CS491/691: Introduction to Aerial Robotics

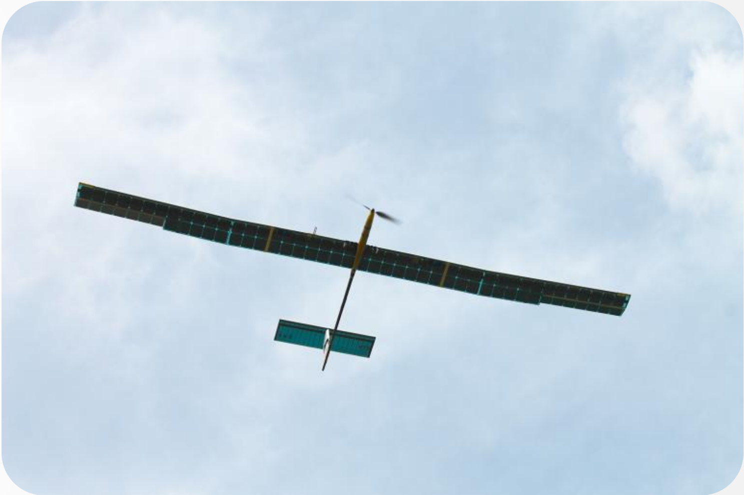
Dr. Kostas Alexis (CSE)

Course Goals

- Develop a broad understanding on how aerial robots fly and operate.
- Develop the capacity to design navigation and other automation and autonomy robot functionalities.
- Combine theory with intuition and practice.
- Be able to implement new ideas in practice.
- Provide the knowledge background and the tools for your further steps in aerial (and not only) robotics.

Course Approach

- **Brief Overview and Focus Sections:** Each topic is overviewed and selected subtopics are thoroughly described.
- **Coding Examples:** Each focus section is accompanied with coding examples using Python, MATLAB and C++
- **Project-oriented:** You will be asked to implement your ideas in practice and therefore develop more solid understanding by doing so.
- *Be Proactive & Autonomous:* come and discuss what you want to understand better or what you want to know more about. Grow your own ideas.



Course Contents

- **Introduction:** Get a broad understanding about aerial robotics, what they are, what they look like, what they can do and how they do so.
- **Modeling:** Understand the physical principles behind the flight dynamics of aerial robotics and develop the capacity to derive their mathematical model.
- **State Estimation:** Learn how on-board estimation of the vehicle full pose (position and orientation) takes place.
- **Flight Controls:** Learn how to design high-performance flight controllers.
- **Motion Planning:** Learn how to develop algorithms for autonomous motion planning for aerial robotics.
- **Case Study and Design Projects:** Go through a design experience.

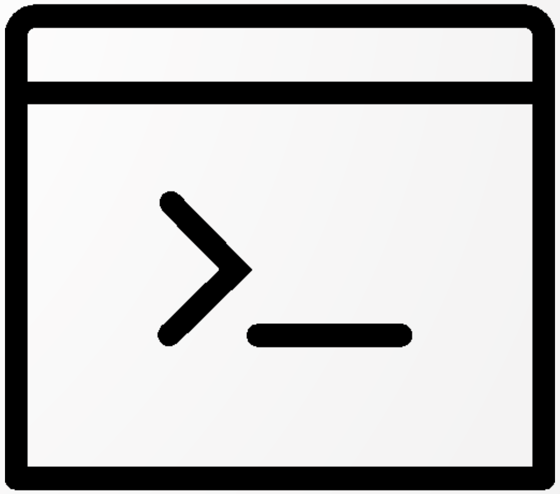
Course Material

- **Online Textbook:** a brief textbook covering the topics of the course. To be continuously updated every year.
- **Textbook:** Small Unmanned Aircraft: Theory and Practice
- **Lecture Slides:** Used for the classroom presentations and also as a way for notes keeping and direct reference to the course contents.
- **Coding Examples:** small programs written in Python, MATLAB, and C++ covering the focus sections of the course.
- **Open-Source Aerial Robots Simulator:** a complete simulation environment for advanced designs.

- **Get the course material:** The complete set of the relevant materials are available at: http://www.autonomousrobotslab.com/introduction-to-aerial-robotics.html

Course Grading System

- **Design Project with intermediate report:** 40%
- **Homework:** 15%
- **Mid-term Exam:** 20%
- **Final Exam:** 25%

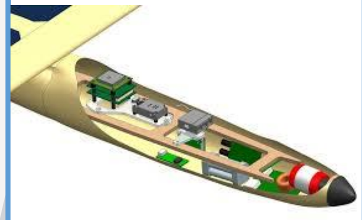


Tentative scale (curve will be applied)

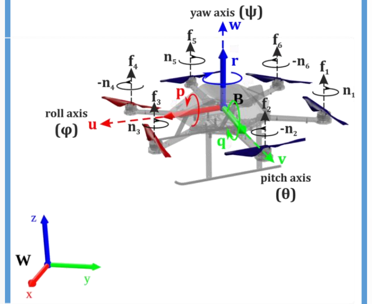
- **Grade >= 90:** A
- **80 <= Grade <= 89:** B
- **70 <= Grade <= 79:** C
- **60 <= Grade <= 69:** D
- **59 >= Grade:** F

Course Projects

System Design



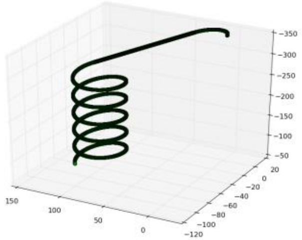
Modeling



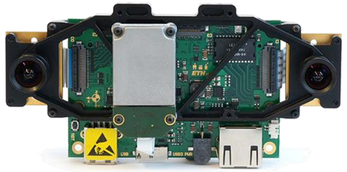
Estimation

Flight Control

Path Planning

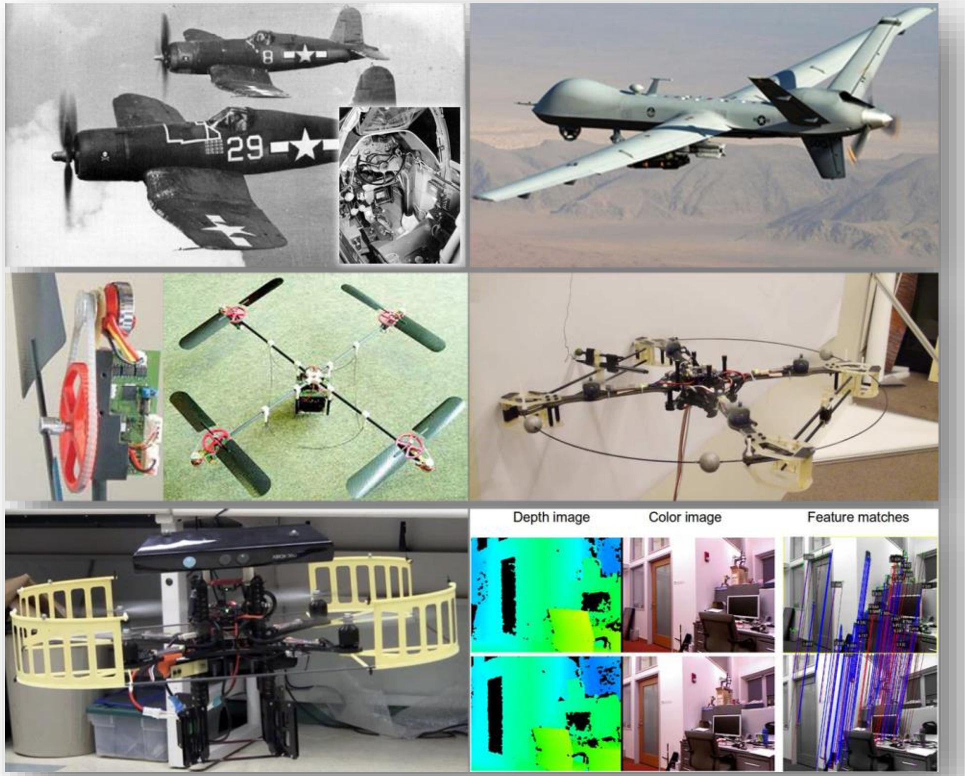


Perception

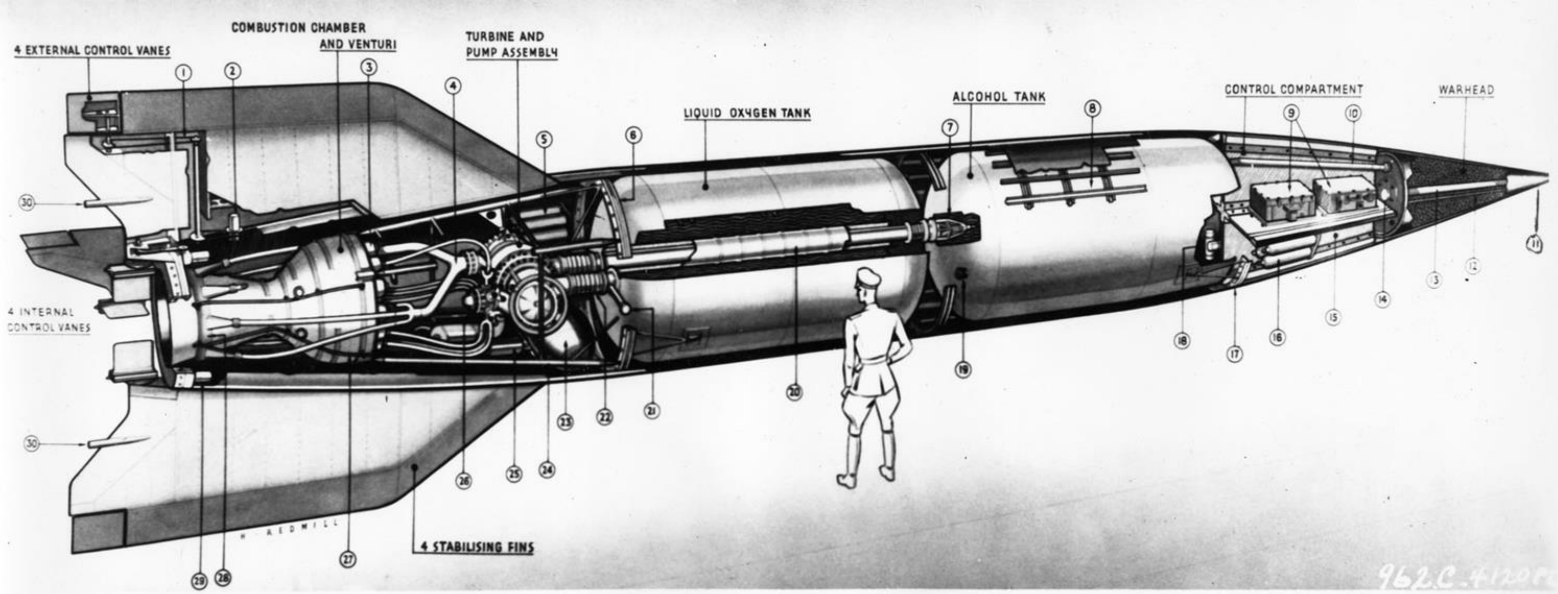


Historical Background of Aerial Robots

- Unmanned Aerial Vehicles lie on the foundations set in aircraft design & automatic flight control.
- First UAVs were based on modifications of manned rocket and aircraft designs.
- Their evolution process has constantly challenged the limits of technology towards miniaturization, flight control agility, perceptual skills, navigational autonomy, flight endurance or even unconventional skills such as aerial manipulation.



Historical Background of Aerial Robots



V2 Rocket photo and diagram

Historical Background of Aerial Robots

Predator UAV used by NASA

AscTec Hummingbird used by TUM

The main challenges of Aerial Robotics

How do I …

The main challenges of Aerial Robotics

Propulsion and Vehicle Dynamics

How do I move?

The main challenges of Aerial Robotics

Perception and State Estimation

Where am I?
What is my
environment?

The main challenges of Aerial Robotics

Guidance and Control

How do I control where to go?

The main challenges of Aerial Robotics

Path Planning

How do I plan my motion and actions?

Current Trends in Aerial Robotics

AscTec Firefly with VI-Sensor, UNR

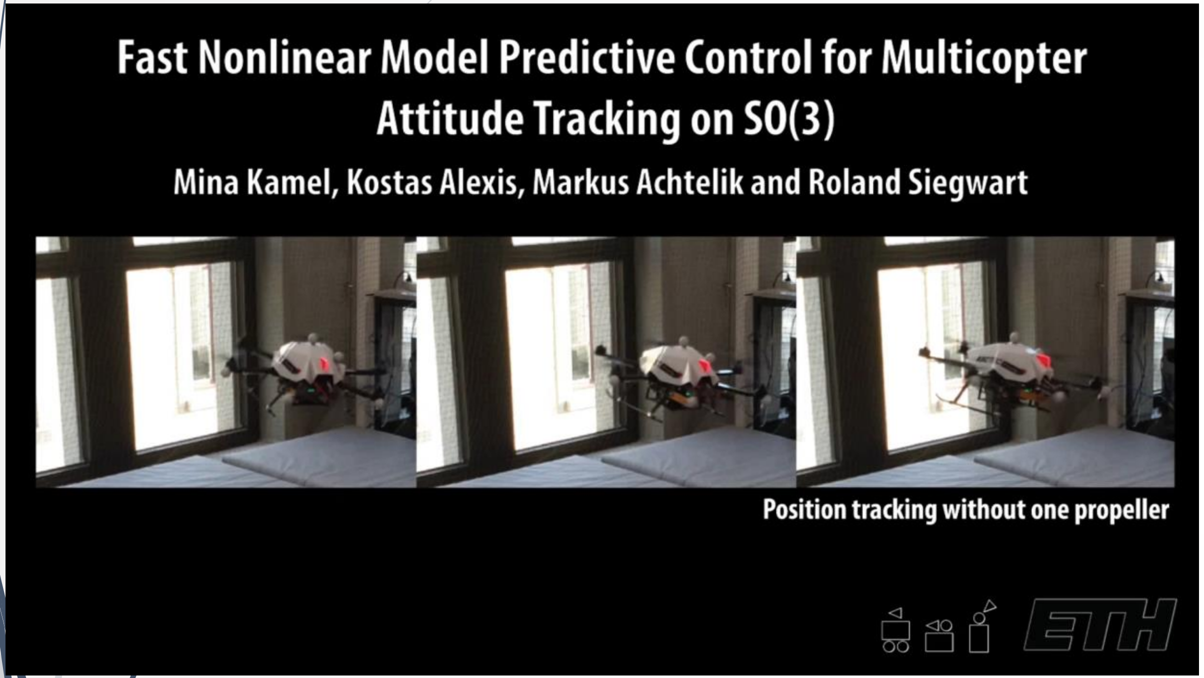
AtlantikSolar UAV, ETH Zurich

- System Miniaturization
- Prolonged Endurance
- Agile Flight Control
- Perception & 3D Mapping
- Autonomous Motion Planning
- Multi-Robot Systems
- Augmented Human-Robot

VI-Sensor, ETH Zurich

Oculus Rift, Oculus

Current Trends in Aerial Robotics

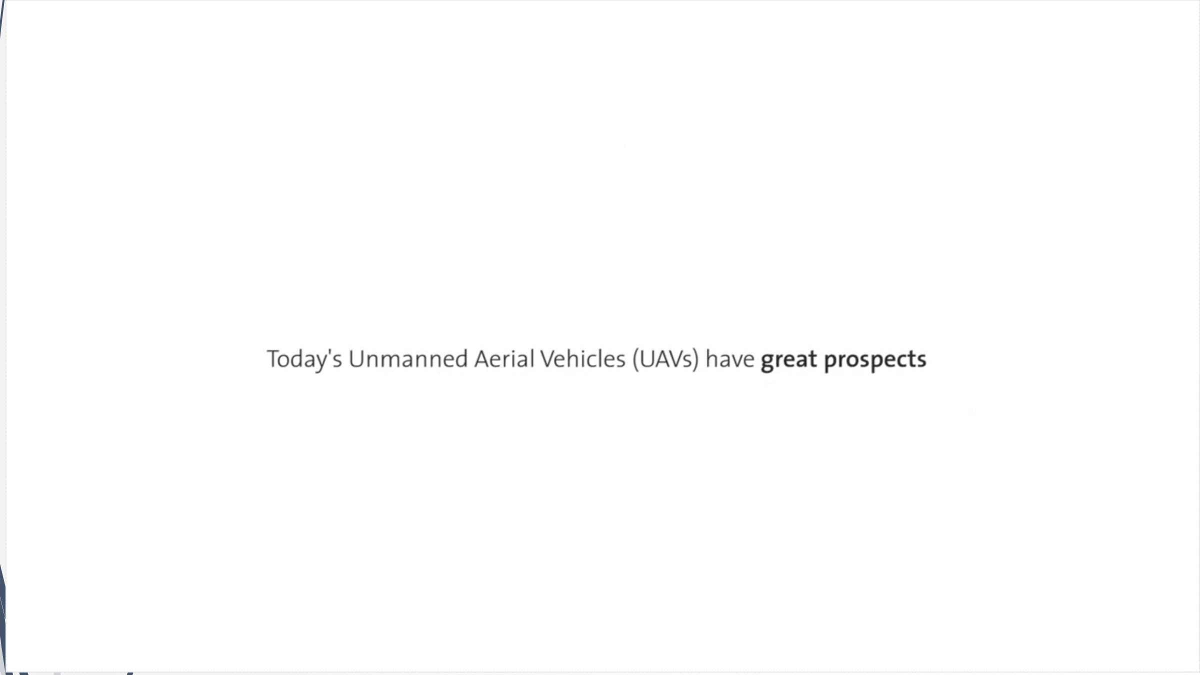


Retaining Stability during Propeller Failure

Convertible Unmanned Aerial Vehicle

Relevant Web link: http://www.autonomousrobotslab.com/agile-and-physical-interaction-control.html

Current Trends in Aerial Robotics

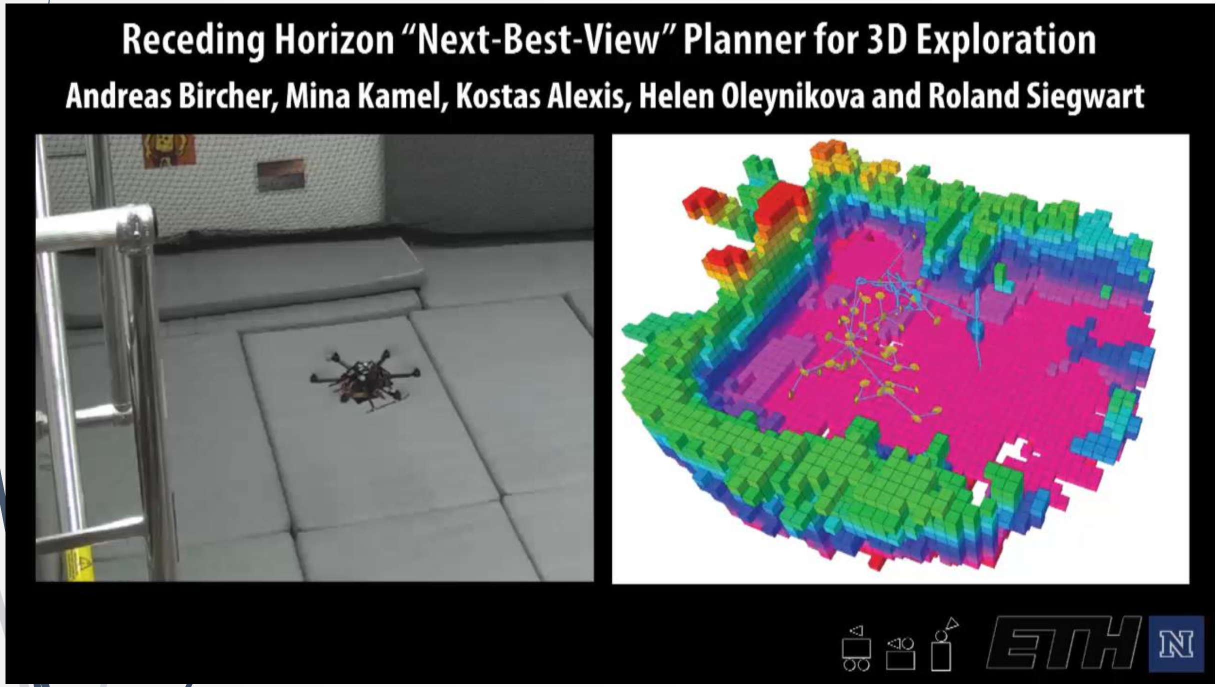


Endurance World Record (81.5 Solar-powered Flight)

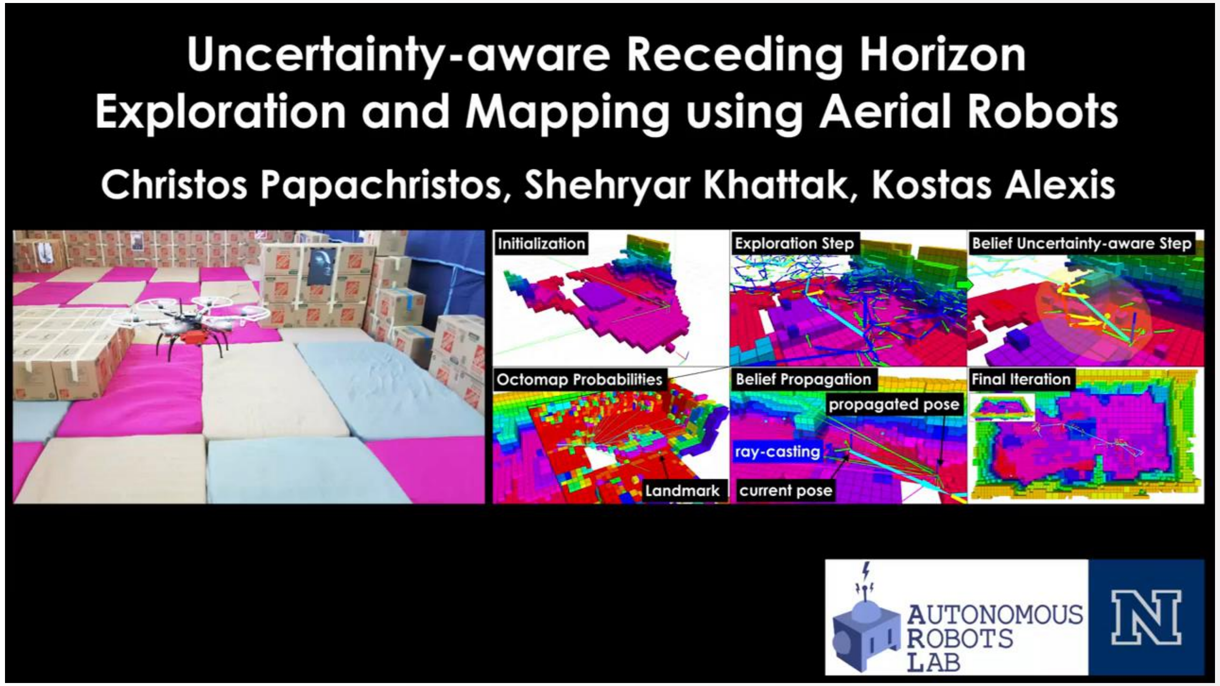
Aerial Mapping

Relevant Web link: http://www.autonomousrobotslab.com/fixed-wing-uavs.html

Current Trends in Aerial Robotics



Information Gain-based Efficient Exploration and 3D mapping of Unknown Environments



Uncertainty-aware Receding Horizon Exploration and Mapping

Relevant Web link: http://www.autonomousrobotslab.com/autonomous-navigation-and-exploration.html

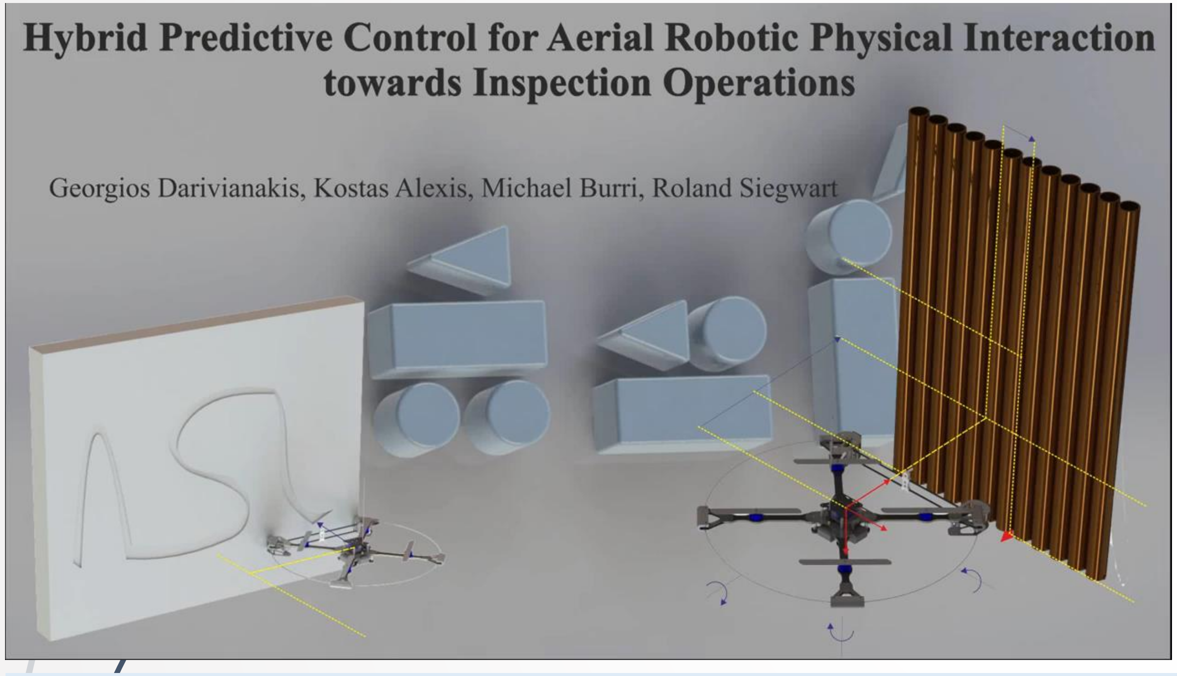
Current Trends in Aerial Robotics

Degraded visual environment exploration and mapping

Multi-modal fusion for localization and mapping

Relevant Web link: http://www.autonomousrobotslab.com/localization-and-3d-reconstruction.html

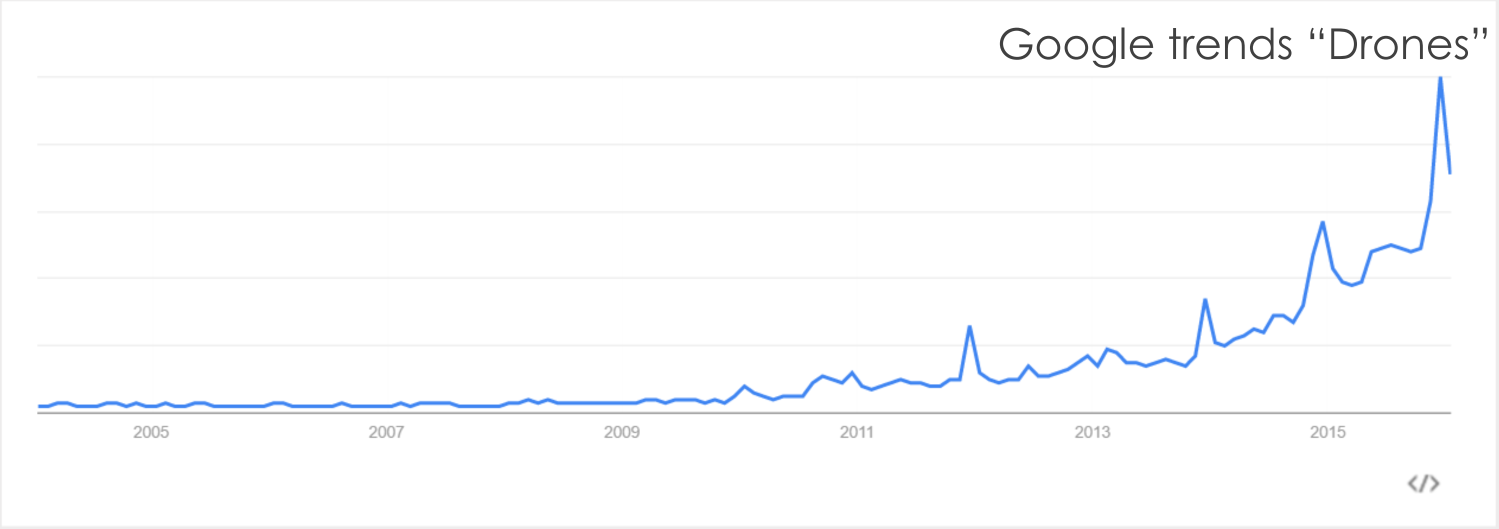
Current Trends in Aerial Robotics



Physical Interaction Control

Relevant Web link: http://www.autonomousrobotslab.com/agile-and-physical-interaction-control.html

Impact in Society



- Unmanned Aerial Vehicles (UAV) Market worth 14.9 Billion USD by 2020

MARKETSANDMARKETS

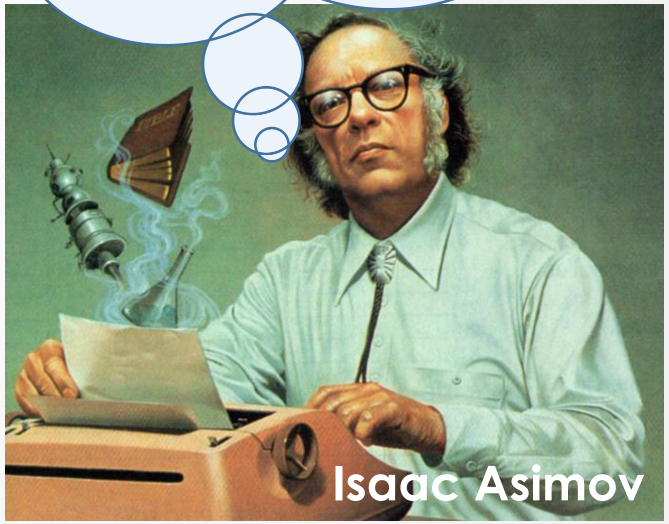
- **Indicative Applications:**
  - Infrastructure Inspection and Maintenance
  - Humanitarian Assistance
  - Precision Agriculture
  - Climate Control
  - Security
  - …and much more!

What are the challenges ahead?

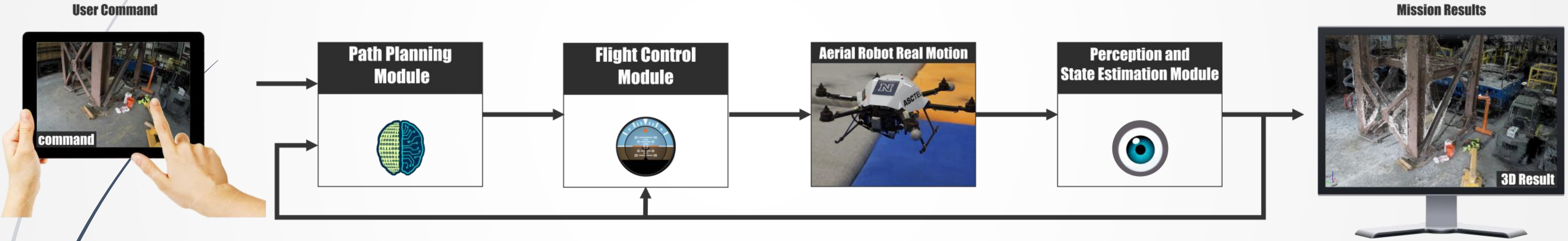
No sensible decision can be made any longer
without taking into account not only
the world as it is, but the world as it will be. ***I.A.***

- a robot may not injure a human being or, through inaction, allow a human being to come to harm
- a robot must obey orders given it by human beings except where such orders would conflict with the first law
- a robot must protect its own existence as long as such protection does not conflict with the first or second law

- Can we operate aerial robots without having special skills?
- Can aerial robots be something more than a flying camera?
- Can we assign complex tasks to autonomous robots?
- Can we ensure collision avoidance?
- Can we trust an aerial robot flying in the urban landscape? In the controlled national airspace?



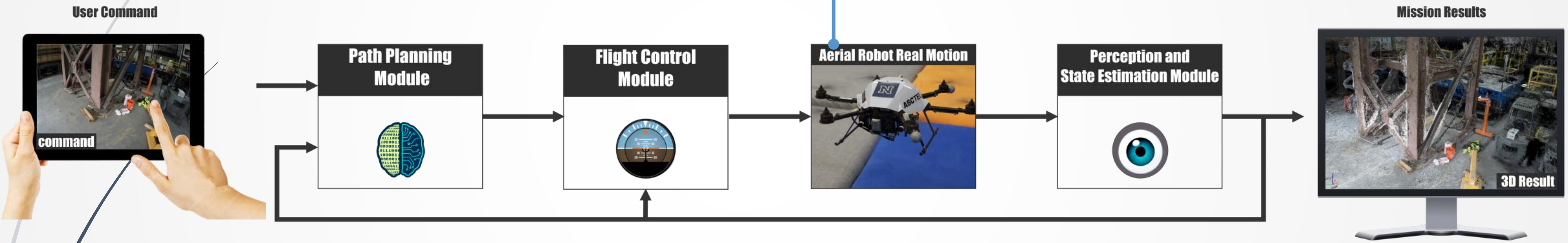
The Aerial Robot Loop



Block diagram of the main loops running at every aerial robot

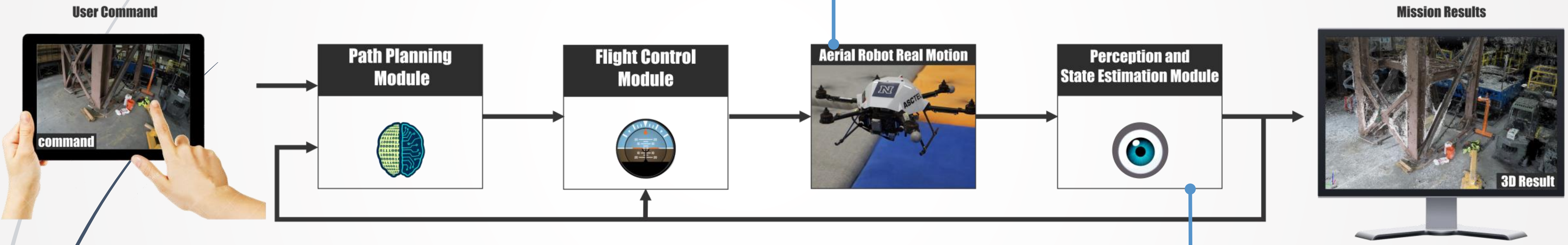
The Aerial Robot Loop

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



The Aerial Robot Loop

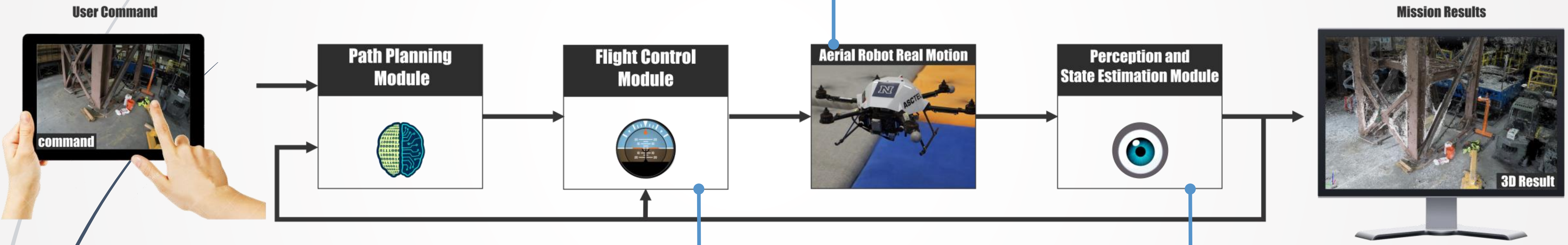
- Real-life Aerial Robot expressing its dynamic behavior in response to the control inputs and external disturbances



- Inertial Navigation System
- Localization & Mapping
- Sensor Fusion

The Aerial Robot Loop

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



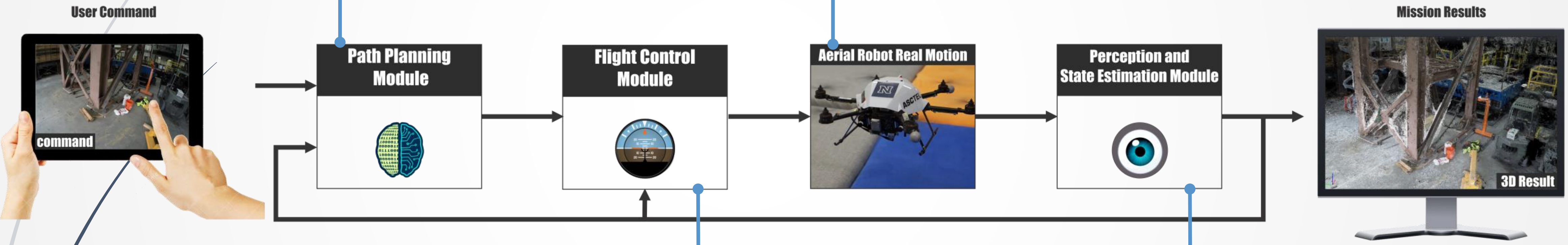
- Flight control system responsible for ensuring flight stability and reference trajectory tracking as well as disturbance rejection.

- Inertial Navigation System
- Localization & Mapping
- Sensor Fusion

The Aerial 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 Aerial Robot expressing its dynamic behavior in response to the control inputs and external disturbances

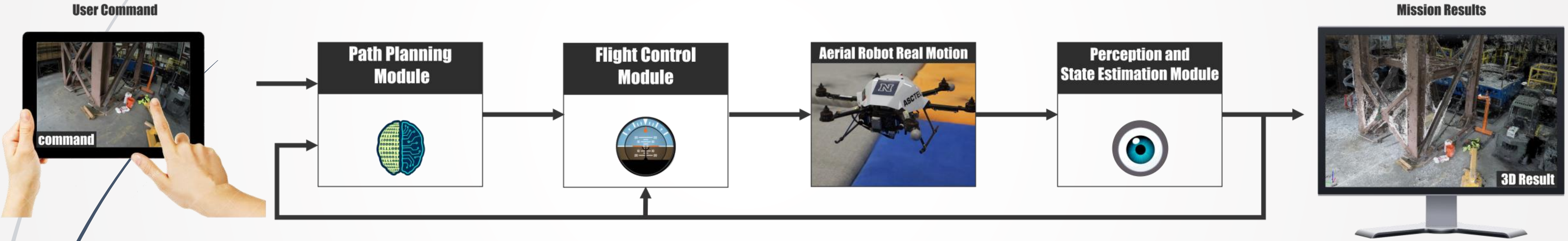


- Flight control system responsible for ensuring flight stability and reference trajectory tracking as well as disturbance rejection.

- Inertial Navigation System
- Localization & Mapping
- Sensor Fusion

The Aerial Robot Loop

A hard real-time system with relatively limited computational resources!

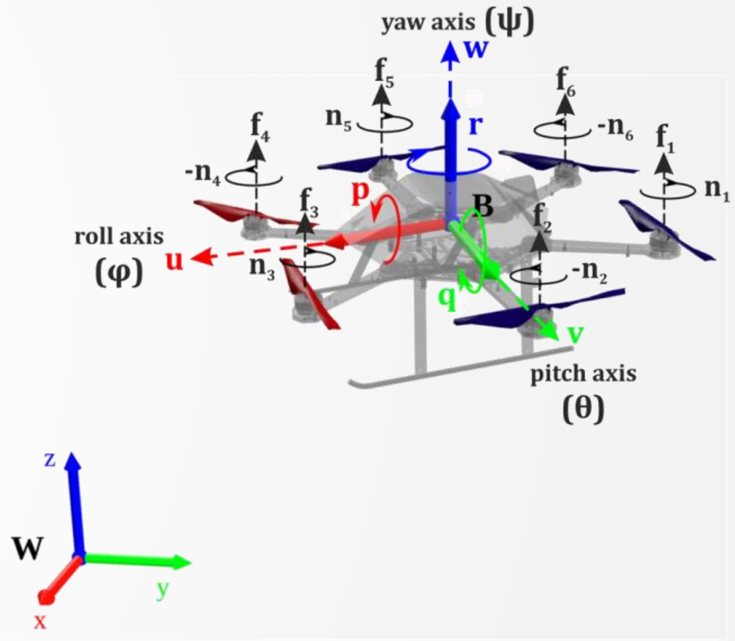


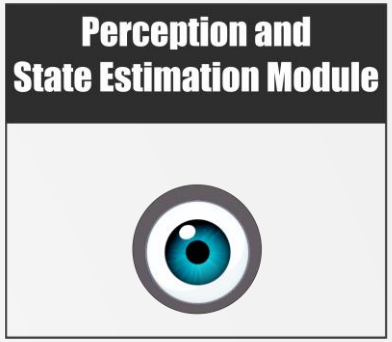
The Robot Platform

- Different aerial vehicle configurations satisfy different needs in terms of precision flight, endurance, operational requirements, robustness, payload capacity and more.
  - Rotorcraft Systems
  - Fixed-Wing Systems
  - Hybrid Systems
  - Biomimetic Systems
  - Lighter-than-Air Systems

The Robot Platform

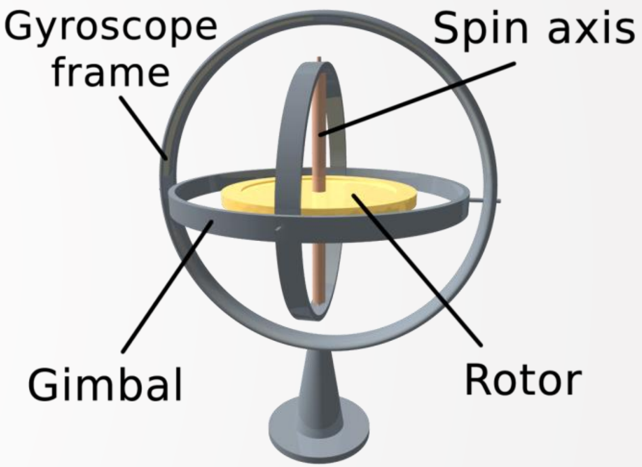
- **Derivation of the Vehicle Dynamics Model:** A complex mathematic process that heavily depends on the good understanding of the following topics:
  - Frame Rotations, Representations and Coordinate Systems
  - Rigid Body Dynamics Modeling
  - Derivation of Aerodynamic Forces
- Modeling is a critical step that enables state estimation, flight control and prediction of the flight behavior of the vehicle.
- As part of this course we will derive a first-level model of a multirotor Micro Aerial Vehicle and a Fixed-Wing UAV





Perception & State Estimation

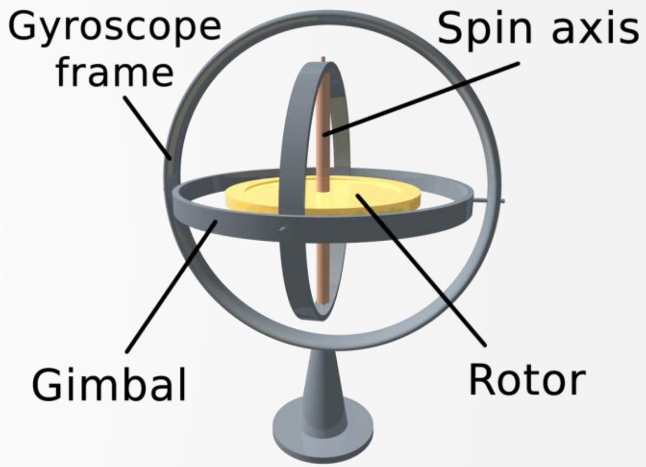
- The process of using data coming from different sensors on-board in order to estimate (in real-time) the state of the vehicle (position, orientation and possibly aerodynamic and other high-order states). Typical sensors employed are:
  - Accelerometers
  - Gyroscopes
  - Magnetometer
  - GPS
  - Camera systems
  - LiDAR
  - Structured-light sensors
  - …and more
- It corresponds to fundamental loop for the robot operation and critical to advance its autonomy.



Perception and State Estimation Module

Perception & State Estimation

- The sensor data fused to estimate the full state in a bias-free and accurate way in high-update rates. This process depends on methods of the state estimation theory. Within this course, we will investigate:
  - Inertial sensing
  - The concepts of Kalman Filtering
  - The design of an Inertial Navigation System



Flight Control System

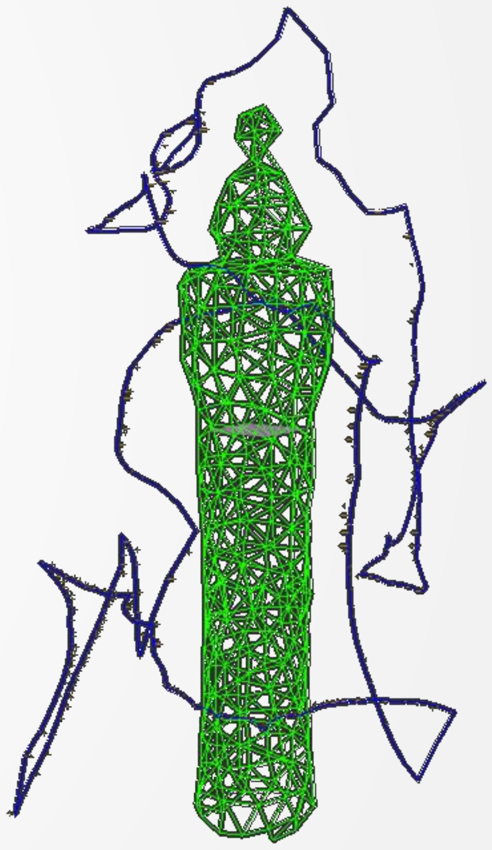
- The Flight Control System is responsible to ensure the closed-loop stability of the vehicle and guarantee high performance trajectory tracking despite possible uncertainty in the modeled dynamics and the effects of external disturbances.
- Flight Control System design relies on concepts of control theory and a precise enough but simple model of the vehicle dynamics that allows model-based control.
- Flight control theory is a huge field and the community has proposed numerous alternative approaches towards providing aerial robots with the desired flying qualities.

Flight Control System

- Within the framework of this course we will examine some basic and a few advanced methods on flight control synthesis. More specifically, we will cover the following topics:
  - Proportional Integral Derivative control
  - Linear Quadratic Regulator control
  - Linear Model Predictive Control
- While, we will then investigate an autopilot design example and apply the relevant control strategies.

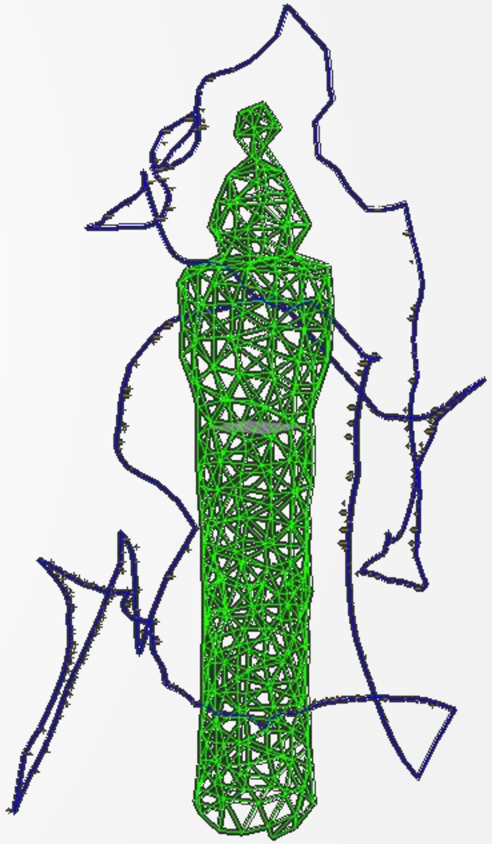
Path Planning

- Path planning is the process of deriving the path that the robot should follow in order to ensure safe navigation and successfully execute its mission. The problems attached through the relevant methods include the following:
  - Collision-free Navigation
  - Inspection Path Planning
  - Target Follow
  - Coordinated Motion
  - Collaborative Aerial Manipulation
  - …and more
- It corresponds to a critical topic to advance the aerial robotics autonomy.



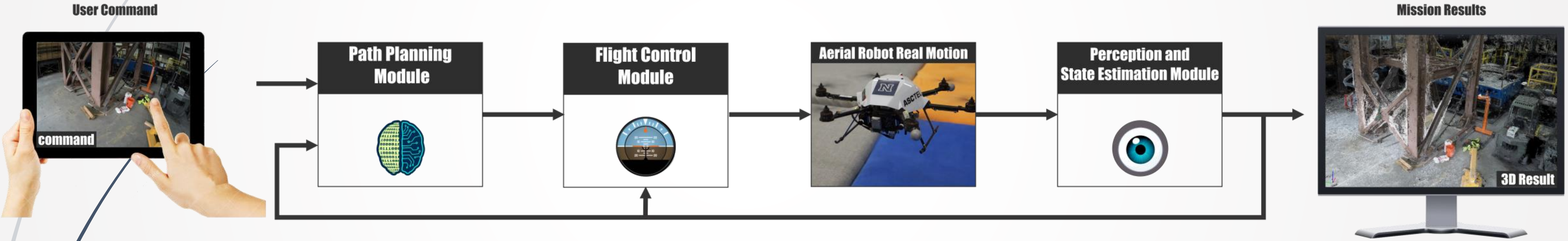
Path Planning

- Path planning is a rich field and several different approaches have been proposed such as sampling-based methods or algorithms relying on convex optimization strategies. Within the framework of this course we will examine Sampling-based algorithms and their applications in the problems of:
  - Collision-free Navigation
  - Structural Inspection Path Planning



The Aerial Robot Loop

These Loops Run Simultaneously!



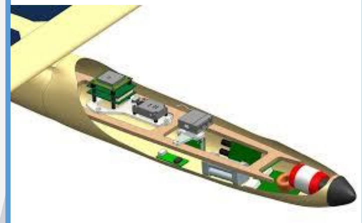
Course Contents

- **Introduction:** Get a broad understanding about aerial robotics, what they are, what they look like, what they can do and how they do so.
- **Modeling:** Understand the physical principles behind the flight dynamics of aerial robotics and develop the capacity to derive their mathematical model.
- **State Estimation:** Learn how on-board estimation of the vehicle full pose (position and orientation) takes place.
- **Flight Controls:** Learn how to design high-performance flight controllers.
- **Motion Planning:** Learn how to develop algorithms for autonomous motion planning for aerial robotics.
- **Case Study and Design Projects:** Go through a design experience.

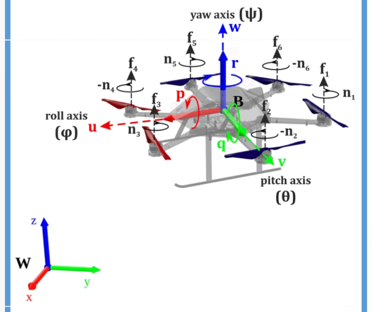
Course Projects

Assemble teams (~5 students), select or think of a Project and schedule a meeting with me

System Design



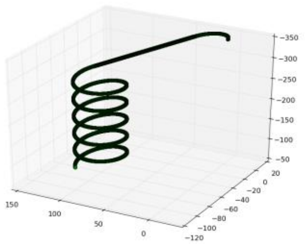
Modeling



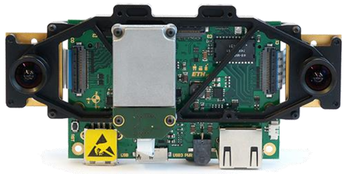
Estimation

Flight Control

Path Planning



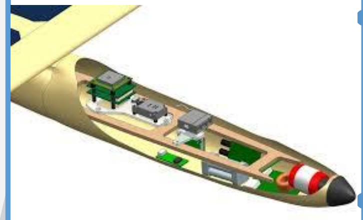
Perception



Relevant Web link: http://www.autonomousrobotslab.com/student-projects.html

Course Projects

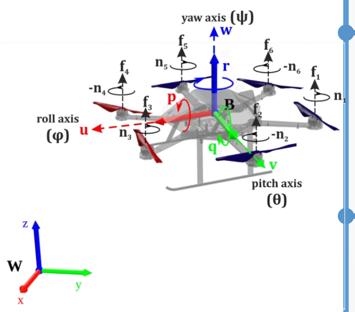
System Design



- Development of a Multirotor Micro Aerial Vehicle
- Development of a Fixed Wing Unmanned Aerial Vehicle
- Development of a Blimp Unmanned Aerial Vehicle

Course Projects

Modeling



- Development of the dynamic model -and simulation suite- of a delta-wing Fixed-Wing UAV
- System Identification of the Dynamics of Multirotor UAVs
- Online learning of dynamic models for Multirotor UAVs

Course Projects

Estimation

- Extended Kalman Filter Design for the Pose Estimation of a Multirotor UAV
- Extended Kalman Filter Design for the Estimation of the AoA of a Fixed-Wing UAV
- Unscented Kalman Filter Design for the Pose Estimation of a Multirotor UAV

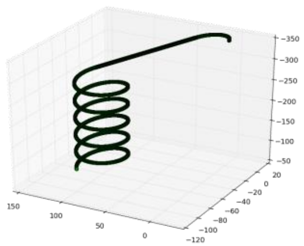
Course Projects

Flight Control

- Design of a Linear Model Predictive Control (MPC) Law for the Pixhawk Autopilot
- Design of a Nonlinear MPC Law for the Position Dynamics of a Multirotor UAV using ROS
- Guidance Laws for Slow-speed Fixed-Wing UAVs

Course Projects

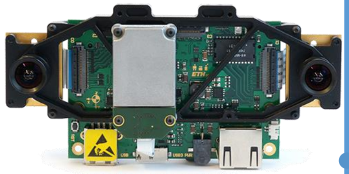
Path Planning



- Collision-free Navigation for Aerial Robotics
- Structural Inspection Path Planning for Aerial Robotics
- Multi-Robot Collaboration for Space Exploration

Course Projects

Perception



- Detection of Landing Spots
- Development of a Stereo Depth Estimation Module for a Non-Rigid Wing
- Tracking of Aerial Vehicles from a Portable Mobile Station

Thank you!

Please ask your question!