Autonomous Mobile Robot Design

Topic: Developing a Broad Understanding

Dr. Kostas Alexis (CSE)

The Basic Robot Questions

How do I move?

Module: Propulsion Systems & Vehicle Dynamics

The Basic Robot Questions

Where am I?
What is my environment?

Module: Perception Systems & State Estimation

The Basic Robot Questions

How do I control where to go?

Module: Guidance & Control Systems

The Basic Robot Questions

How do I plan my motion and actions?

Module: Path Planning Algorithms

The Basic Robot Questions

How to handle abstract tasks?

Module: Path Planning & Task Decomposition

The Basic Robot Questions

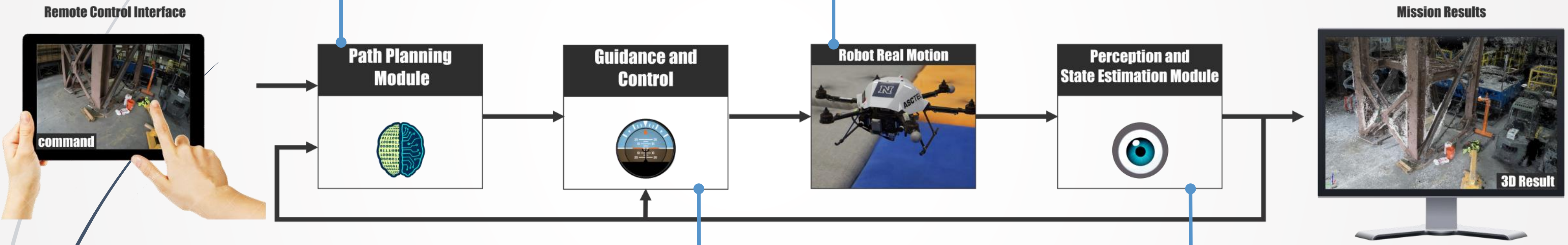
How to provide a good interface to the human?

Module: Human-Robot Interface

The Basic Robot Loop

- Path planning in order to compute the path the robot should follow to ensure safe navigation and execute the desired mission.

- Real-life Robot expressing its dynamic behavior in response to the control inputs and external disturbances



- Control and Guidance system responsible for ensuring vehicle stability and reference trajectory tracking as well as disturbance rejection.

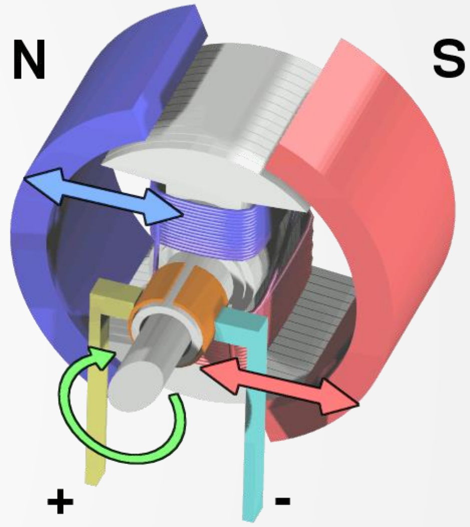
- Inertial Navigation System
- Localization & Mapping
- Sensor Fusion
- Semantic Understanding

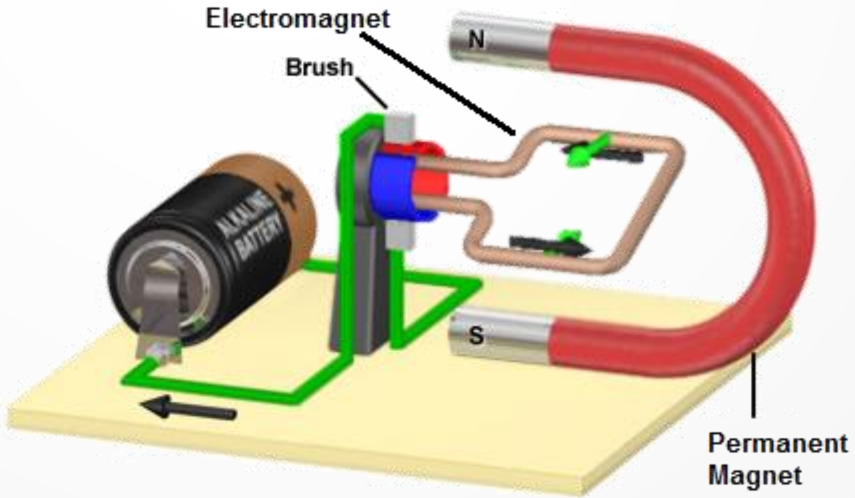
Propulsion & Vehicle Dynamics

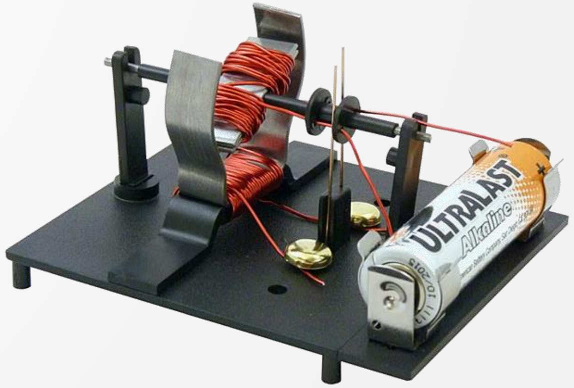
- Different propulsion systems designs are employed for different robotic configurations.
- Miniaturization of propulsion systems –in combination with good efficiency– is among the reasons for the success of small robotics.
- Within this course we will focus on:
  - DC Motors
  - DC Brushless Motors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

Propulsion & Vehicle Dynamics

- Robots are using motors and as long as small systems are concerned, these are typically electric DC-brushed or DC-brushless motors.







Propulsion & Vehicle Dynamics

- Aerial robots are using propellers and rotorheads for their operation. A propeller is a much more simplified propulsion system compared to a full rotorhead.
  - It is only used to produce thrust.
  - It has a fixed blade pitch angle or collective changes only.

Propulsion & Vehicle Dynamics

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

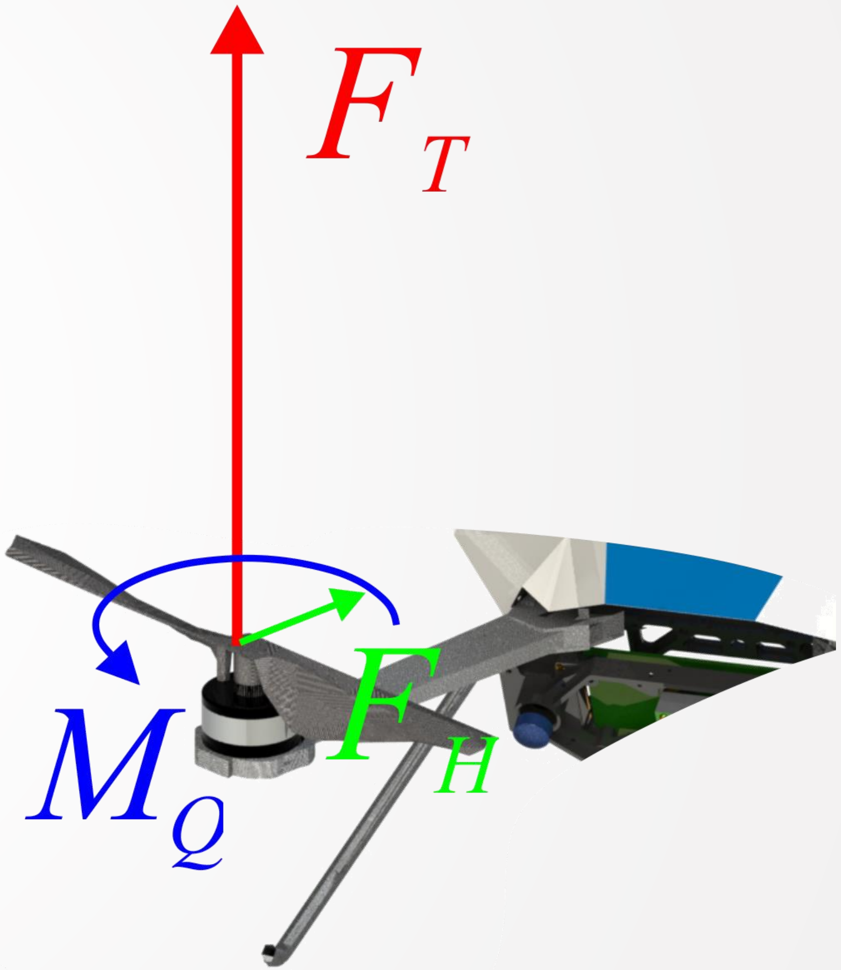
$$F_T = T = C_T \rho A (\Omega R)^2$$

  - **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.

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



Propulsion & Vehicle Dynamics

- **Understand the motion principles and model of a car-like wheel**
- **Circular Motion – Rotational Formulas**
  - Angular Velocity

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

  - Angular Velocity and Acceleration

    $$\omega = \omega_0 + at$$

  - Angular Displacement

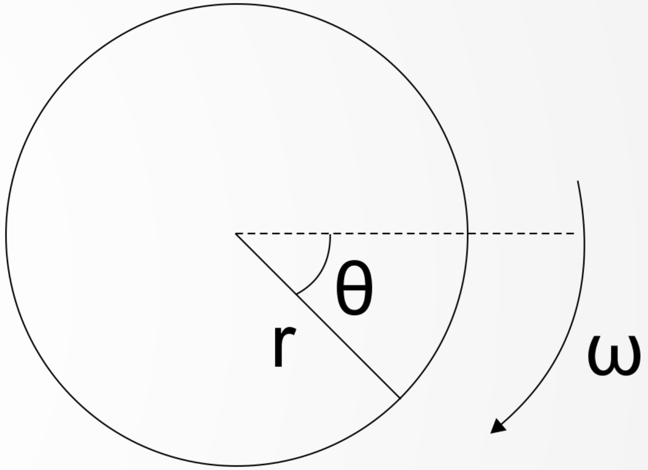
    $$\theta = \omega_0 t + \frac{1}{2} a t^2$$

  - Angular Acceleration

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

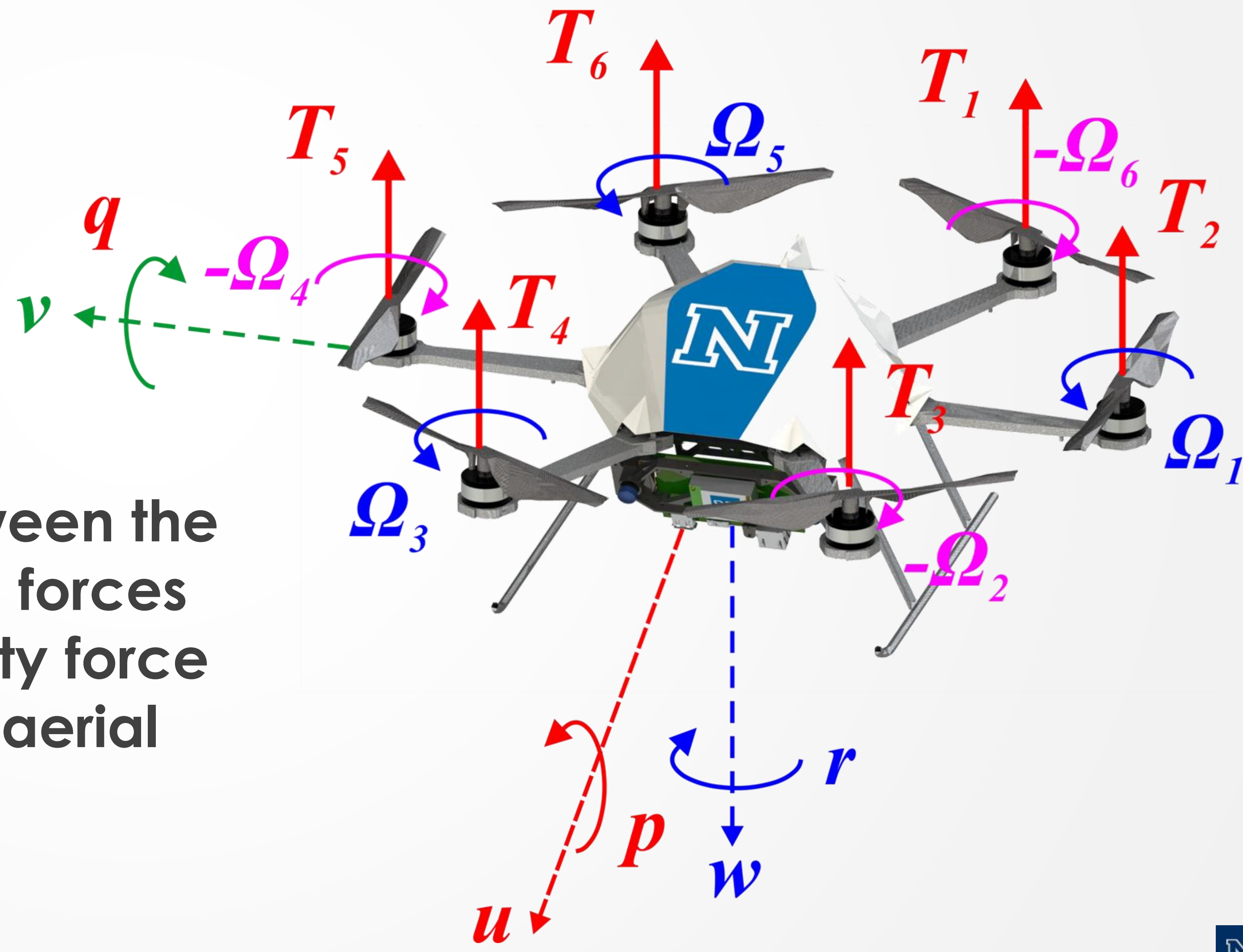
  - Angular Momentum or Torque

    $$T = aJ_w$$



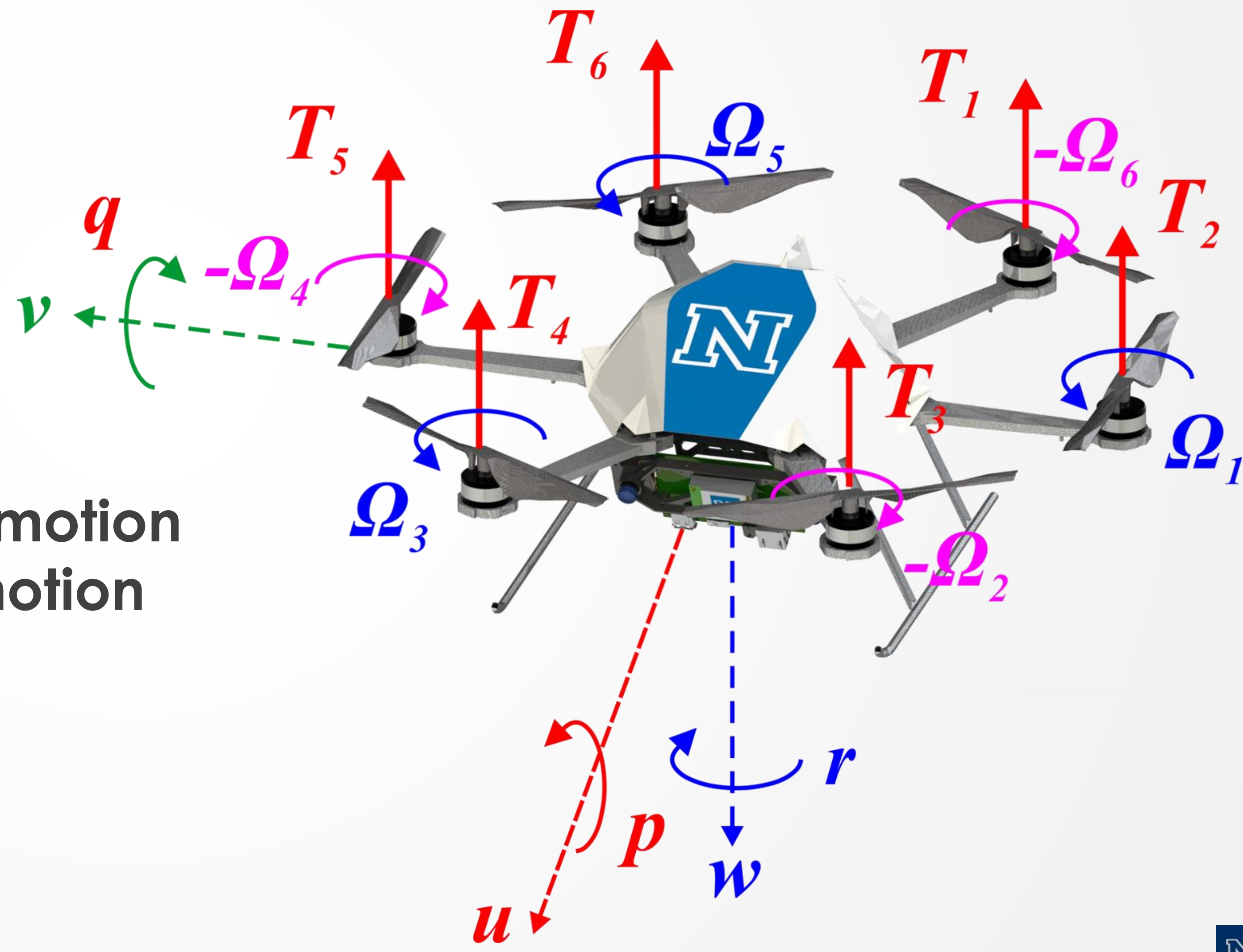
- ω = angular velocity
- θ = angular position
- r = radius of the wheel
- a = angular acceleration
- J_w = moment inertia
- T = angular momentum

Propulsion & Vehicle Dynamics



What is the relation between the propeller aerodynamic forces and moments, the gravity force and the motion of the aerial robot?

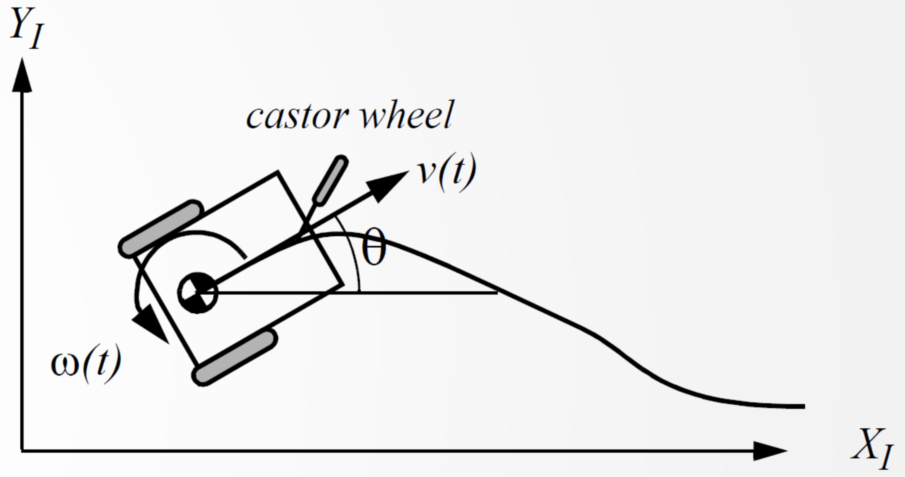
Propulsion & Vehicle Dynamics



How is Roll, Pitch, Yaw motion created? How is 3D motion achieved?

Propulsion & Vehicle Dynamics

- Understand the motion principles of a nonholonomic vehicle that relies on the coordination of throttle and steering commands.



Full Attitude Control of a VTOL Tailsitter UAV

S.Verling, B.Weibel, M. Boosfeld, K. Alexis, M. Burri, and R.Siegwart

Perception & State Estimation

- Providing the capacity to estimate the **state and the map** of the aerial robot
  - **Self-Localize and estimate its pose in the environment**
  - **Often this infers to also derive the map of the environment**
  - **In some cases also rely in external systems (e.g. GPS), while a lot of work is undergoing into making aerial robots completely autonomous.**

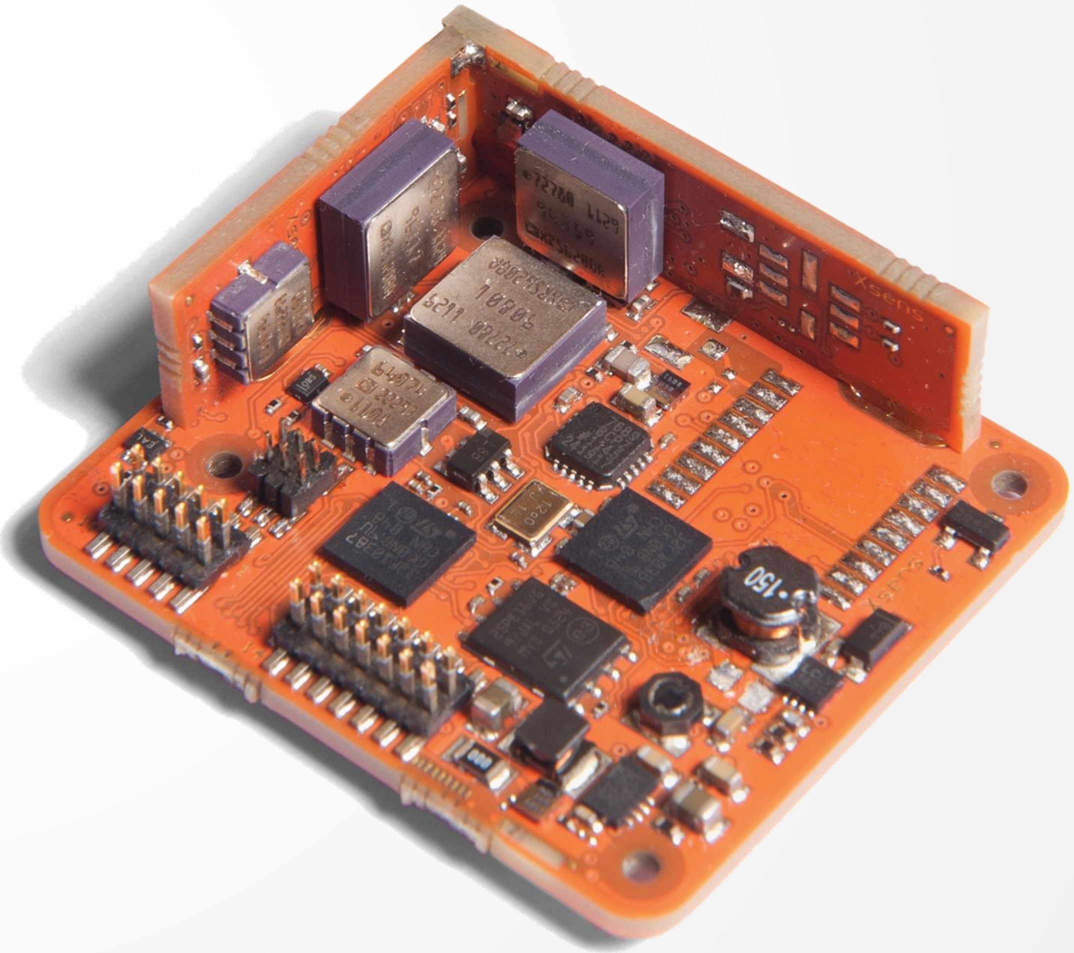
Perception & State Estimation

- *Learn about sensor classifications:*
  - **Proprioceptive sensors**
    - Measure values internally to the robot.
      - Angular rate, heading.
  - **Exteroceptive sensors**
    - Information from the robot environment
      - Distances to objects, extraction of features from the environment.

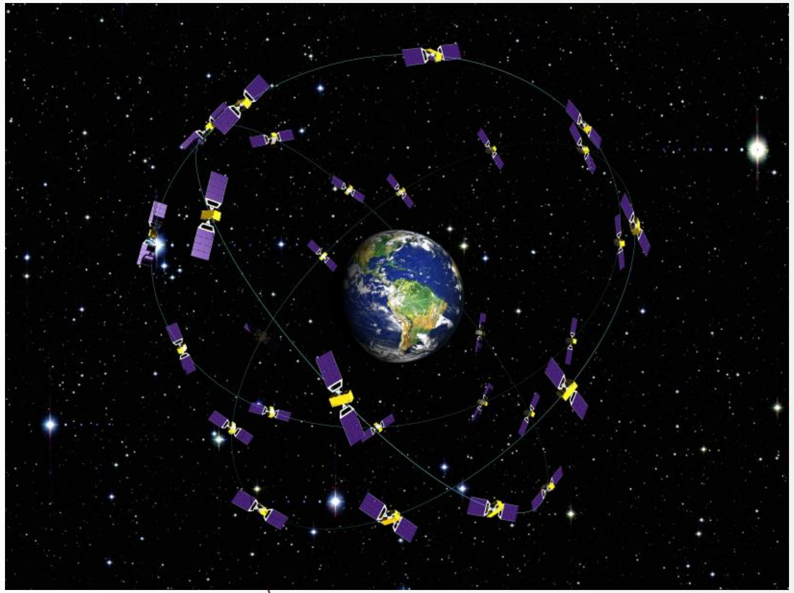
- *And principles of operation:*
  - **Passive Sensors**
    - Measure energy coming from a signal of the environment – very much influenced from the environment.
  - **Active Sensors**
    - Emit their proper energy and measure reaction.
    - Better performance, but some influence on the environment.
    - Not always easily applicable concept.

Perception & State Estimation

- Model and Understand the Role of Inertial Sensors:
  - **Inertial Sensors:**
    - Accelerometers
    - Gyroscopes
  - **Magnetometers (digital compass)**
  - **Pressure Sensors**
    - Barometric pressure for altitude sensing
    - Airspeed measurements
  - **GPS**
  - **Camera based systems**
  - **Time-of-Flight sensors**



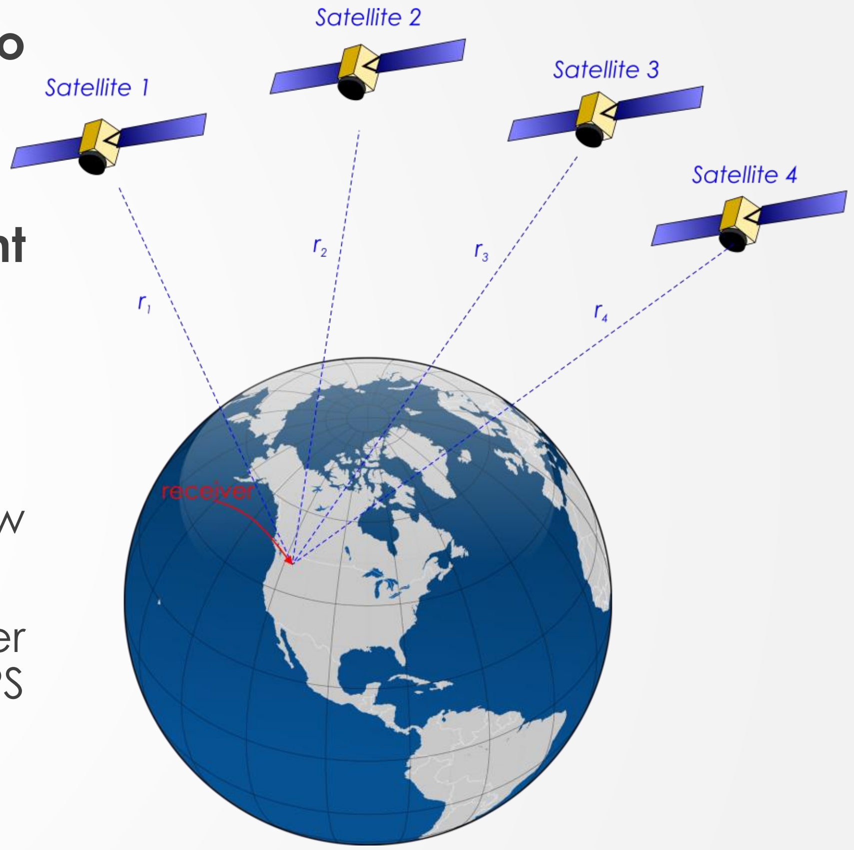
Perception & State Estimation



- Learn about the Global Navigation System and its operational principles-accuracy limitations
- 24 Satellites orbiting the Earth (*and some back-ups*).
- Altitude set at 20,180km
- Any point on Earth's surface can be seen by at least 4 satellites at all times.
- Time-of-Flight of radio signal from 4 satellites to receiver in 3 dimensions.
- 4 range measurements needed to account for clock offset error.
- 4 nonlinear equations in 4 unknown results:
  - Latitutde
  - Longitutde
  - Altitude
  - Receiver clock time offset

Perception & State Estimation

- **Time-of-Flight of the radio signal from satellite to receiver used to calculate pseudorange.**
  - Called pseudorage to distinguish it from true range.
- **Numerous sources of error in time-of-flight measurement:**
  - Ephemeris Data – errors in satellite location
  - Satellite clock – due to clock drift.
  - Ionosphere – upper atmosphere, free electrons slow transmission of the GPS signal.
  - Troposphere – lower atmosphere, weather (temperature and density) affect speed of light, GPS signal transmission.
  - Multipath Reception – signals not following direct path
  - Receiver measurement – limitations in accuracy of the receiver timing.
- **Small timing errors can result in large position deviations:**
  - 10ns timing error leads to 3m pseudorange error.



Perception & State Estimation

Understand how LiDAR works and how it can provide accurate 3D maps

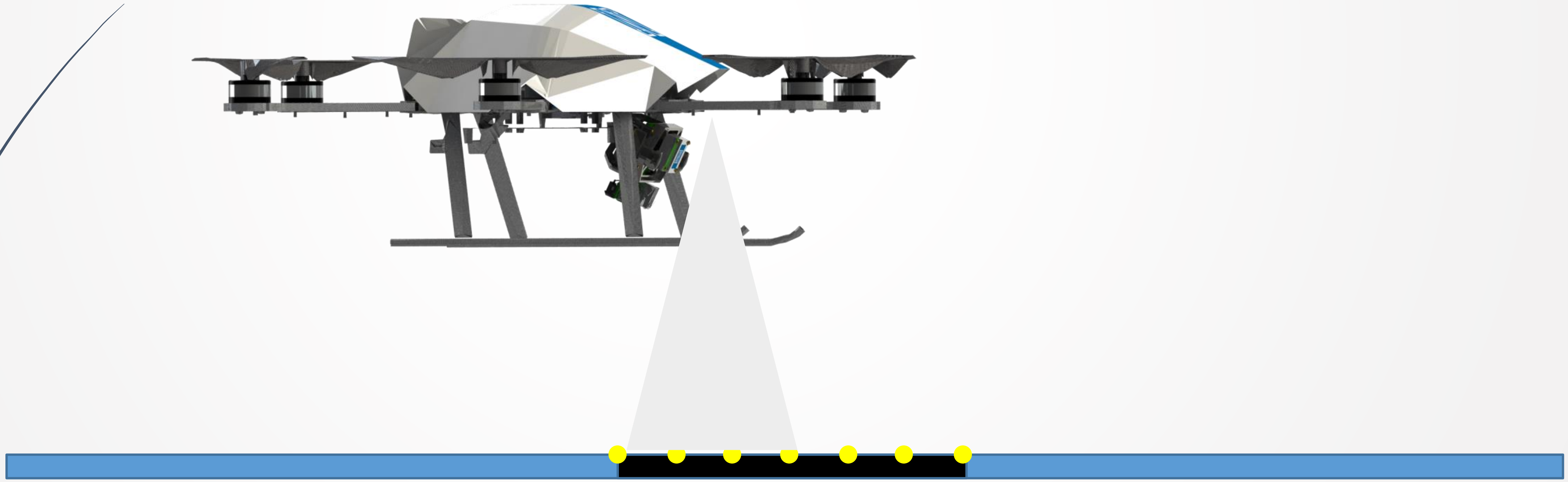
Video from ETH Zurich – Autonomous Systems Lab.

Perception & State Estimation

- Model and Understand Camera Systems
  - **Camera models**
  - **Calibration methods**
  - **Monocular, Stereo, Multi-Camera systems**

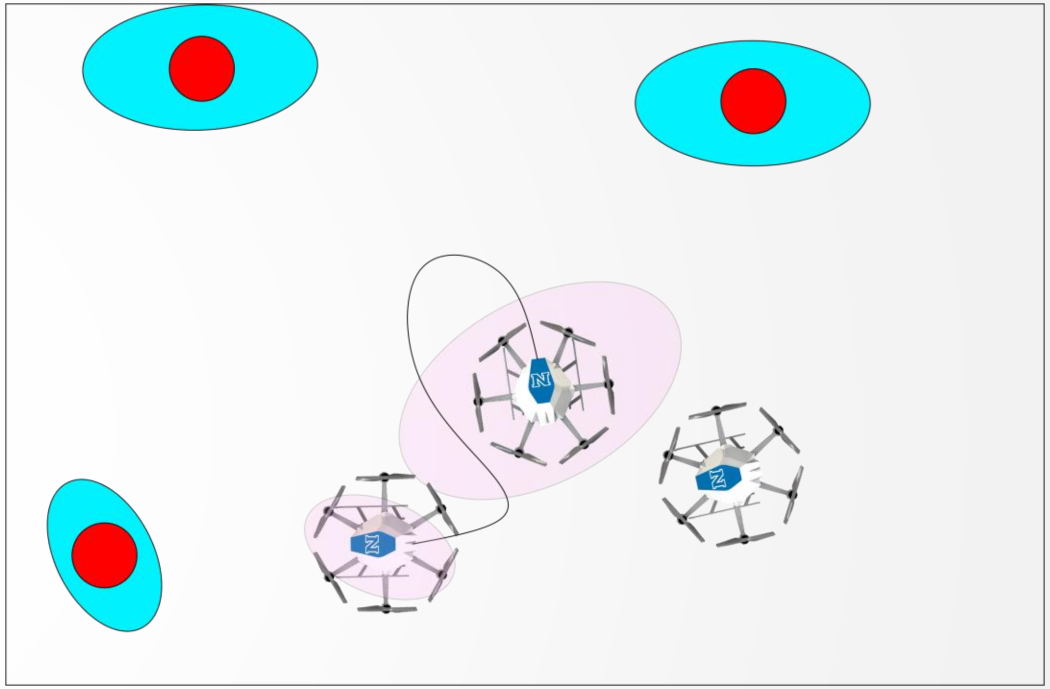
Perception & State Estimation

- Learn the concepts of State Estimation and Kalman Filtering
- Understand how the robot's understanding is always the result of a probabilistic process.



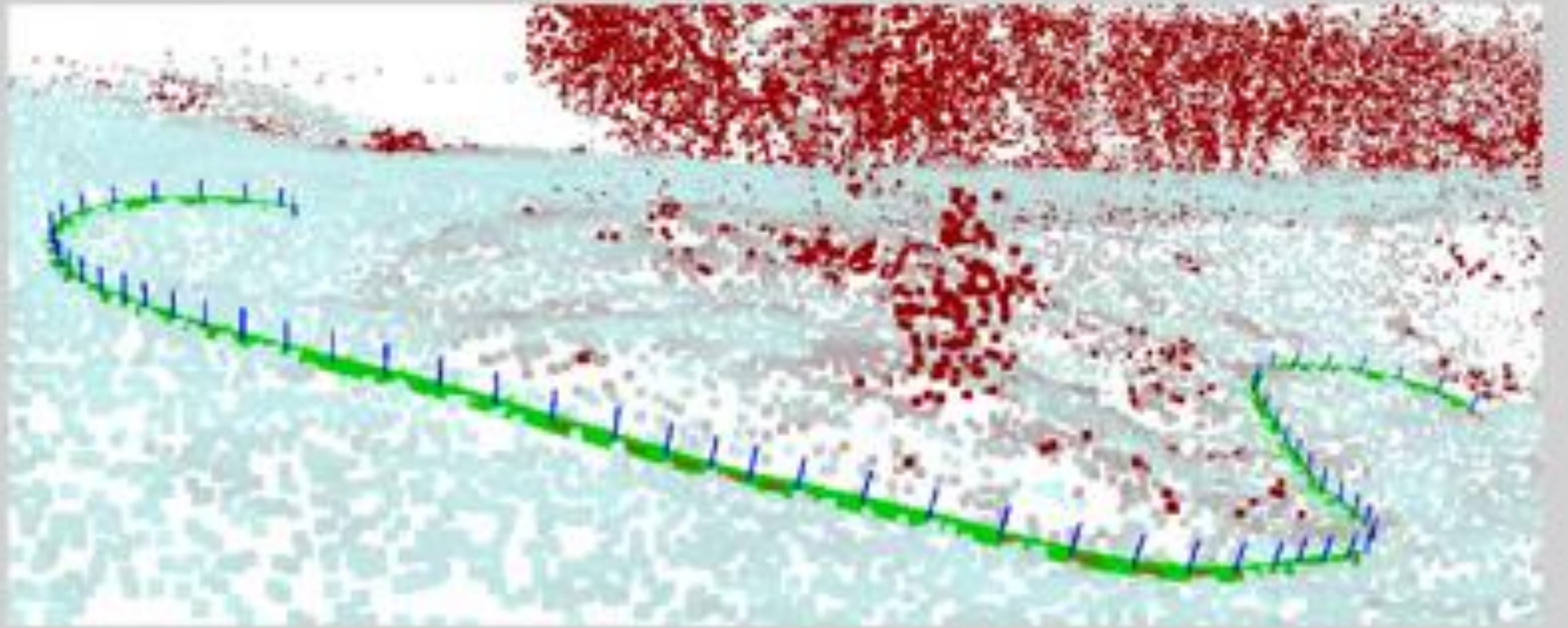
Perception & State Estimation

- Understand Simultaneous Localization And Mapping (SLAM)
  - How a robot solves the problem of knowing where it is and how the map looks based only on on-board sensors and no external information (GPS-denied)
- Learn how localization and mapping is handled as a probabilistic process.
- Learn how to fuse different sensing modalities to assist/improve the SLAM problem.



Driving on Point Clouds

Motion Planning, Trajectory Optimization, and Terrain Assessment in Generic Nonplanar Environments



Philipp Krüsi
Paul Furgale
Michael Bosse
Roland Siegwart

August 25, 2015

ETH zürich

Autonomous Systems Lab

Guidance & Control Systems

- Learn how to design an Autopilot

Guidance & Control Systems

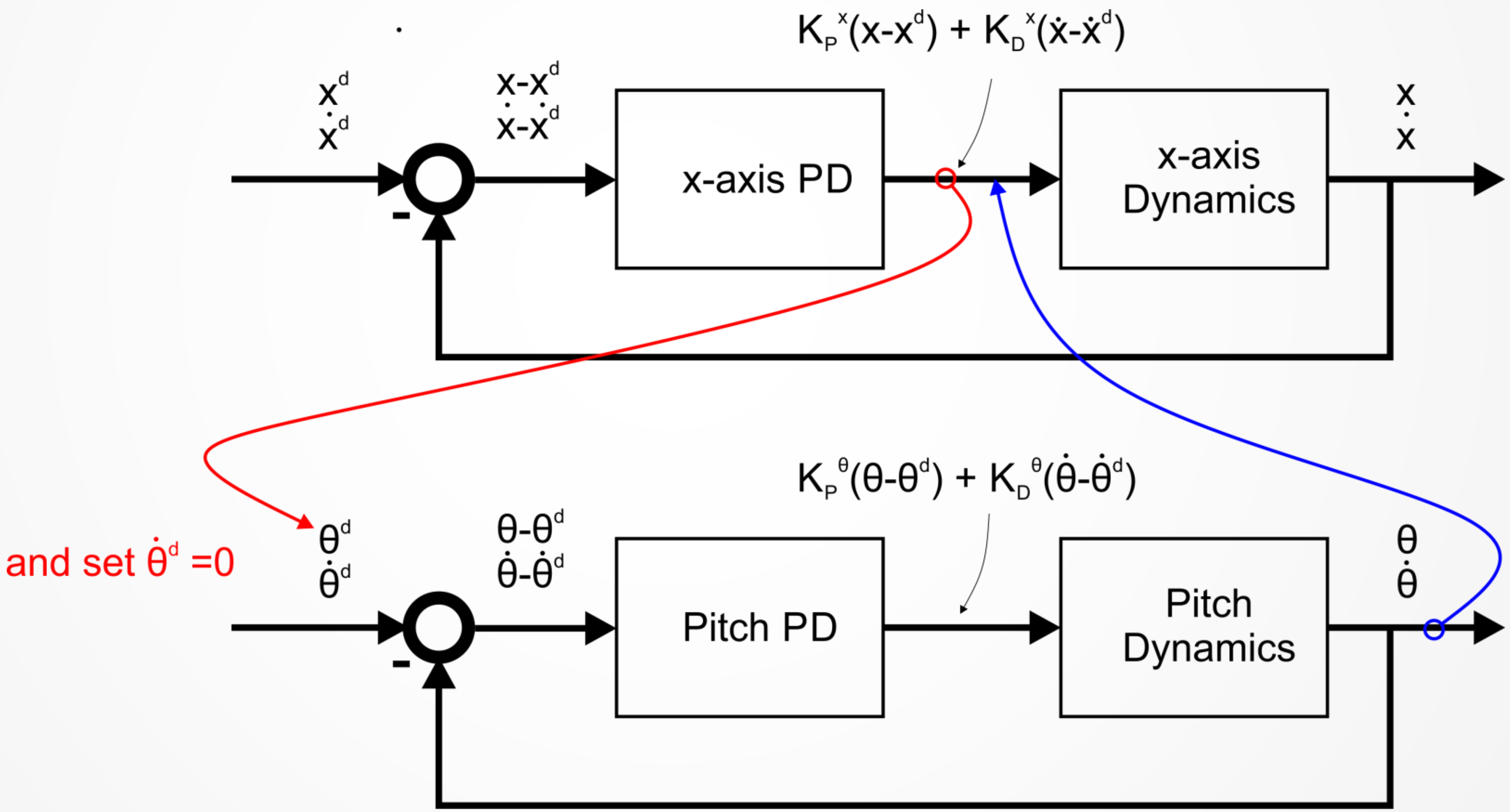
- Lear State Space Representations of vehicle dynamics
- Generic linear (time invariant) state space form:

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}\\ \mathbf{y} &= \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}\end{aligned}$$

- **A** is the system matrix (nxn), **B** is the input matrix (nxp), **C** is the output matrix (qxn), **D** is the feedforward matrix (qxp).
- In general a MIMO system (Multi-Input, Multi-Output)
- In fact a Linear Time Invariant system (LTI). More complex representations exist.

Guidance & Control Systems

- Learn PID Control



Guidance & Control Systems

- And Optimal Control methods such as the Linear Quadratic Regulator
- LQR is an optimal control method for unconstrained systems of the kind

$$\dot{x} = Ax + Bu$$

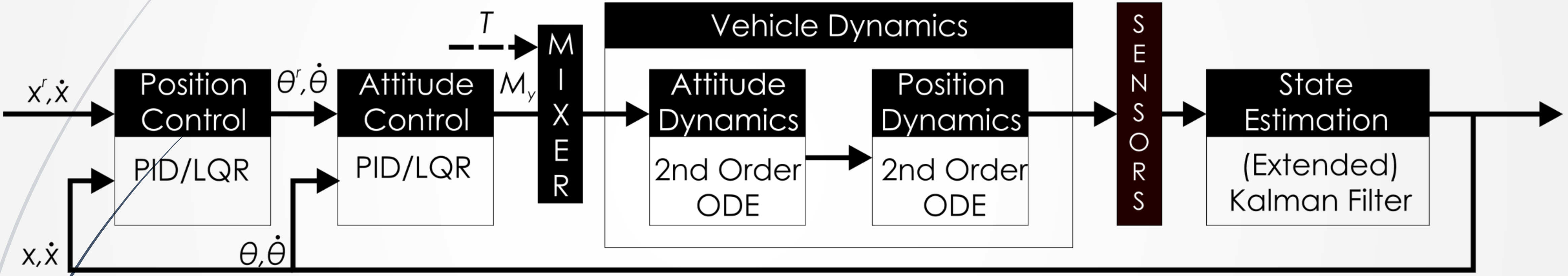
- Supposing we want to design state feedback control $u=Fx$ to stabilize the system, the design of F is a trade-off between the transit response and the control effort. The optimal control approach to this design trade-off is to define the performance index (cost functional):

$$J = \int_0^\infty \left[x^T(t)Qx(t) + u^T(t)Ru(t)\right] dt$$

- and search for the control $u=Fx$ that minimizes this index. Q is an nxm symmetric positive semidefinite matrix and R is an mxm symmetric positive definite matrix.

Guidance & Control Systems

- Learn how each control loop is interconnected to enable full 3D control



Fast Nonlinear Model Predictive Control for Multicopter Attitude Tracking on SO(3)

Mina Kamel, Kostas Alexis, Markus Achtelik and Roland Siegwart

Position tracking without one propeller

Path Planning Algorithms

- **Learning how a robot can determine its robot path based on a set of goals and objectives, a set of robot constraints and subject to a representation and map of the environment.**

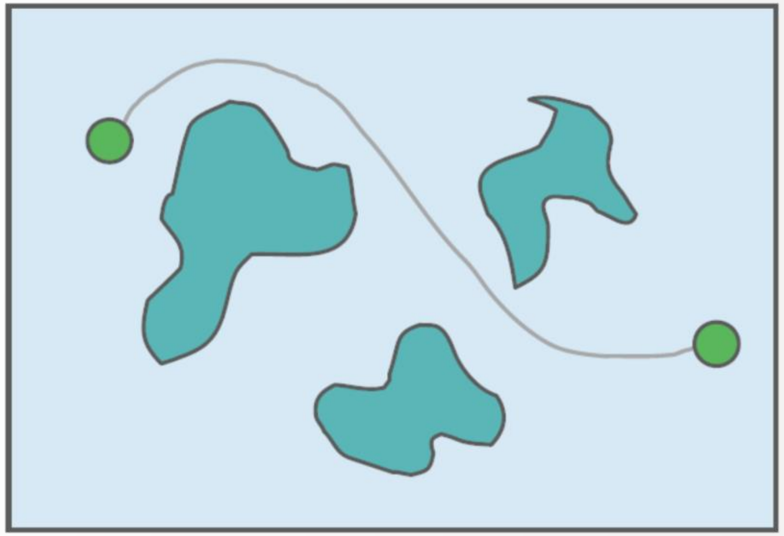
Path Planning Algorithms

- **And its many subtopics and fields**

Motion Planning	Decision-theoretic planning	Planning Under Differential Constraints
Geometric representations and transformations The robot configuration space Sampling-based motion planning Combinatorial motion planning Feedback motion planning	- Sequential decision theory - Sequential decision theory - Sensors and information - Planning under uncertainty	- Differential models - Sampling-based planning under differential constraints - System theory and analytical techniques

Path Planning Algorithms

- **Problem Statement:**
  - Compute a continuous sequence of collision-free robot configurations connecting the initial and goal configurations.



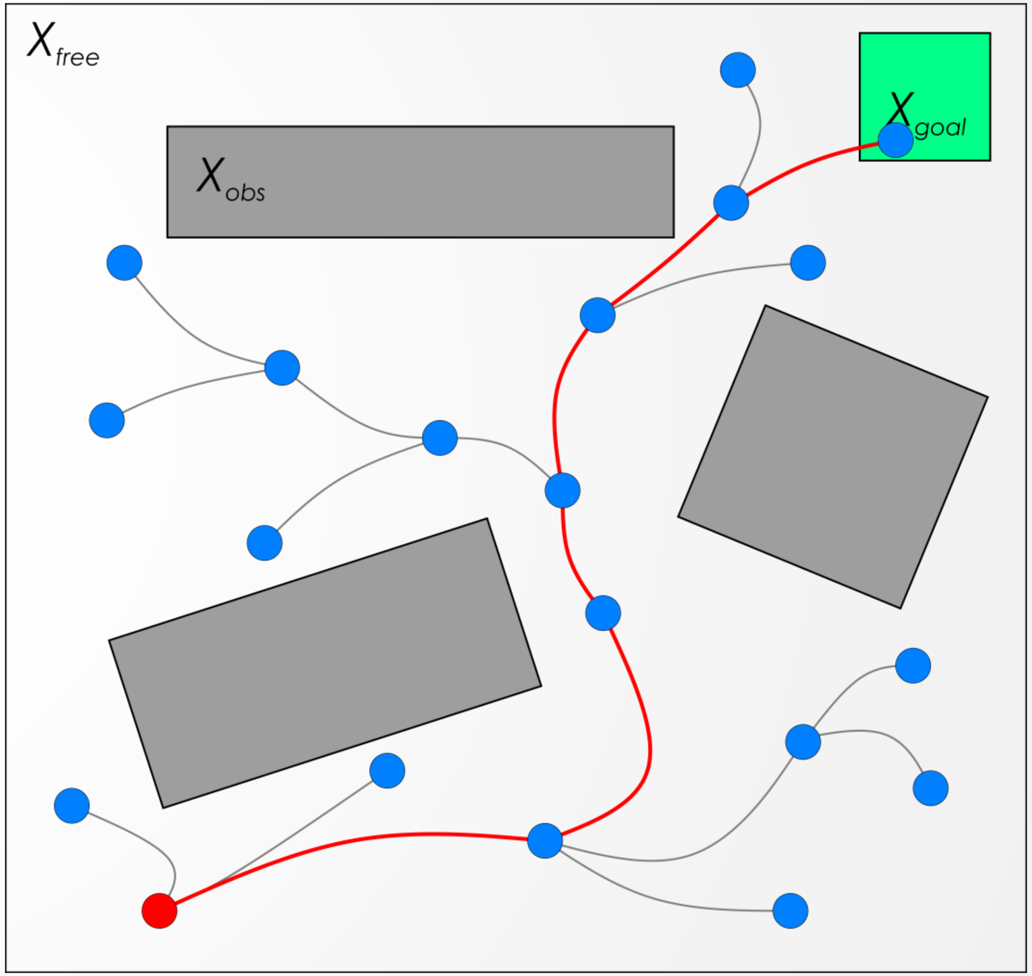
- Geometry of the environment
- Geometry and kinematics of the robot
- Initial and goal configurations

Path Planner

Collision-free path

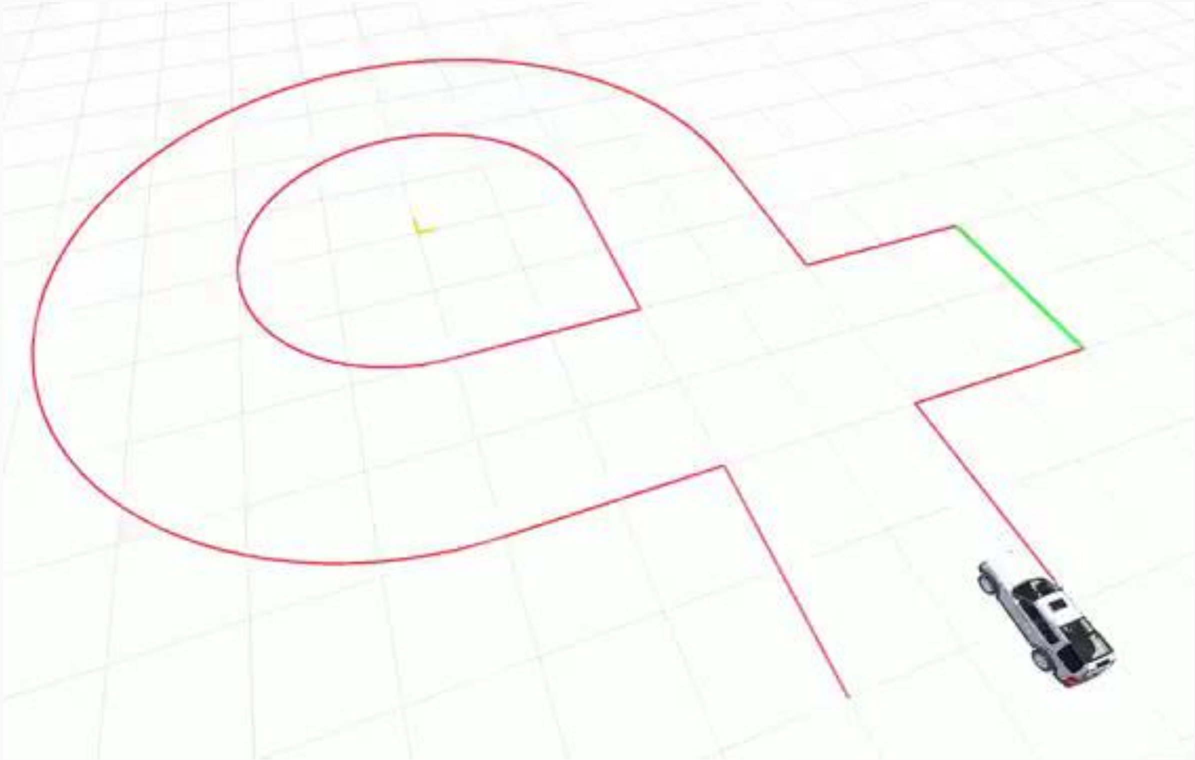
Path Planning Algorithms

- Understanding Sampling-based planning algorithms.
  - How randomized sampling can provide probabilistic completeness
  - How randomized sampling through trees and graphs can be used to solve point-to-point navigation, inspection and exploration problems.



Path Planning Algorithms

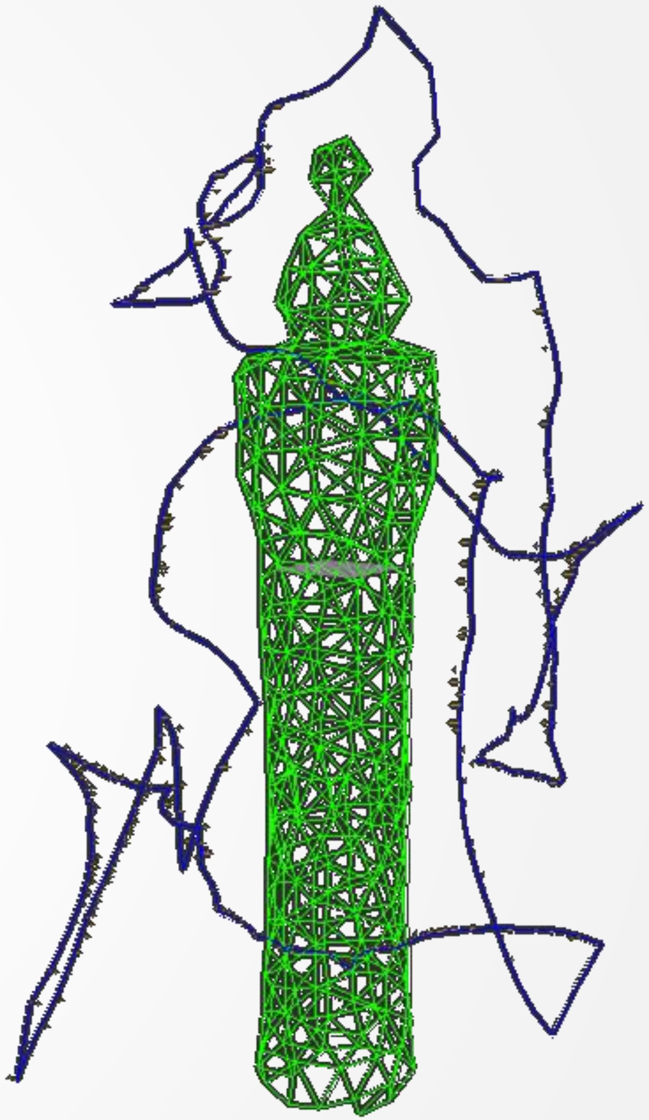
- How to optimally navigate inside a complex environment?



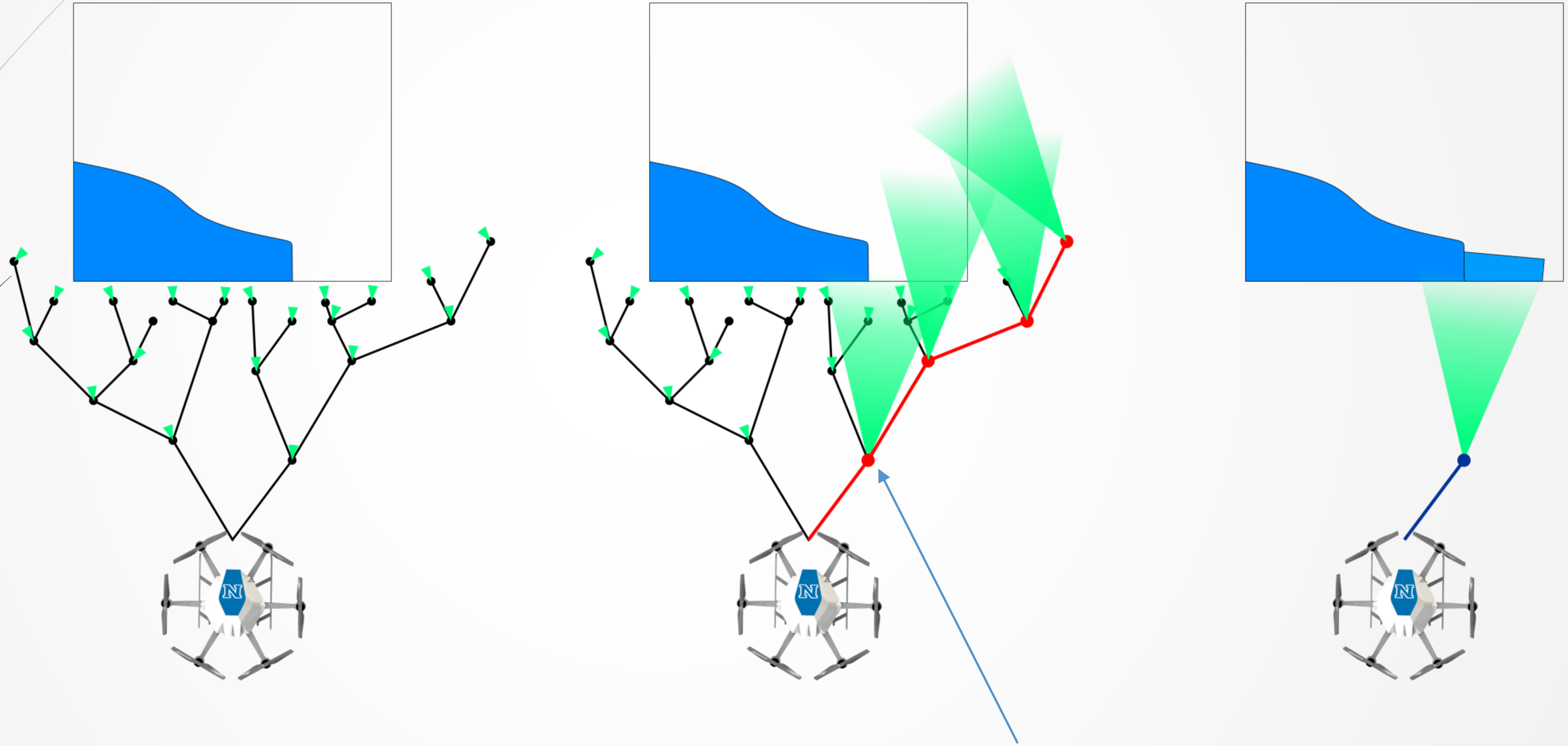
Video Sertac Karaman, MIT

Path Planning Algorithms

- **How to find a solution to inspection the whole surface?**



Path Planning Algorithms



- How to efficiently explore unknown space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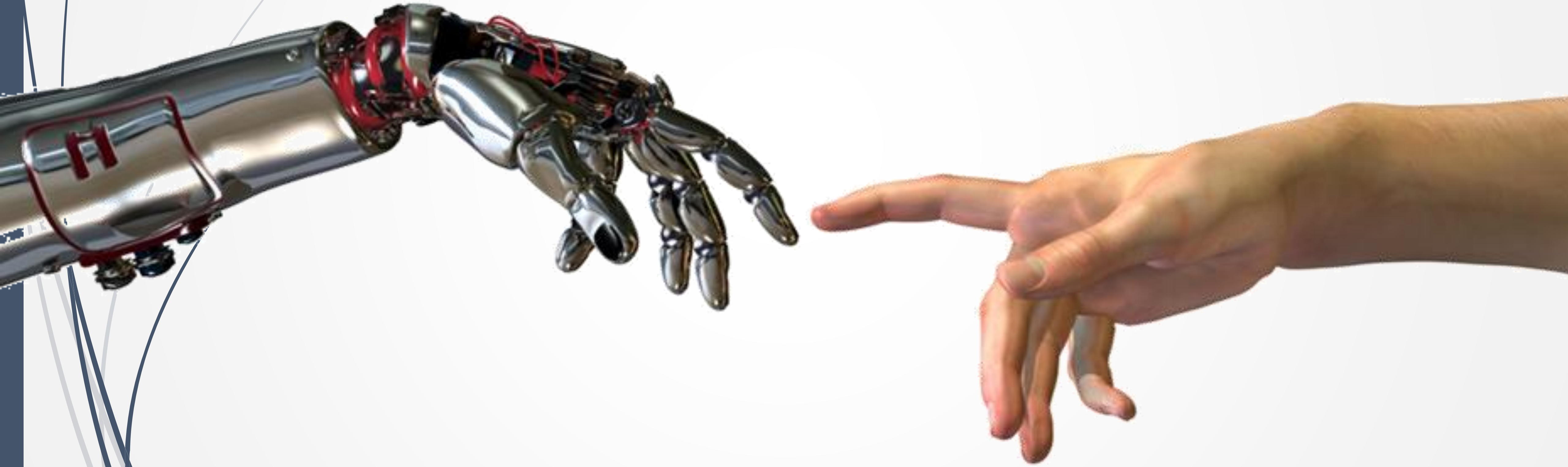
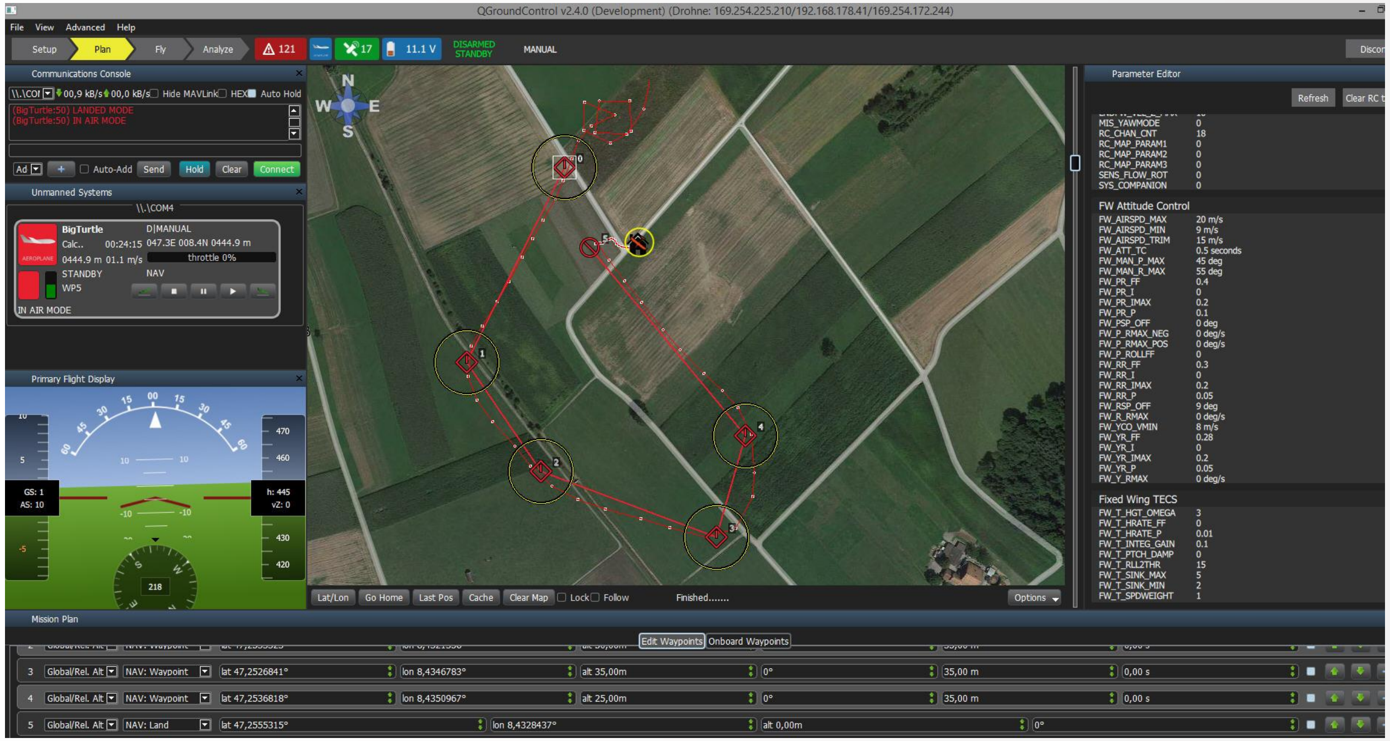
Human-Robot Interface

- Learn intuitive methods to integrate a human with an autonomous robot



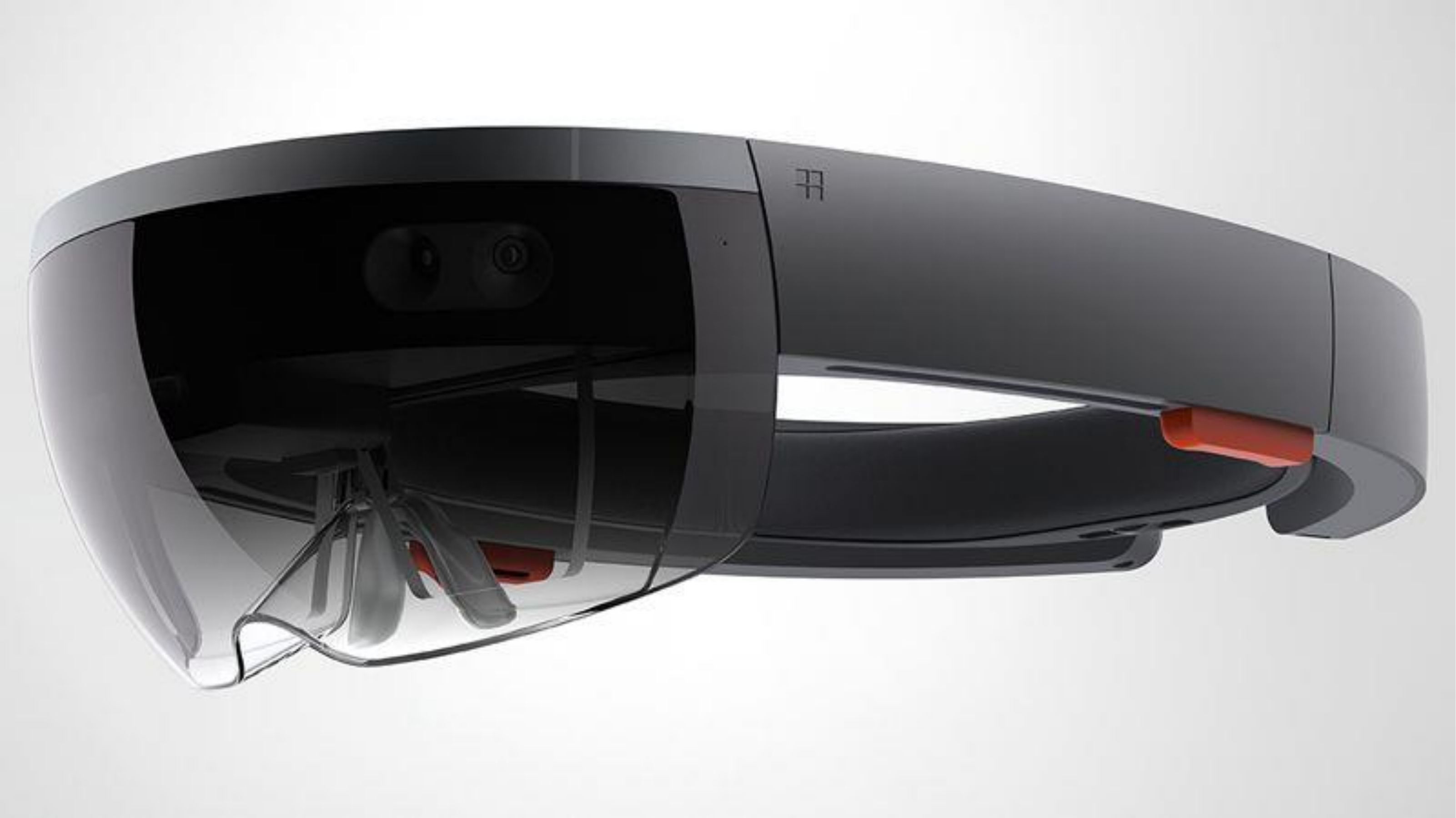
Human-Robot Interface

- From efficient and simple GUI design



Human-Robot Interface

- To augmented reality integration

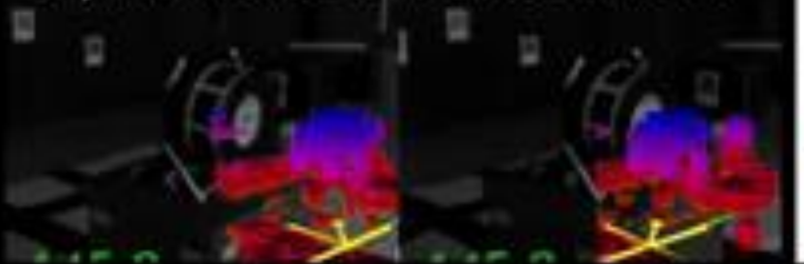


Augmented Reality-enhanced Structural Inspection using Aerial Robots

Christos Papachristos, Kostas Alexis

Augmented Reality

Synthetic Stereo View



Autonomous Flight

Accurate 3D Reconstruction

Autonomous Robots Lab, University of Nevada, Reno

Thank you!

Please ask your question!