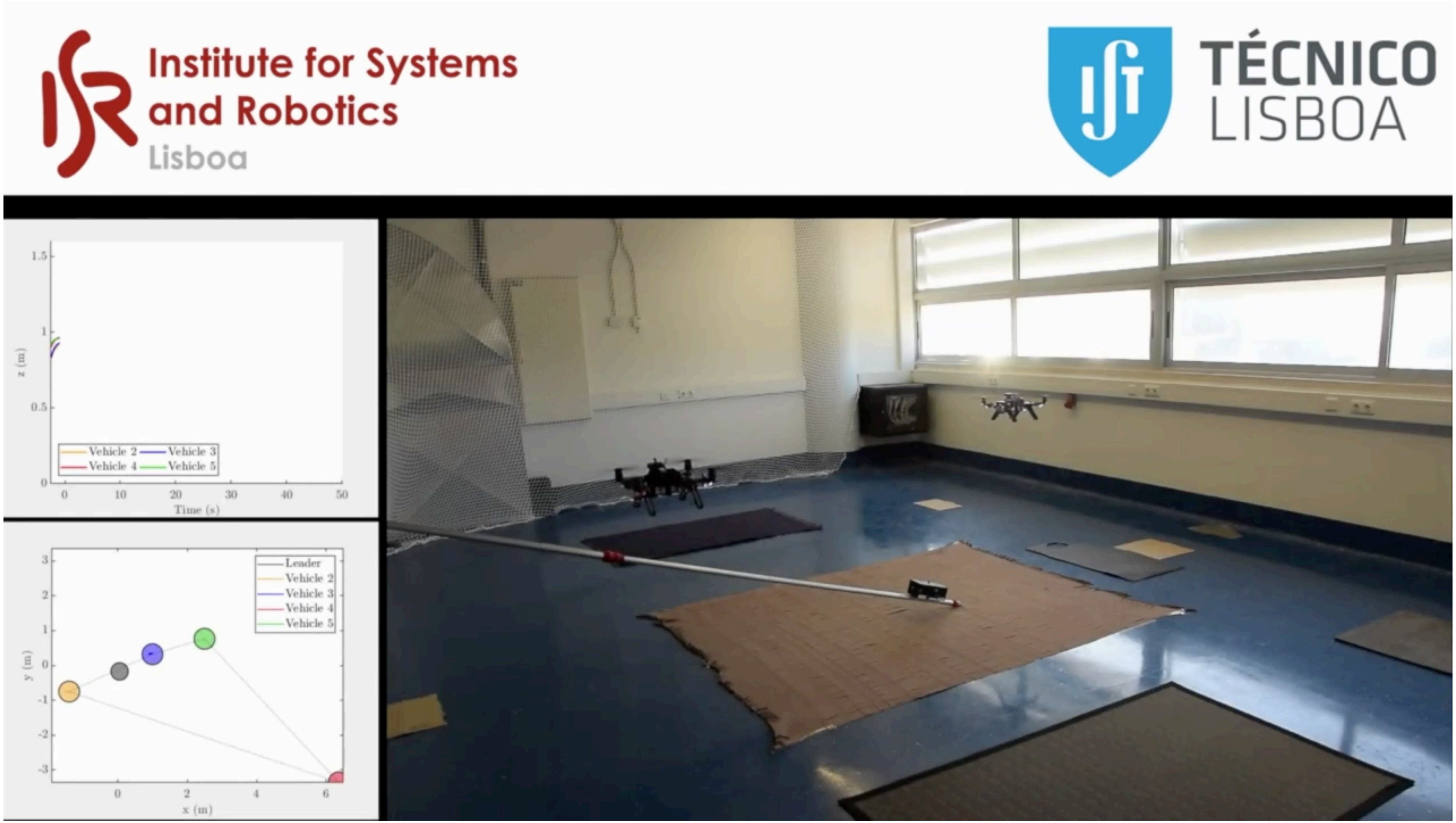


In inertial frame:
Translated identical paths



In trailer frame:
Different paths, no superposition

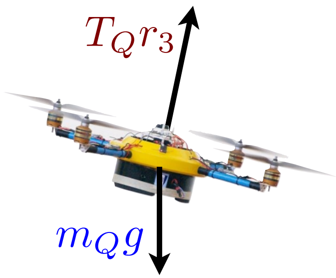
http://users.isr.ist.utl.pt/~rmac/videos/multi_vehicles.mp4


Institute for Systems
and Robotics
Lisboa
TÉCNICO
LISBOA
z (m)
Time (s)
Vehicle 2
Vehicle 3
Vehicle 4
Vehicle 5
Leader
y (m)
x (m)

Slung-load transportation using quadrotors

Modeling

Quadrotor



State

$(p_Q, v_Q, R_Q, \omega_Q)$

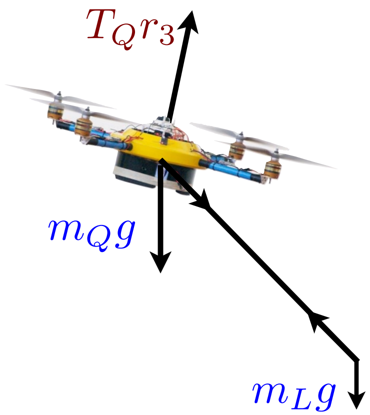
Input

$(T_Q, n_Q) \in \mathbb{R}^4$

Flat output

$(p_Q, \psi_Q) \in \mathbb{R}^4$

Quadrotor + Load



State

$(p_Q, v_Q, R_Q, \omega_Q, p_L, v_L)$

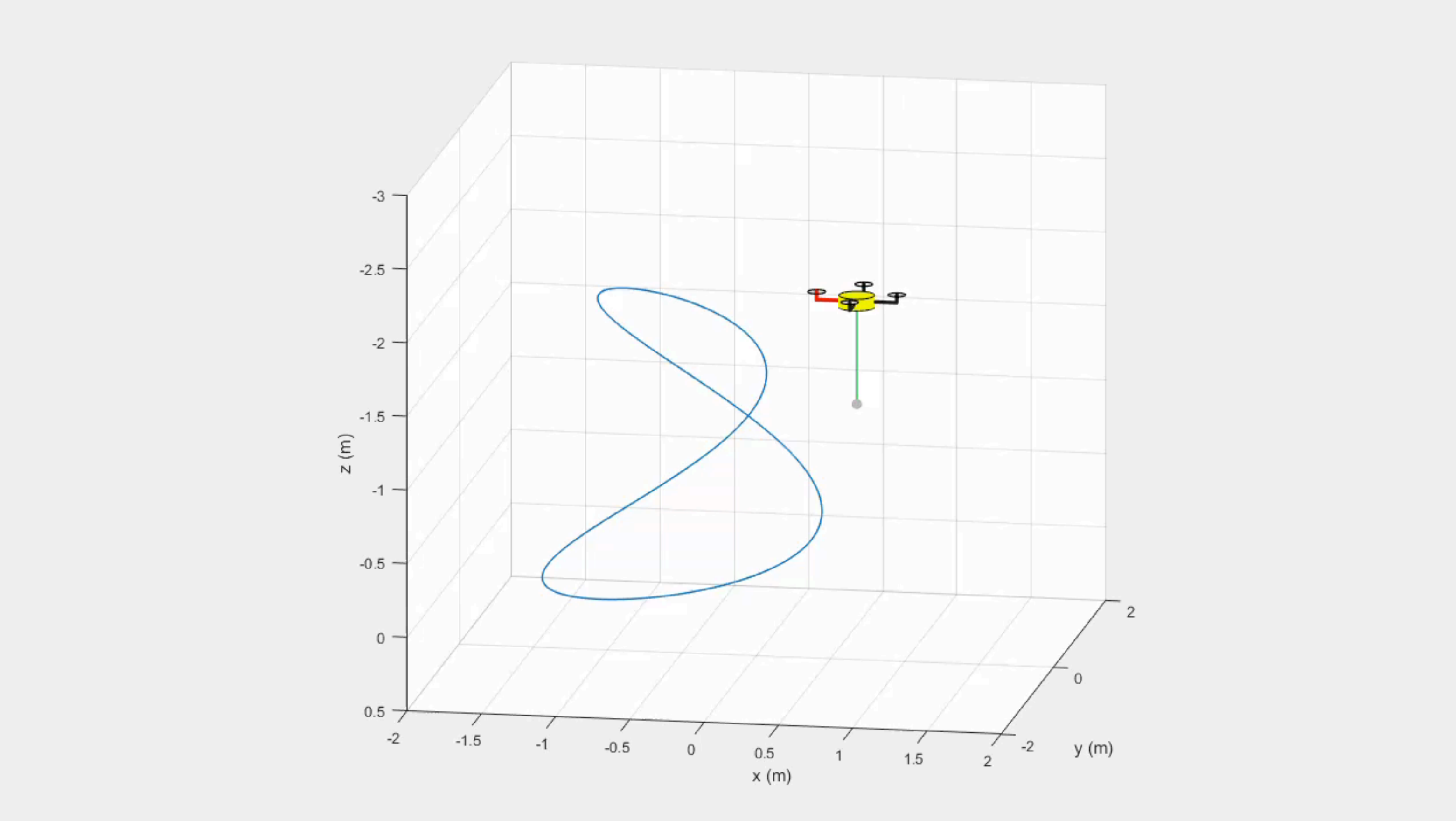
Input

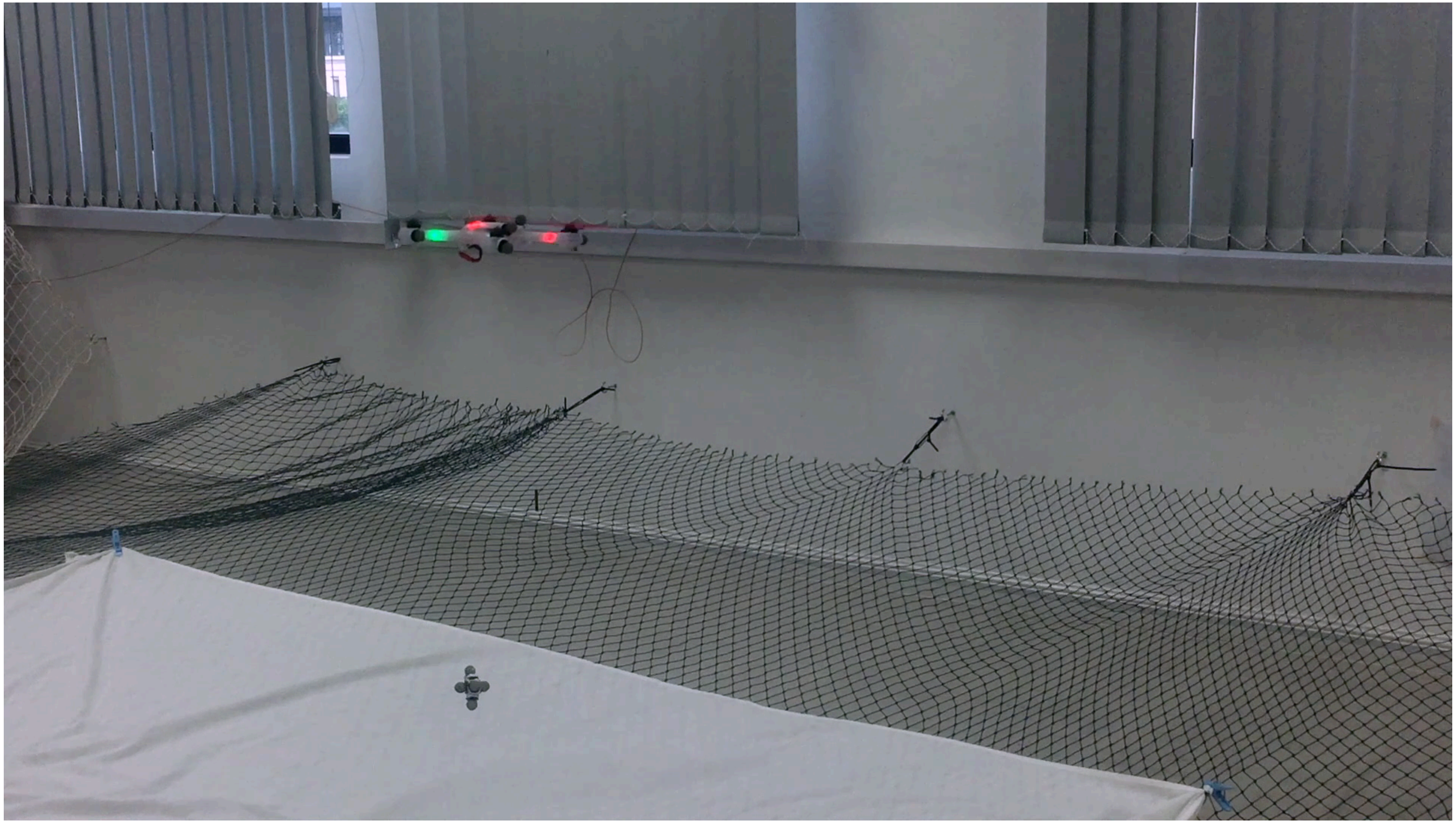
$(T_Q, n_Q) \in \mathbb{R}^4$

Flat output

$(p_L, \psi_Q) \in \mathbb{R}^4$

Simulation results





http://users.isr.ist.utl.pt/~rmac/videos/load_transportation.mp4

Acknowledgments

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