Aerial Robotic Autonomy

> *Introduction & Course Outline*

Kostas Alexis
Autonomous Robots Lab

Norwegian University of Science and Technology

What is this course about

- The overarching goal of this course is to educate students on the core methods and systems that facilitate autonomy for aerial robotic systems.
  - With a certain focus regarding operational interests.
- To achieve this goal, the course:
  - Covers the "breadth" of topics that - in their combination – give rise to autonomous aerial robots.
  - Dives into selected topics which we cover with depth. The selection of topics to dive in is necessarily relatively arbitrary and reflects research interests.
  - Takes an experimental approach offering a semester-long course project in which students develop autonomous aerial robots.

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:** Understanding the physical principles behind the flight dynamics of aerial robotics and develop the capacity to derive their mathematical model.
- **Estimation:** Learn how on-board sensor fusion and estimation of the vehicle full pose and its map take place.
- **Flight Controls:** Learn how to design high-performance flight controllers.
- **Motion Planning:** Learn how to develop algorithms for the autonomous planning of missions, paths and optimized motions for aerial robots.
- **Design Project:** Go through the experience of develop an autonomous aerial robot.

Course Material

- **Website:** https://www.autonomousrobotslab.com/aerial-robotic-autonomy.html

Aerial Robotic Autonomy

Level: TTK3 | TTK455 (MSc Specialization Course)
Overview: The course relates to the problem of Resilient Autonomy for Aerial Robots. Topics will cover:

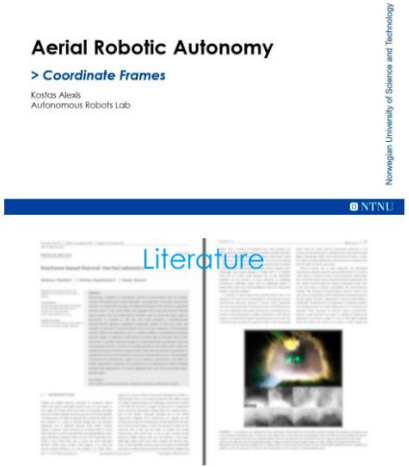
- **T1:** Modeling and Control of Micro Aerial Vehicles
- **T2:** State Estimation & Localization And Mapping
- **T3:** Path Planning for Collision-free Flight and Extrinsic Objective Optimization
- **T4:** Data-driven Navigation Policies

The class follows a breadth-first approach followed by deep-dive on one particular topic every year. For this year (2022), the deep dive will be in the domain of state estimation and GPS-denied Localization And Mapping for flying robots. There is a semester-long research-oriented project in which students work as teams. Coding assignments relate to robot control, state estimation and path planning. Coding takes place in C++ and Python.

Fall 2022: Class meets on Thursdays from 10:15-12 at MA24.

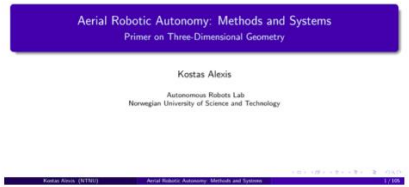
Figure. The RMF-Owl aerial robot performing autonomous exploration and inspection inside an industrial tank.

"Breadth" Topics 2022



NB! The course material is currently being added!

"Deep-dive" Topics 2022



NB! The course material is currently being added!

Let's first watch some videos

Graph-based Exploration Path Planning - Aerial Robot Field Test inside an Underground Mine

T. Dang, M. Tranzatto, S. Khattak,
F. Mascarich, K. Alexis, M. Hutter

The research effort for the results depicted is sponsored by the Defense Advanced Research Projects Agency. The presented content and ideas are solely those of the authors.

Motion Primitives-based Path Planning for Fast and Agile Exploration using Aerial Robots

Mihir Dharmadhikari, Tung Dang, Lukas Solanka, Johannes Loje,
Huan Nguyen, Nikhil Khedekar, Kostas Alexis

The research effort for the results depicted is sponsored by the Defense Advanced Research Projects Agency. The presented content and ideas are solely those of the authors.

Autonomous Exploration and Inspection inside Industrial Tank Environments

M. Dharmadhikari, M. Kulkarni, H. Nguyen, P. De Petris, K. Alexis

The Research of Norway

AUTONOMOUS ROBOTS LAB

Autonomous Teamed Exploration of Subterranean Environments using Legged and Aerial Robots

M. Kulkarni,
M. Dharmadhikari,
M. Tranzatto,
S. Zimmermann,
V. Reijgwart,
P. De Petris,
H. Nguyen,
N. Khedekar,
C. Papachristos,
L. Ott,
R. Siegwart,
M. Hutter,
K. Alexis

DARPA

The research effort for the results depicted is sponsored by the Defense Advanced Research Projects Agency. The presented content and ideas are solely those of the authors.

AUTONOMOUS ROBOTS LAB

RSL Robotic Systems Lab

Autonomous Systems Lab

ETH zürich

CERBERUS

Winning Run in the DARPA Subterranean Challenge Final Event

Atlantik Solar

AtlantikSolar 2 UAV
Flight Endurance Record Attempt

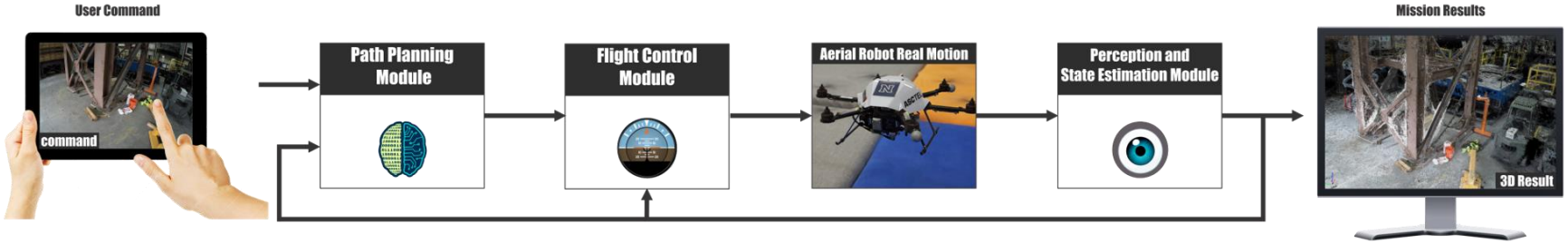
Test Flight #5
July 14th-17th 2015
Rafz, Switzerland

Note: Video sequences that are marked with an asterisk (*) were not recorded during this record flight but during previous test flights.

Autonomous Systems Lab

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

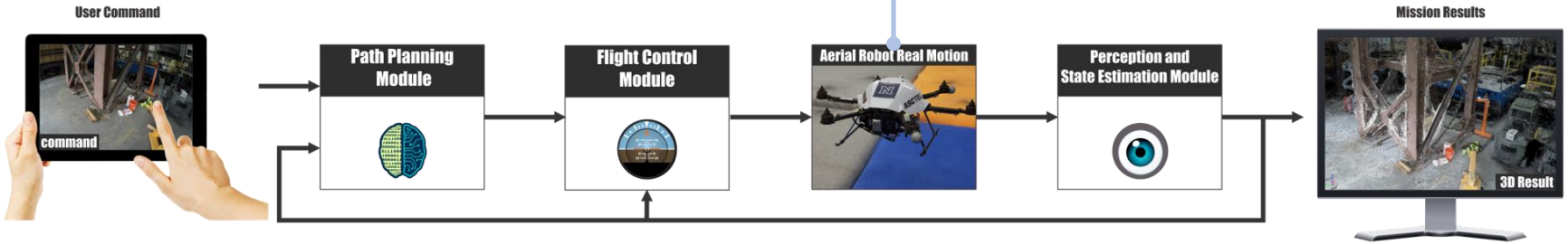
Core Building Blocks of Autonomy



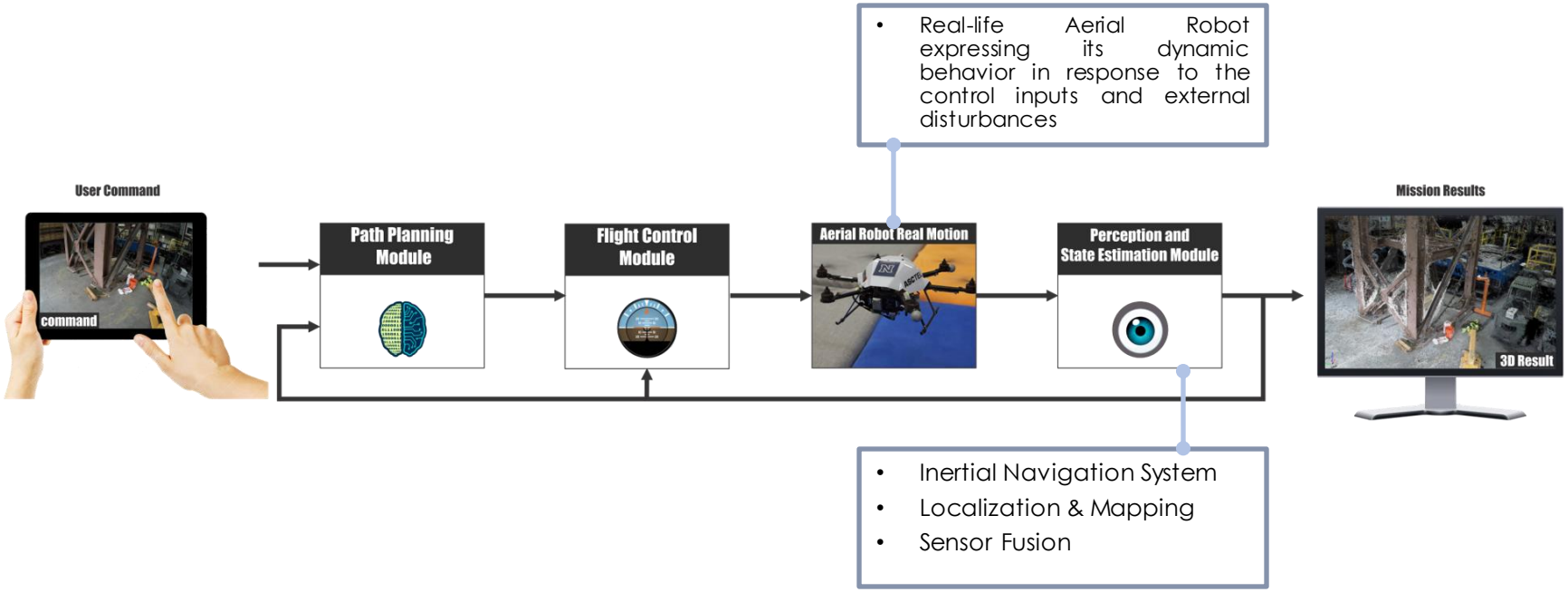
Block diagram of the main loops running at an autonomous aerial robot (conventionally)

Core Building Blocks of Autonomy

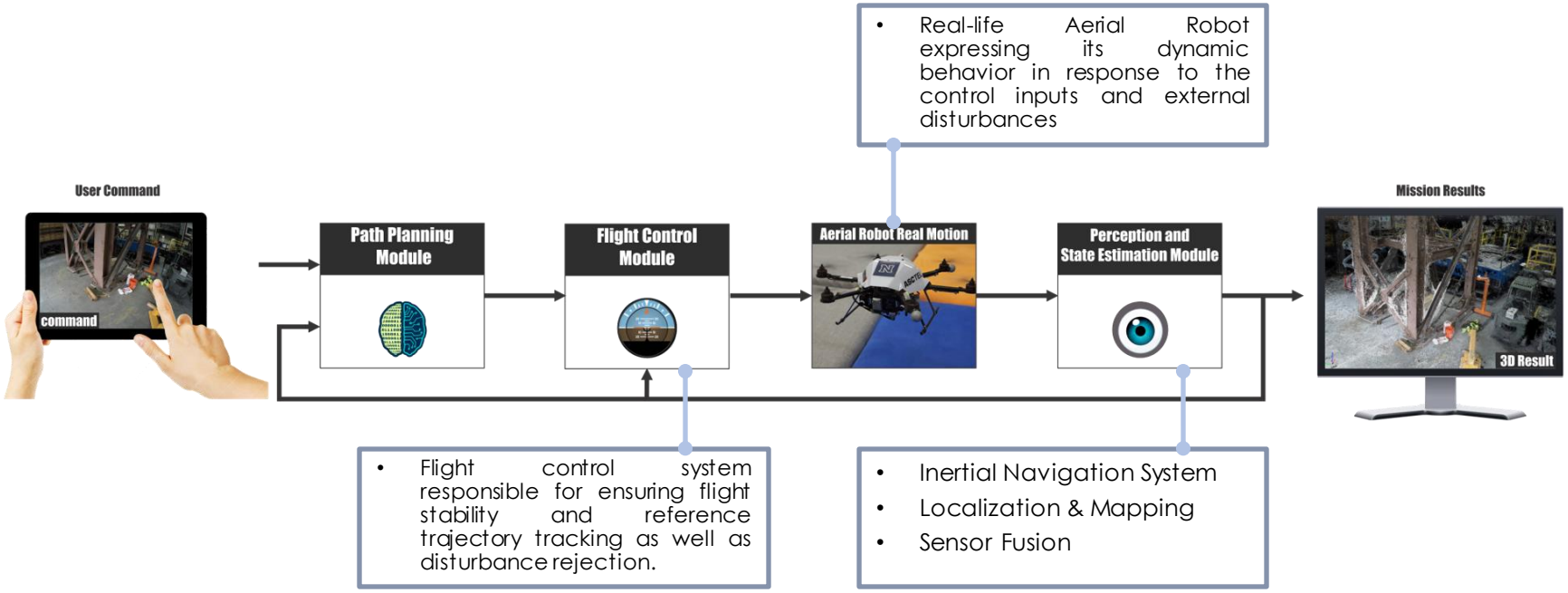
- Real-life Aerial Robot expressing its dynamic behavior in response to the control inputs and external disturbances



Core Building Blocks of Autonomy



Core Building Blocks of Autonomy



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

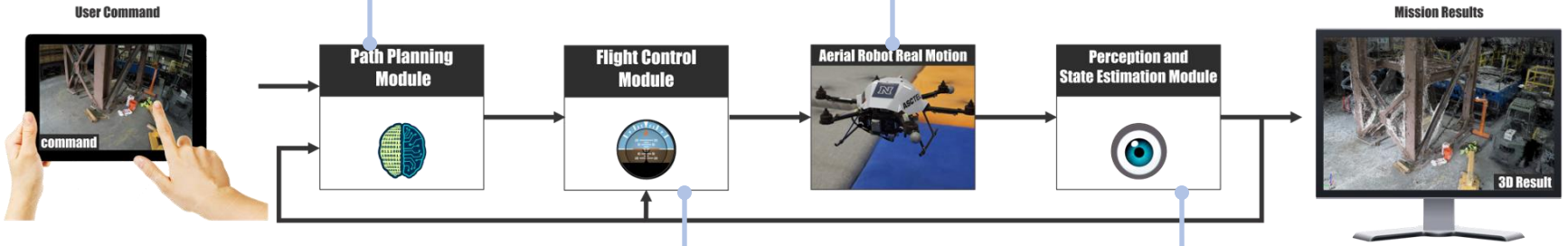
- Flight control system responsible for ensuring flight stability and reference trajectory tracking as well as disturbance rejection.

- Inertial Navigation System
- Localization & Mapping
- Sensor Fusion

Core Building Blocks of Autonomy

- 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.

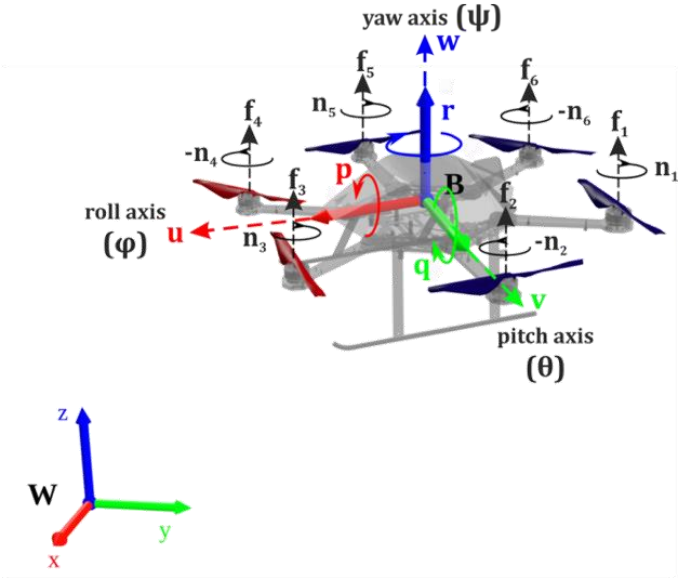
- Inertial Navigation System
- Localization & Mapping
- Sensor Fusion

The 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

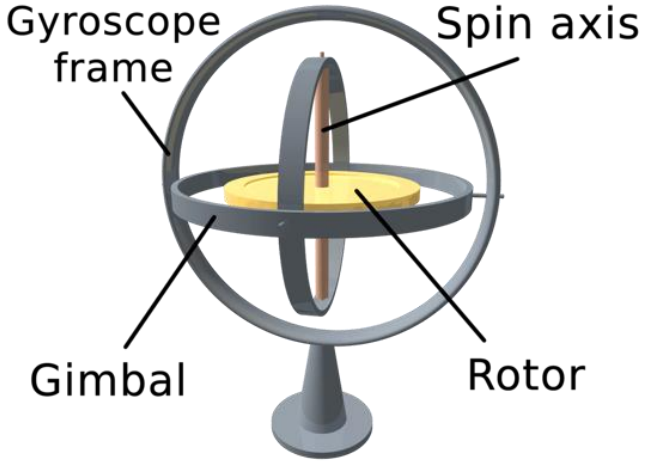
The Robot Model

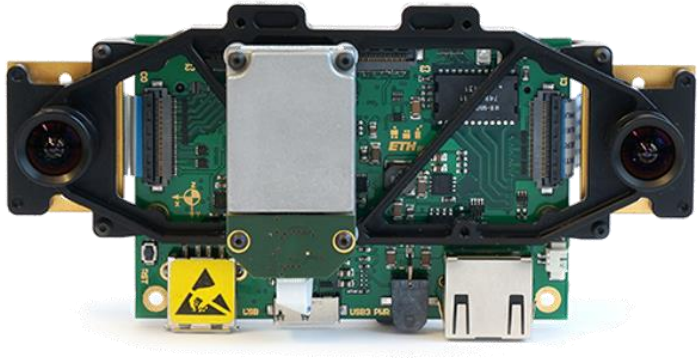
- Derivation of the Vehicle Dynamics Model: A complex mathematic process that heavily depends on the good understanding of the following topics:
  - Frame Rotations, Representations and Coordinate Systems
  - Rigid Body Dynamics Modeling
  - Derivation of Aerodynamic Forces
- Modeling is a critical step 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 & 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.



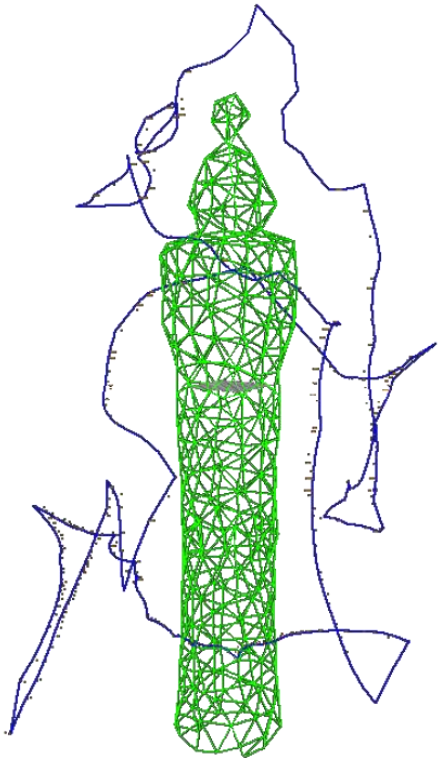


Flight Control System

- 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.

Path Planning

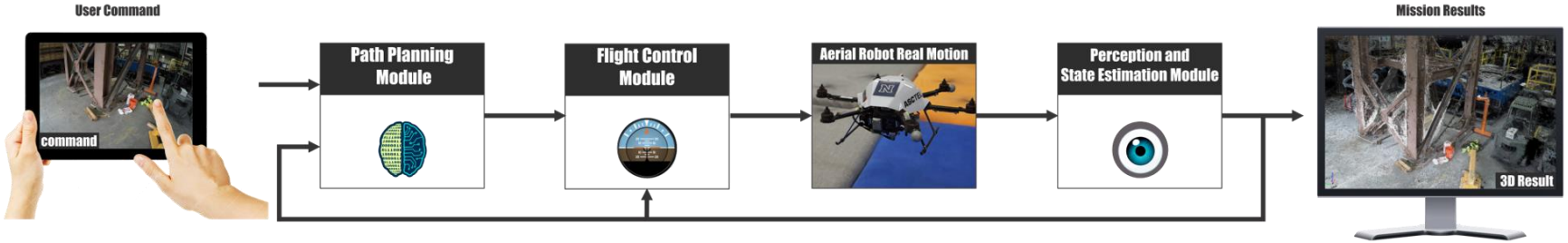
- Path planning is the process of deriving the path that the robot should follow in order to ensure safe navigation and successfully execute its mission. The problems attached through the relevant methods include the following:
  - Collision-free Navigation
  - Inspection Path Planning
  - Target Follow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



Alternative Architectures exist!

- The above is a "conventional" view to autonomy.
- Alternative architectures exist and in the class we will take some brief time to have a look to other examples.

Core Building Blocks of Autonomy



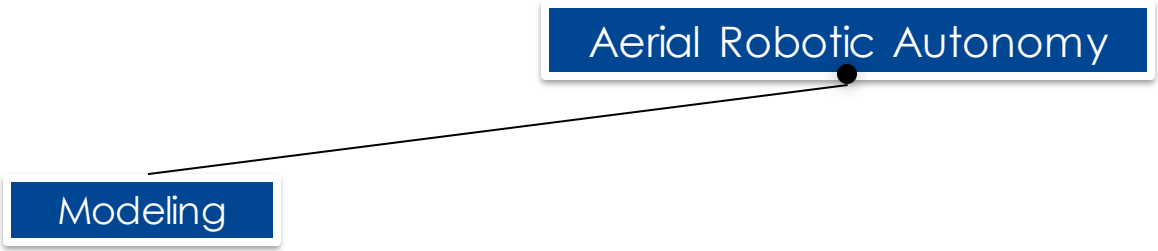
These loops all run simultaneously and rapidly onboard!

The approach in this course

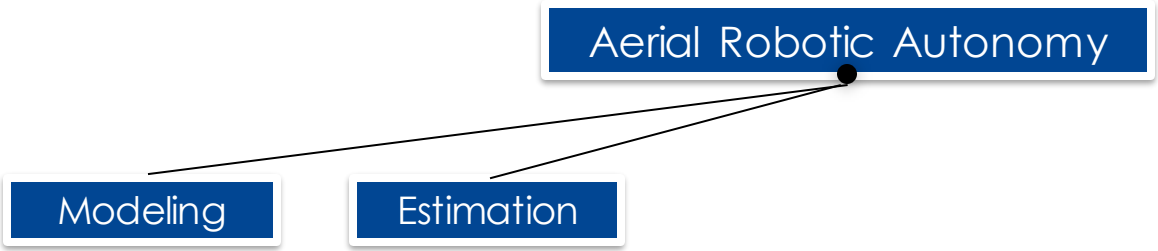
The approach in this course

Aerial Robotic Autonomy

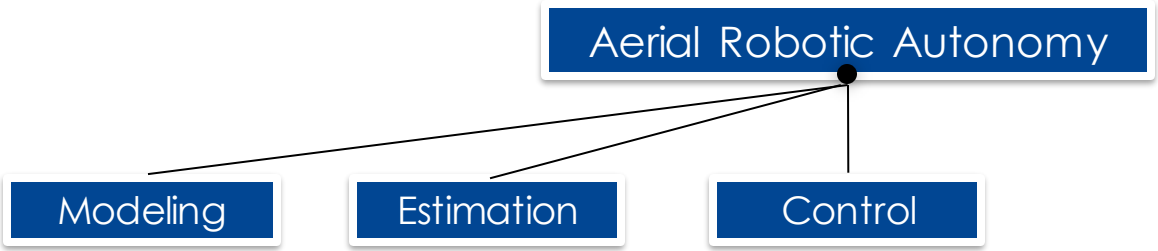
The approach in this course



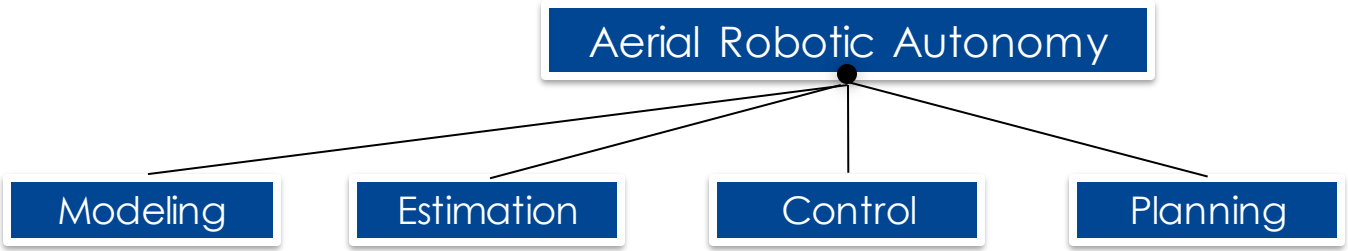
The approach in this course



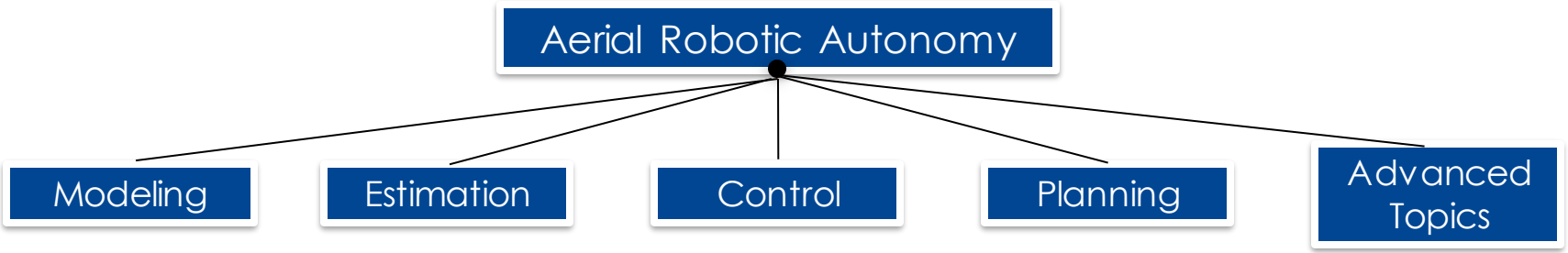
The approach in this course



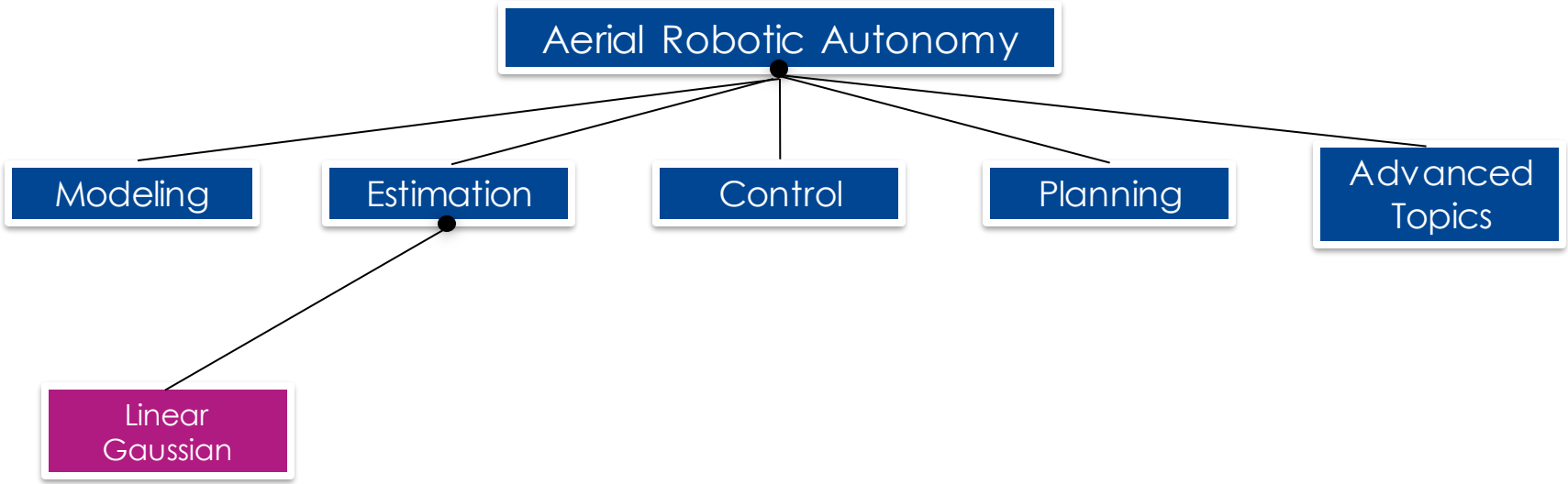
The approach in this course



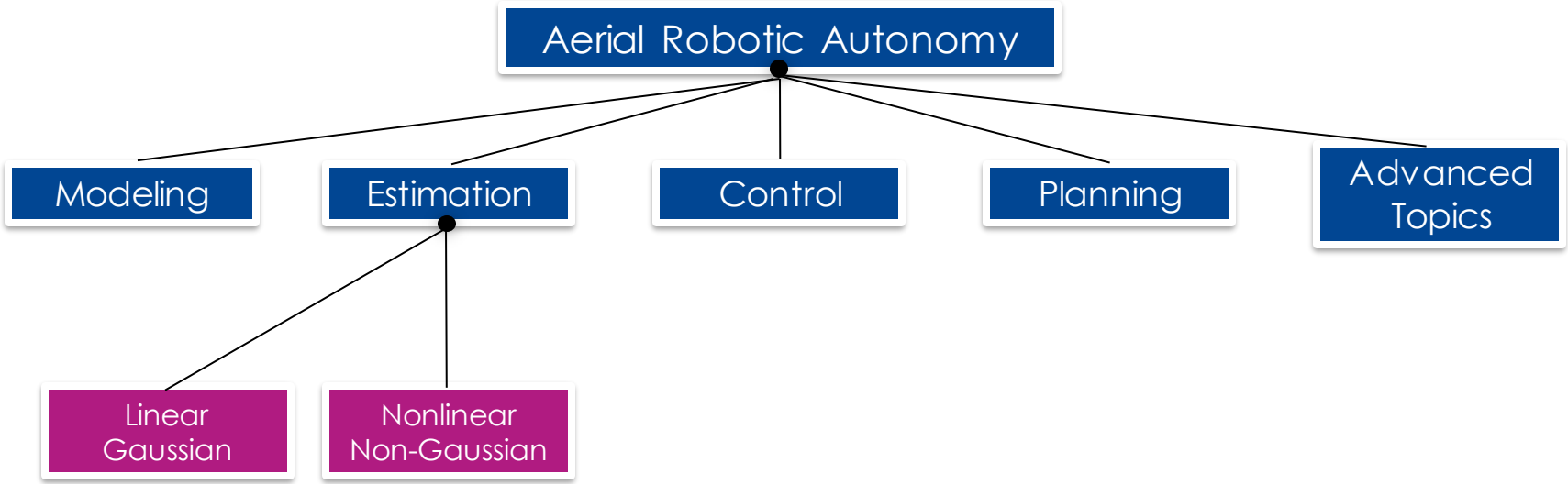
The approach in this course



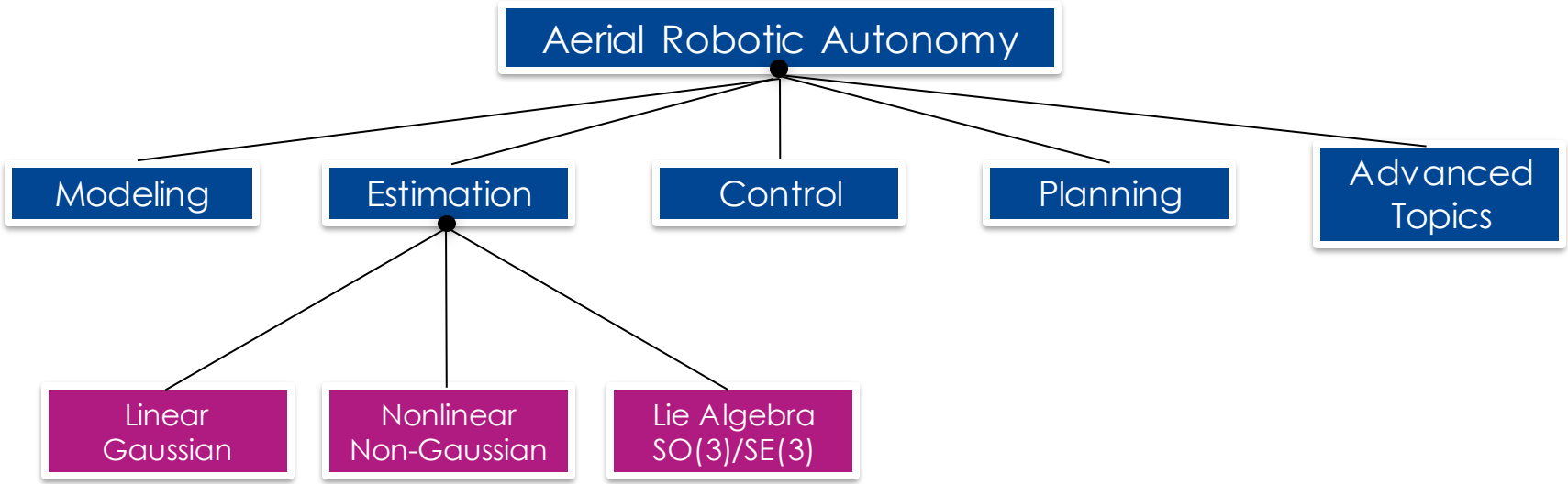
The approach in this course



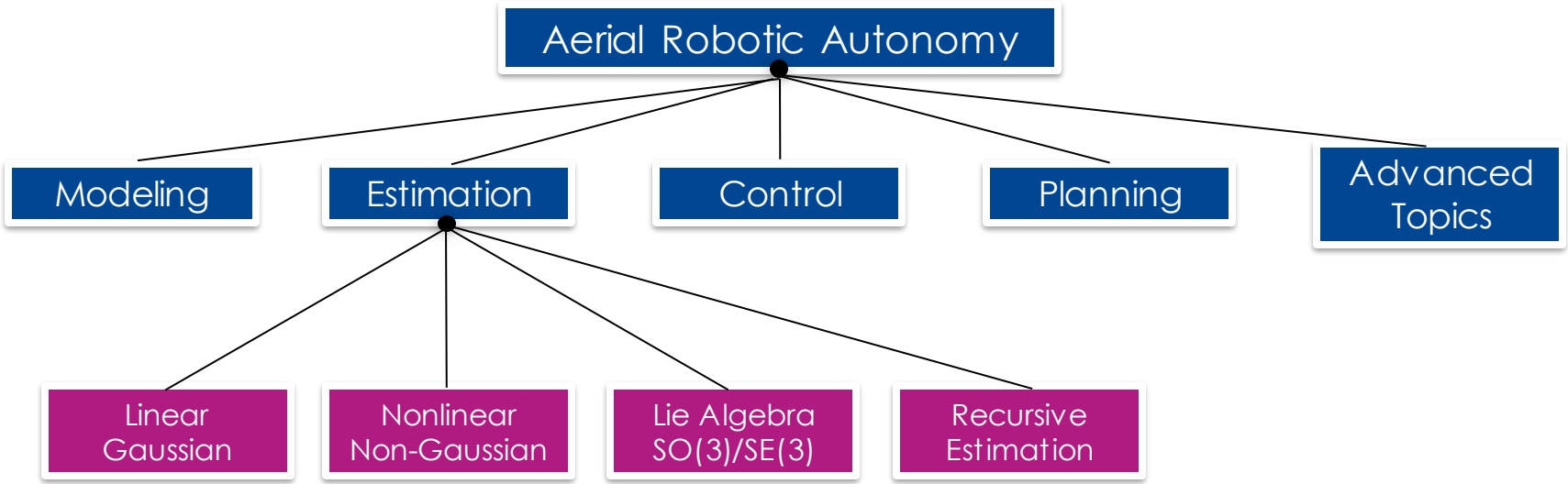
The approach in this course



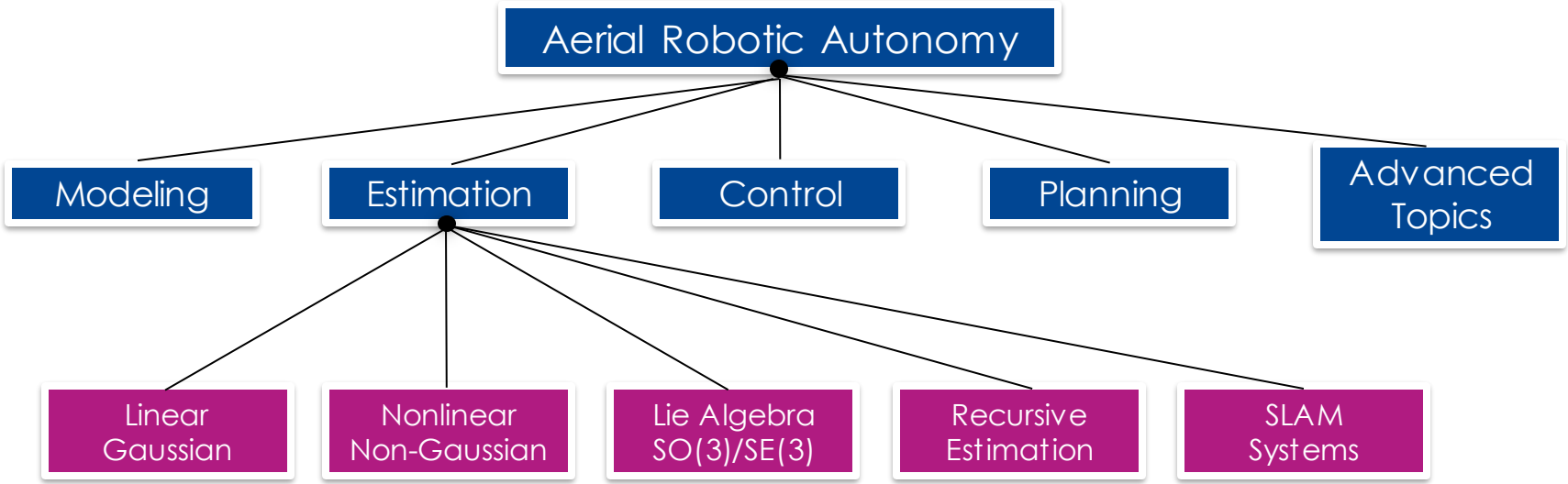
The approach in this course



The approach in this course



The approach in this course

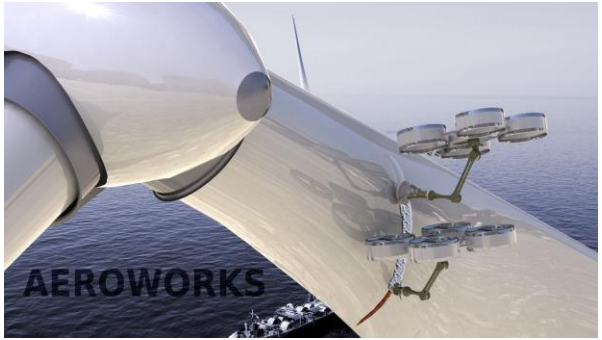


Underlying Fundamental Fields

- Autonomous robotics research builds upon a massive set of underlying fields and sub-domains, including but not limited to
  - Linear algebra, probability and statistics, optimization theory, discrete math and more
  - Modeling, kinematics, dynamics
  - Control theory and engineering
  - Estimation theory
  - Computer vision
  - Machine learning
  - Data structures and search methods
  - … (a host of other fields!)

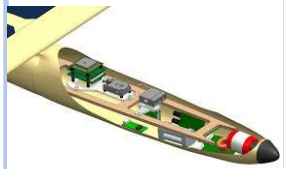
Coursework

- One semester-long project on developing an autonomous aerial robot capable of physical interaction with the environment.
  - All students of the class organized on different sub-modules of the complete autonomous system.
  - Details will be provided in different lecture.
- A small number (2) of small homework assignments on essential topics.

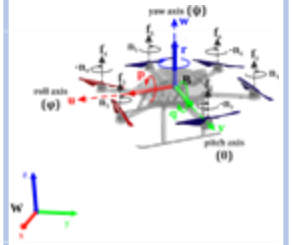


Course Project Sub-domains

System Design



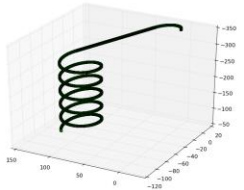
Modeling



Estimation

Flight Control

Path Planning



Perception

Thank you