Lecture 1: Introduction to Aerial Multi-Robot Systems

B3M33MRS — Aerial Multi-Robot Systems

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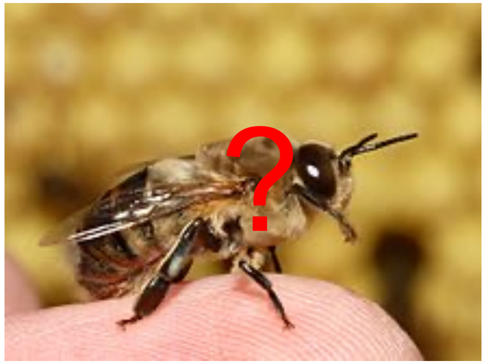
Basic terminology

- UAVs – Unmanned Aerial Vehicles
- Drones
- UASs – Unmanned Aircraft Systems
- Aerial Robots
- RPAVs – Remotely Piloted Aerial Vehicles
- RPASs – Remotely Piloted Aircraft Systems



A drone is a male honey bee

UAVs = Drones   Aerial Robots = Autonomous UAVs

UAS = UAV + ground control station, communication, dock, etc.

UAVs = Remotely Piloted Vehicles ∪ Autonomous UAVs

Classification of Unmanned Aerial Vehicles

- Structure of airfoil and propulsion system
- Size and weight of UAVs (wingspan, size of the frame)
- Performance (e.g. High Altitude, Long Endurance (HALE))
- Application specified

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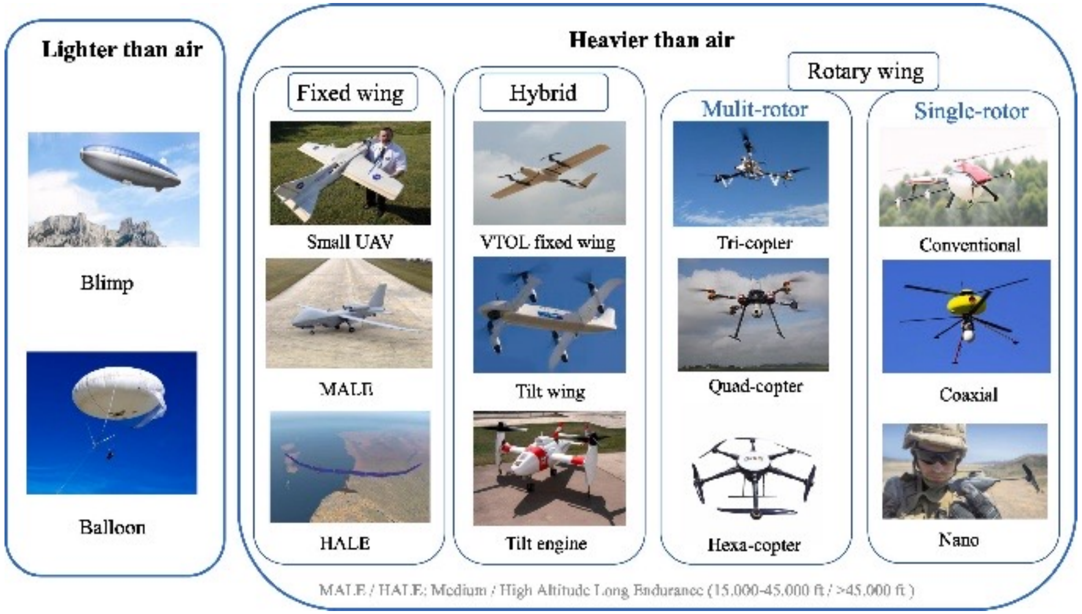
- Application specified
  - ✓ Fixed wing
  - ✓ Rotary wing
  - ✓ Hybrid (Vertical Take-Off and Landing (VTOL))
  - ✓ Flapping wing

Source: GRIFFIN EU project



Source: DRONEII.com.org

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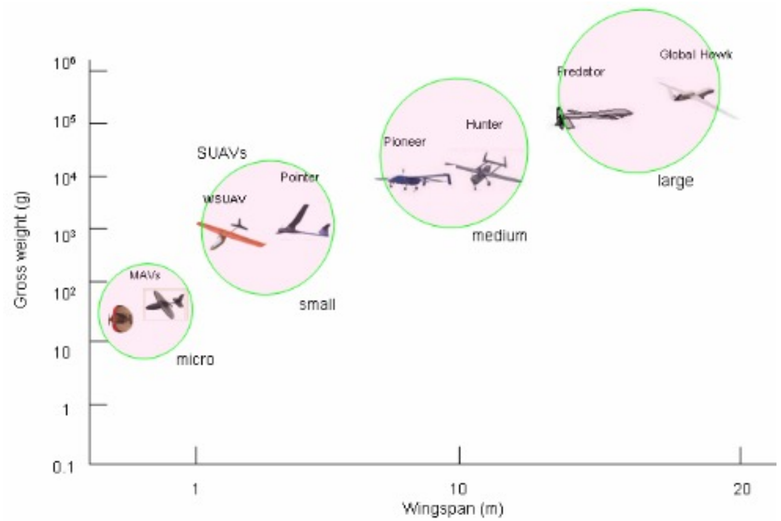
✓ Micro Aerial Vehicles (MAVs)

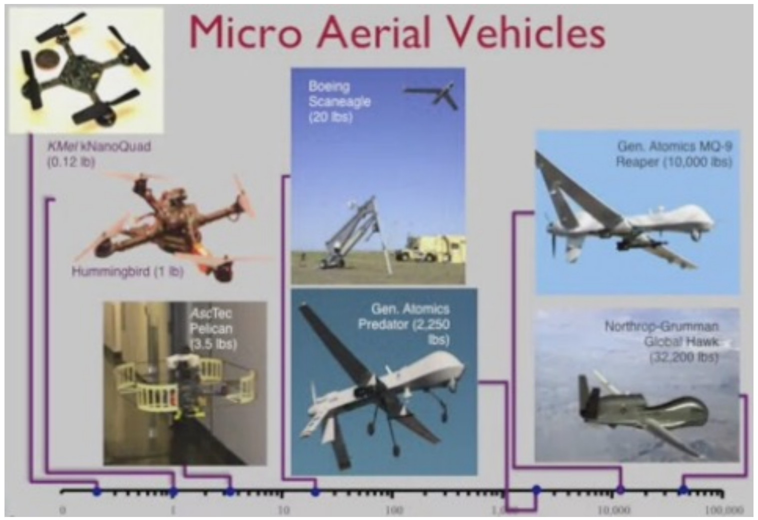
✓ Small-UAVs (SUAVs)

✓ Medium-UAVs

✓ Large-UAVs



Source: www.airdomainintelligence.mil



Source: www.af.mil

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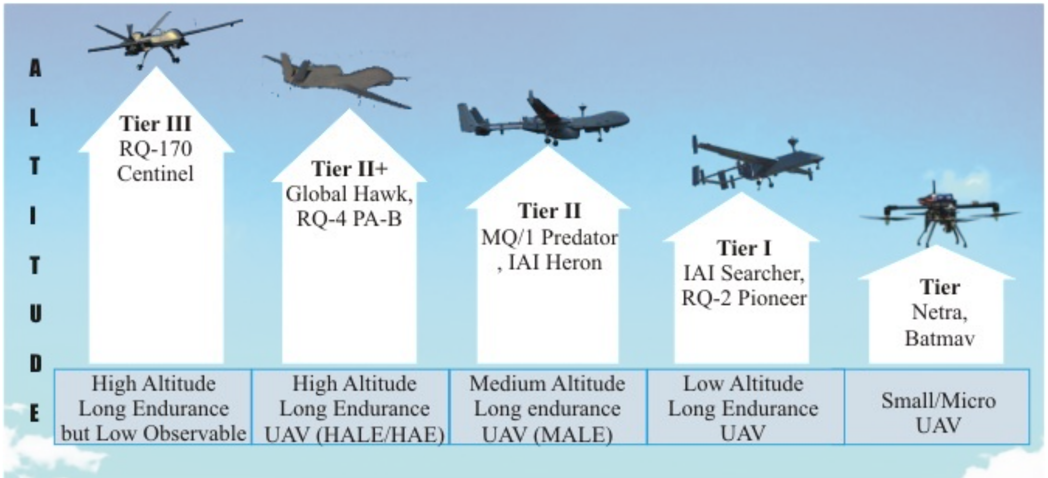
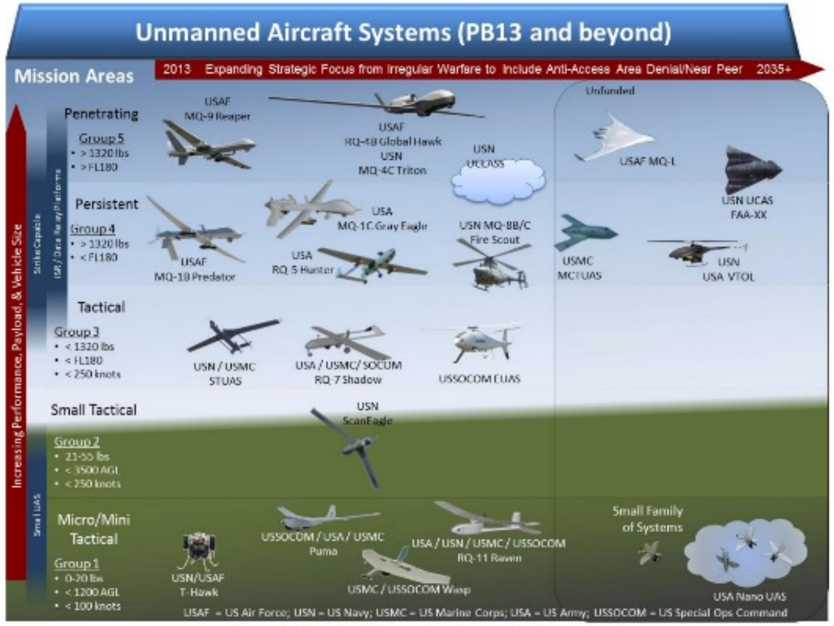


Source: defproac.com



Source: missiledefenseadvocacy.org

Classification of Unmanned Aerial Vehicles

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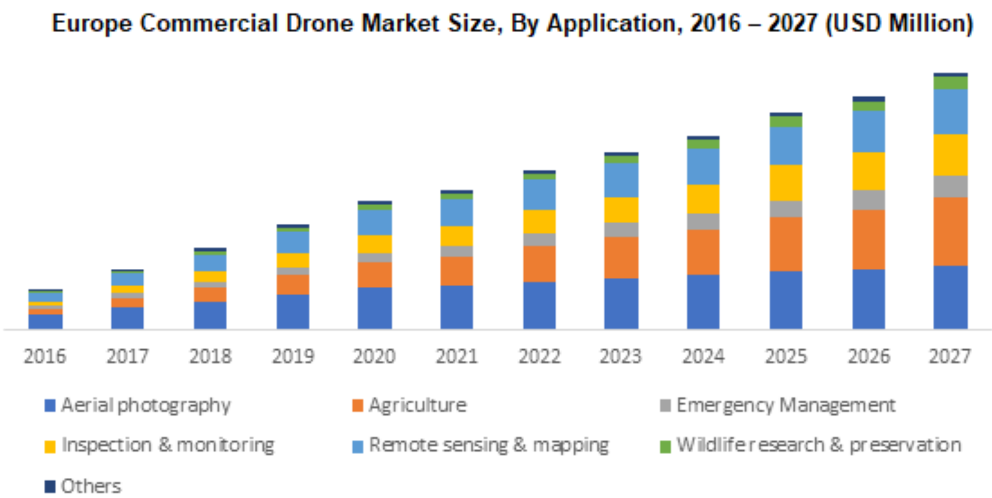
- Application specified

Source: cfdflowengineering.com

- ✓ Aerial photography
- ✓ Agriculture
- ✓ Inspection
- ✓ Remote sensing
- ✓ Urban mobility
- ✓ Military



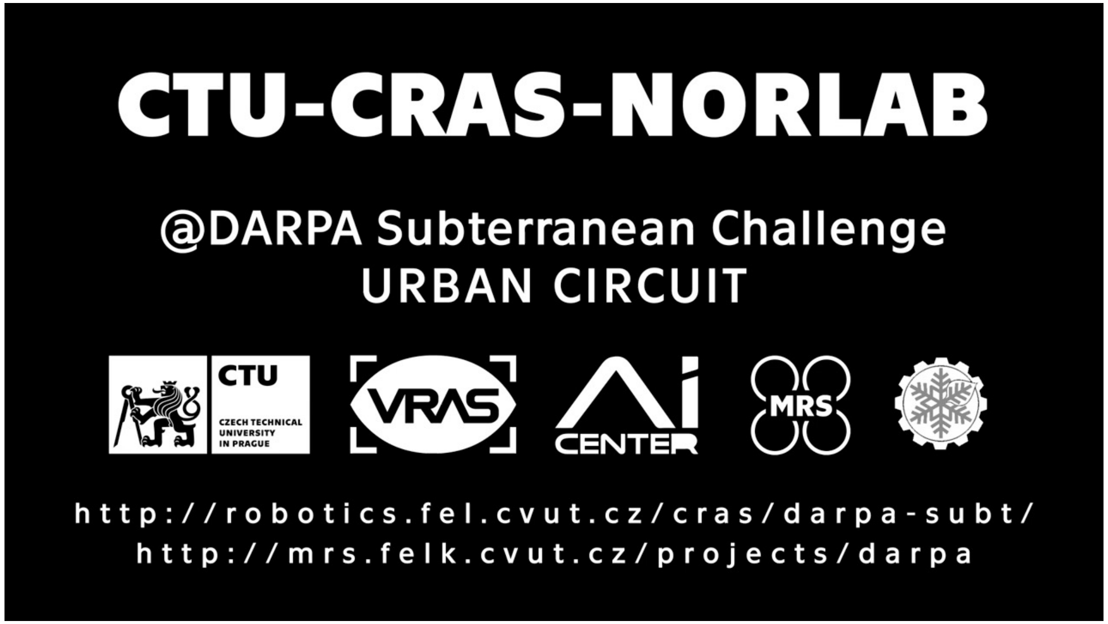
Source: Graphical Research

Source: www.scielo.br

Classification of Unmanned Aerial Vehicles - Degree of autonomy

- RPAVs – Remotely Piloted Aerial Vehicles
- Semi-autonomous UAVs (e.g. go home capability)
- Optionally Piloted UAVs (OPVs)
- Pre-programmed automated flight
- Fully autonomous aerial robots with onboard artificial intelligence

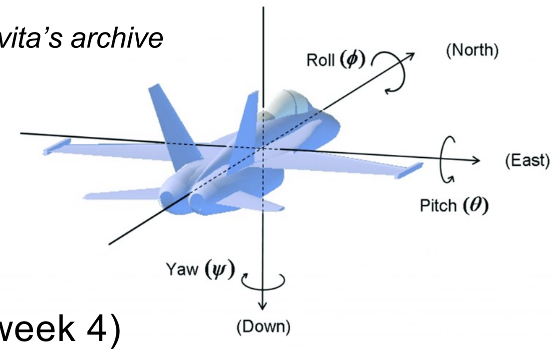
Source: DJI



https://youtu.be/60nKXamV2ds

Towards fully autonomous aerial robots - basic terms

Source: A. Civita's archive



$\boldsymbol{r} = \begin{pmatrix} r_x \\ r_y \\ r_z \end{pmatrix}$ - position of the robot

φ, θ, ψ - Euler angles (yaw, pitch and roll)

$\omega_x, \omega_y, \omega_z$ - angular velocities

$\boldsymbol{x} = (r_x, ry, rz, \varphi, \theta, \psi)$ - configuration (state) of the robot for planning (week 4)

C - configuration space (C-space): the space of all robot configurations

O - set of obstacles

$A(\boldsymbol{x}) \subset W$ - geometry of the robot at a configuration $\boldsymbol{x}$ in the world W

$C_{obs} = \{\boldsymbol{x} \in C \mid A(\boldsymbol{x}) \cap O \neq \emptyset\}$ - set of configurations, where the robot is in a collision

$C_{free} = C \setminus Cobs$ - free space (the space, where the robot can move)

$\boldsymbol{x} = (\boldsymbol{r}^T, \dot{\boldsymbol{r}}^T, \ddot{\boldsymbol{r}}^T, \varphi, \theta, \psi, \omega_x, \omega_y, \omega_z)$ - configuration (state) of the robot for state estimation (week 2)

$$\boldsymbol{x} = (\boldsymbol{r}^T, \dot{\boldsymbol{r}}^T, \ddot{\boldsymbol{r}}^T, \dddot{\boldsymbol{r}}^T, \ddddot{\boldsymbol{r}}^T \underbrace{\varphi, \theta, \psi}_{\dot{\boldsymbol{R}}(\varphi, \theta, \psi)}, \underbrace{\omega_x, \omega_y, \omega_z}_{\dot{\boldsymbol{R}}(\omega_x, \omega_y, \omega_z)})$$ - configuration (state) of the robot for control (week 2)

Jerk ($\dddot{\boldsymbol{r}}$), Snap ($\ddddot{\boldsymbol{r}}$)

Towards fully autonomous aerial robots – necessary SW components

- State estimation and localization (week 3)
- Control and motion planning (week 2)
- Mapping (week 4)
- Planning (week 4)

Towards fully autonomous aerial robots – necessary SW components

- State estimation and localization (week 3)
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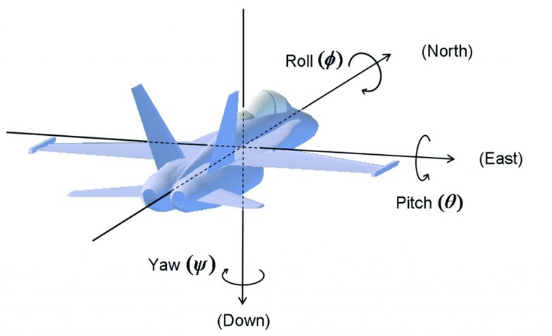
✓ UAV state: position, linear velocity, linear acceleration, orientation, angular velocity

$$\boldsymbol{x} = (\boldsymbol{r}^T, \dot{\boldsymbol{r}}^T, \ddot{\boldsymbol{r}}^T, \varphi, \theta, \psi, \omega_x, \omega_y, \omega_z)$$

✓ Various sources of sensory information

✓ Depending on the sensory setup and the surrounding environment



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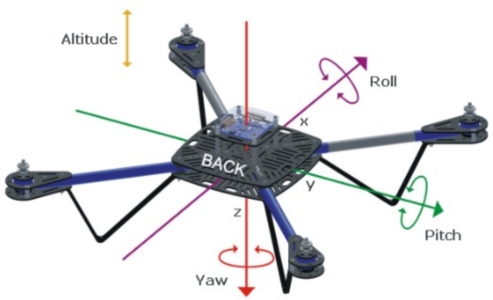
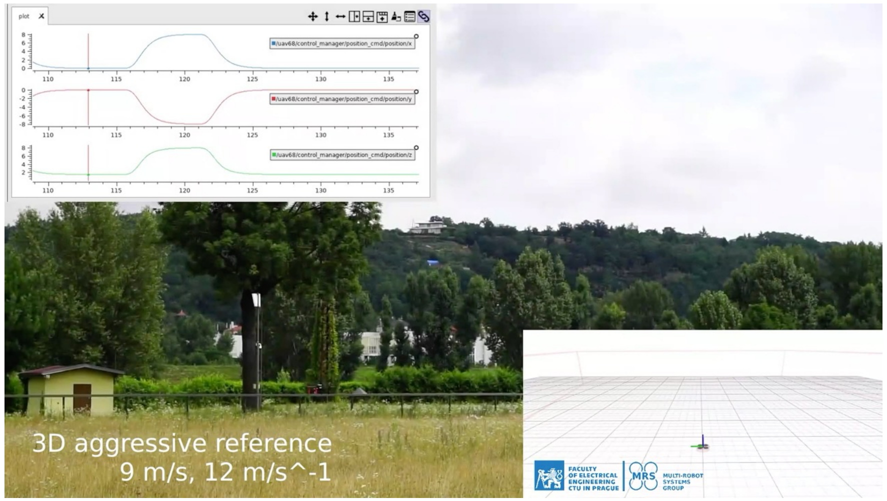


Source: S. Juan's archive



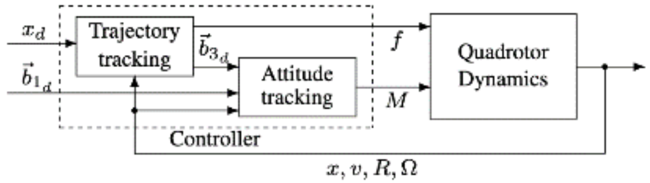
Towards fully autonomous aerial robots – necessary SW components

- State estimation and localization (week 3)
- Control and motion planning (week 2)
- Mapping (week 4)
- Planning (week 4)

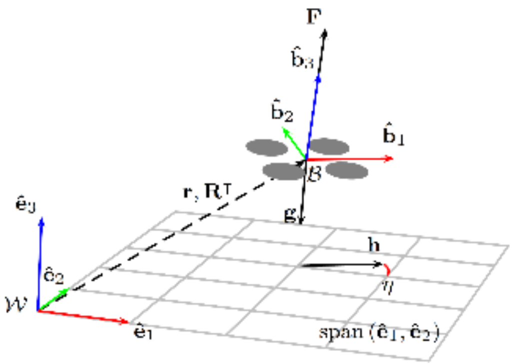
✓ How to command motors

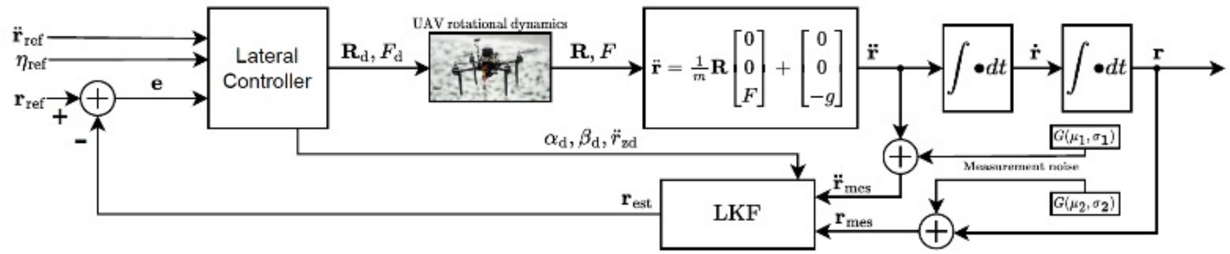
✓ Producing desired actions to reach a desired state

✓ PID, MPC, NMPC, End-to-End control using reinforcement learning



T. Lee, M. Leok, N. McClamroch, "Geometric Tracking Control of a Quadrotor UAV on SE(3)," *CDC, 2010.*





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Towards fully autonomous aerial robots – necessary SW components

- State estimation and localization (week 3)
- Control and motion planning (week 2)
- Mapping (week 4)
- Planning (week 4)

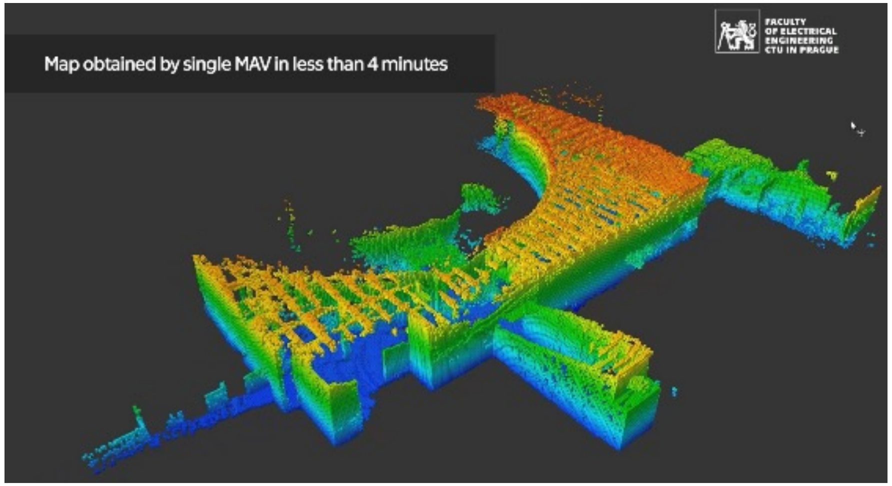
✓ To allow autonomous robots deployment in unknown environments

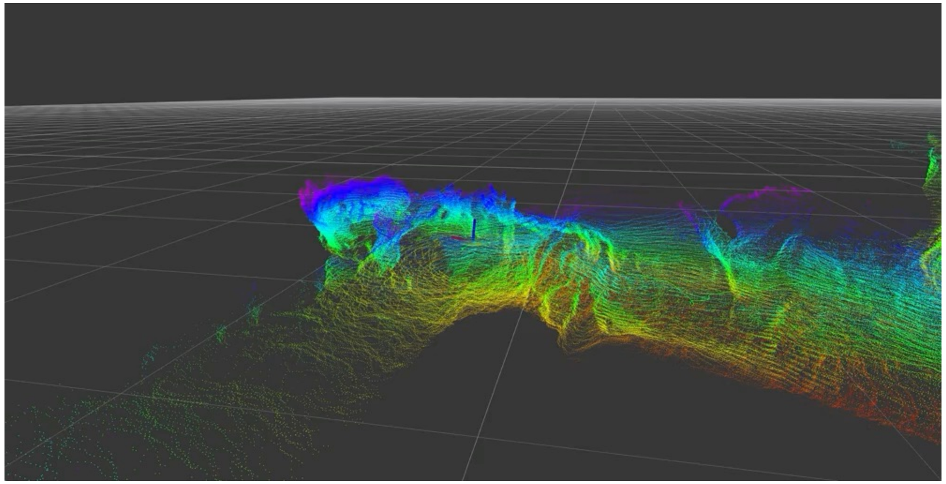
✓ To gain and collect data from onboard sensors into a map

✓ To process the data for efficient planning of trajectories and reasoning about the environment

✓ Various sensors – 2D & 3D LiDARs, cameras, …

✓ In exploration, the map may be a result of the mission





Towards fully autonomous aerial robots – necessary SW components

- State estimation and localization (week 3)
- Control and motion planning (week 2)
- Mapping (week 4)
- Planning (week 4)

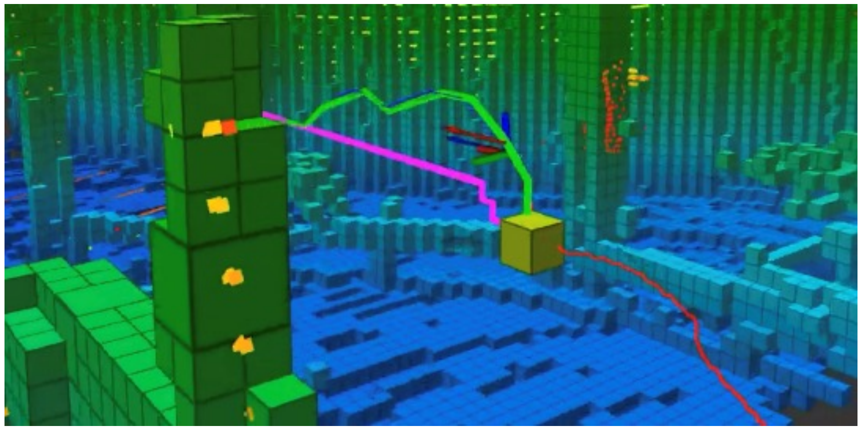
✓ To get from A to B in an environment with obstacles

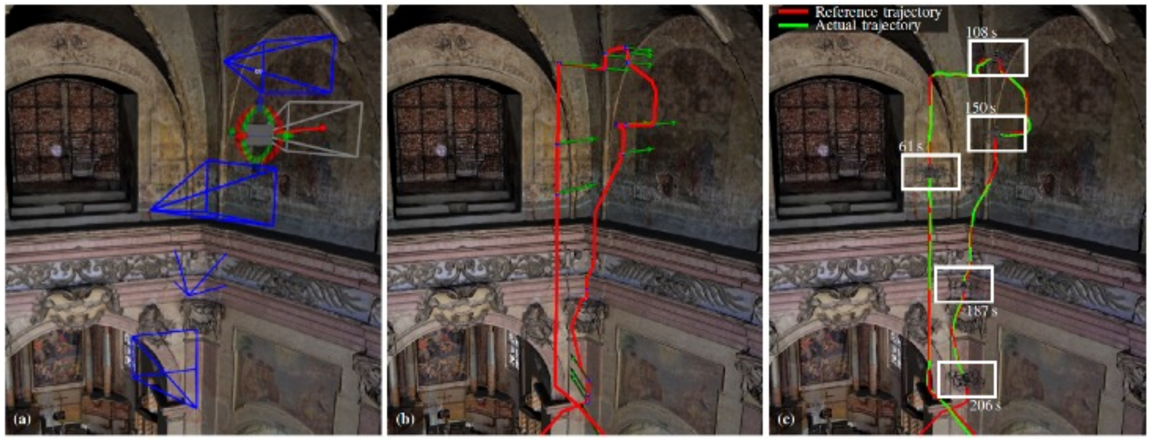
✓ Path planning: finding a sequence (discrete) of positions of the robot or a curve (continues)

✓ 2D or 3D path planning

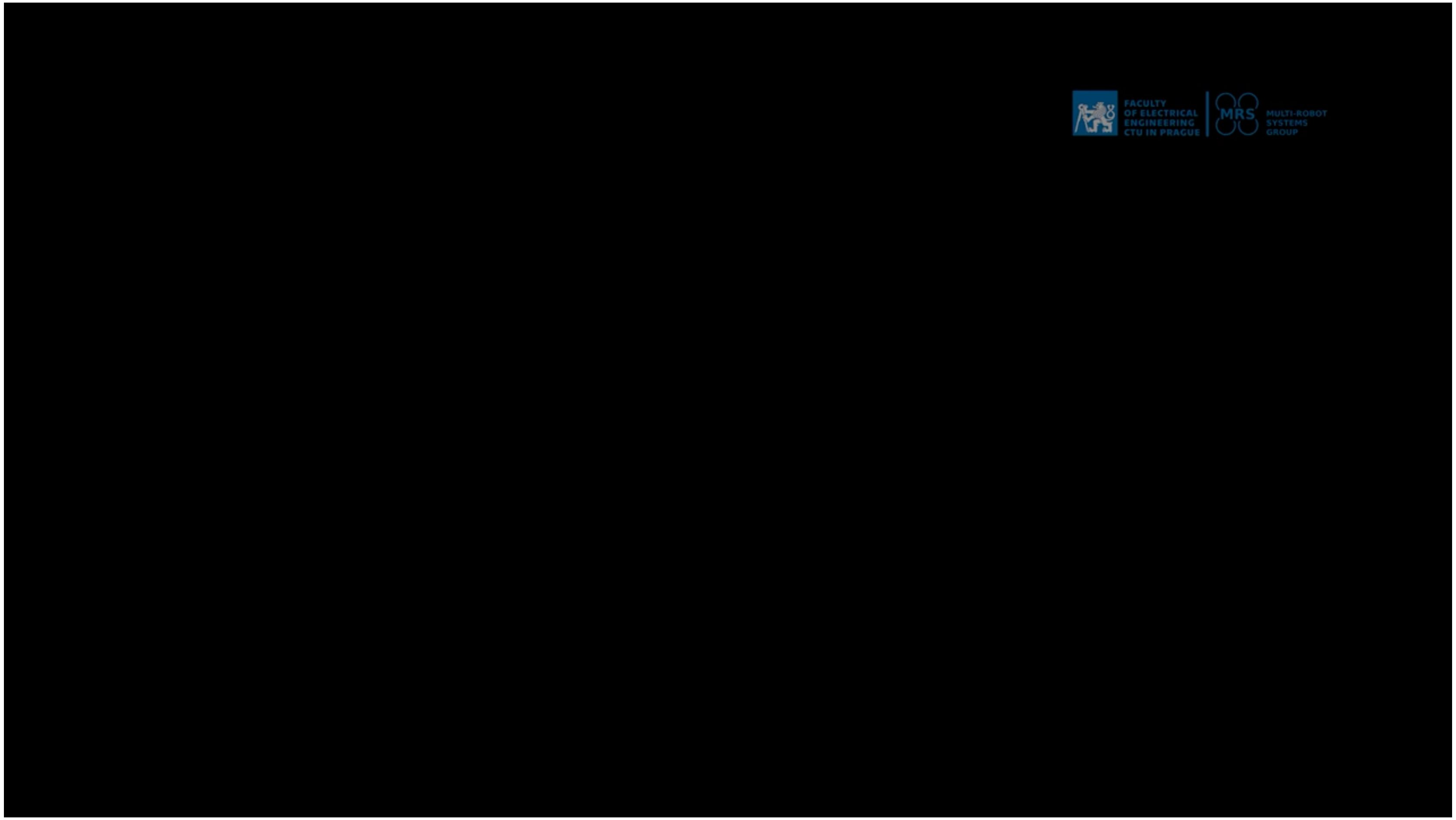
✓ Trajectory planning: finding a sequence/curve in the configuration space C_{free}

✓ Optimal planning: finding an optimal path or trajectory (optimization criteria: length, flight time, power consumption, distance to obstacles, …)





Towards fully autonomous aerial robots



https://youtu.be/WT1s3gry69Y

Structure of an intelligent UAV

- Frame, airframe
- Sensors
- Onboard computers
- Flight controllers
- Actuators (motors, manipulators)

Structure of an intelligent UAV

- Frame, airframe
- Sensors
- Onboard computers
- Flight controllers
- Actuators (motors, manipulators)

For 3D model see: https://myfel82.autodesk360.com/g/shares/SH35dfcQT936092f0e43ad283f586a8de440

Source: mydronelab.com

Source: J. Shahmoradi 's archive

Fleet of various UAVs at MRS group at CTU in Prague

UAV sensors to achieve autonomy

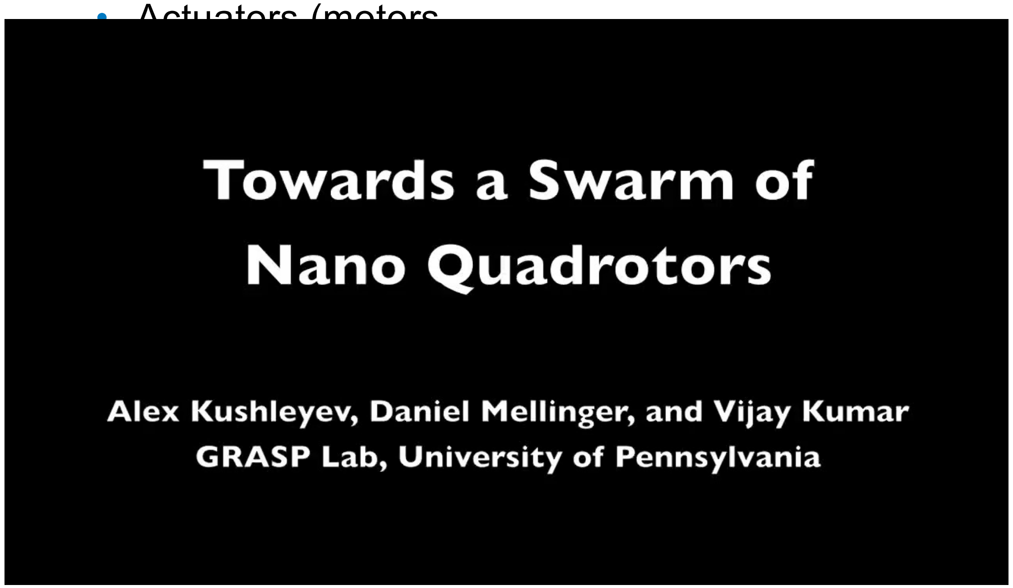
- Frame, airframe
- Sensors
- Onboard computers
- Flight controllers
- Actuators (motors

✓ GNSS - Global Navigation Satellite System

✓ Motion capture systems (mocap or mo-cap)

✓ Relatively simple state-estimation and localization

✓ GNSS denied – no global localization available



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2012

Xin. Zhou, …, Fei Gao, "Swarm of micro flying robots in the wild," *SCIENCE ROBOTICS, 7(66) 2022.*

2022

UAV sensors to achieve autonomy

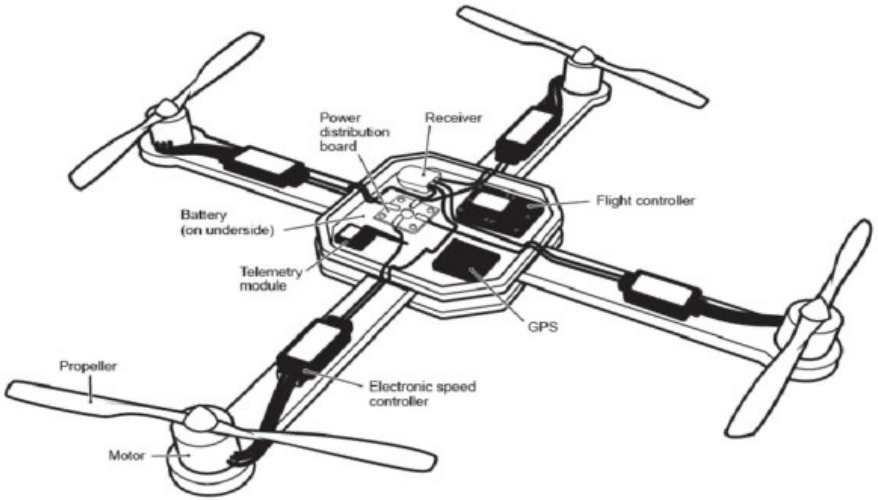
- Frame, airframe
- Sensors
- Onboard computers
- Flight controllers
- Actuators (motors, manipulators)

- GNSS and motion capture available
- GNSS/mocap - denied

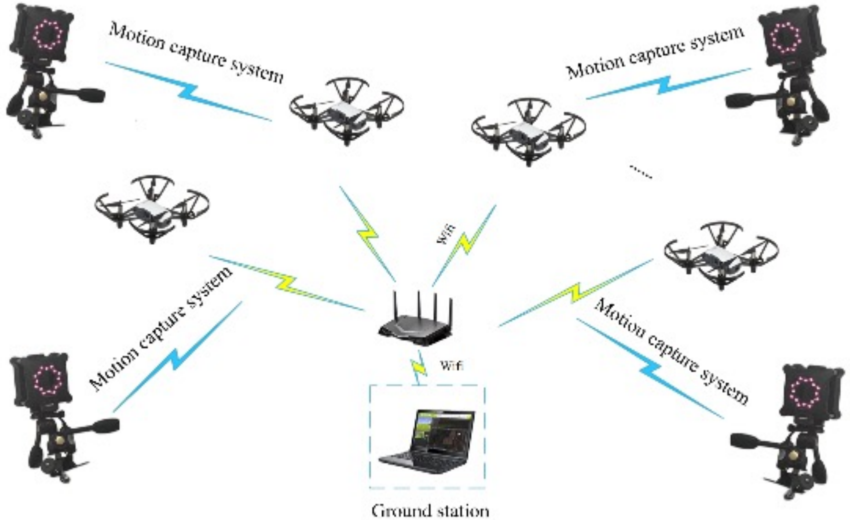
  ✓ Global position information available

  ✓ Relatively simple state-estimation (IMU + GNSS/mocap)

Source: Bitcraze (Crazyflie)



Source: Q. Li's archive



Source: K. Pothuganti's archive

UAV sensors to achieve autonomy

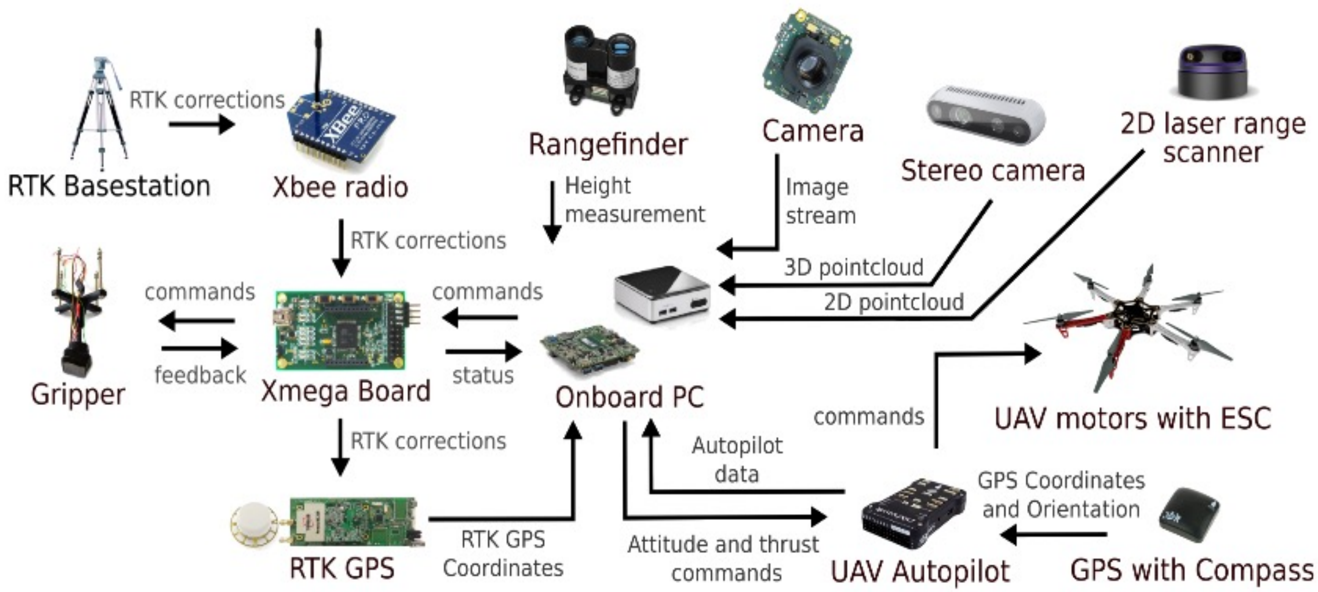
- Frame, airframe
- Sensors
- Onboard computers
- Flight controllers
- Actuators (motors, manipulators)

- GNSS and motion capture available
- GNSS/mocap - denied

✓ Global position information not available

✓ State-estimation using onboard sensors

✓ Different localization sensors based on environment properties



D. Hert, …., M. Saska, "MRS Drone: A Modular Platform for Real-World Deployment of Aerial Multi-Robot Systems," *Journal of Intelligent & Robotic Systems 108:1–34, July 2023.*

UAV sensors to achieve autonomy

- Frame, airframe
- Sensors
- Onboard computers
- Flight controllers
- Actuators (motors, manipulators)

✓ **RGB cameras**: light-weight, low power consumption, high bandwidth, demanding processing, illumination sensitive. Monocular Simultaneous Localization and Mapping (SLAM), Visual-Inertial Odometry (VIO), Optic Flow (OF), Convolutional Neural Network (CNN), …

✓ **Stereo (3D) cameras**: larger dimensions (range depends on a baseline), low power consumption, high bandwidth, demanding processing, sensitive to number of image features. 3D SLAM, 3D mapping, obstacle detection and avoidance

✓ **Time-of-flight (ToF) cameras**: less demanding processing, sensitive to sun light

Basler daA1600-60uc

RealSense 3D camera

Nerian 3D camera

Terabee ToF camera

UAV sensors to achieve autonomy

- Frame, airframe
- Sensors
- Onboard computers
- Flight controllers
- Actuators (motors, manipulators)

✓ **1D LiDARs**: light-weight, low power consumption, low bandwidth, simple processing. Height above ground or from ceiling estimation, simple bumper.

✓ **2D LiDARs**: larger dimensions, low power consumption, low range. 2D SLAM, 2D mapping, obstacle detection and avoidance.

✓ **3D LiDARs**: heavy, high power consumption, high bandwidth, higher range. 3D SLAM, 3D mapping, 3D model reconstruction, robust obstacle detection and avoidance.

Garmin 1D LiDAR

RP 2D LiDAR

Ouster 3D LiDAR

UAV sensors to achieve autonomy

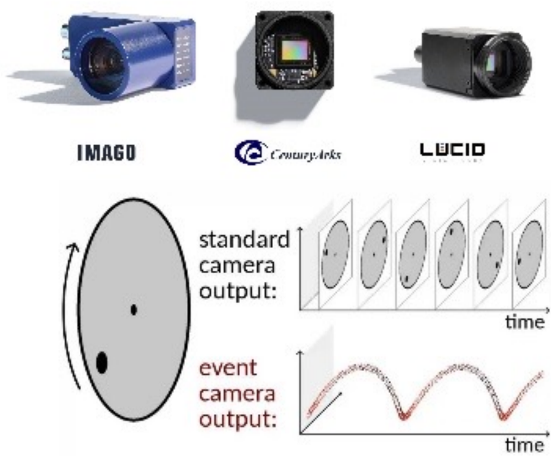
- Frame, airframe
- Sensors
- Onboard computers
- Flight controllers
- Actuators (motors, manipulators)

✓ **Radars**: under intensive development, high-range, difficult processing. Sense and avoid, obstacle avoidance, target tracking, SLAM.

✓ **Event based cameras:** high range of illumination, sensitive to small changes of detected light intensity by each pixel. SLAM in bad light conditions.

✓ **Thermal and multi-spectral cameras**: heavier, expensive, high bandwidth. Specialized inspection, object of interest localization.

Echodyne radar



G. Gallego, …., D. Scaramuzza, "Event-based Vision: A Survey," *IEEE Trans. on PAMI, 44(1):154 - 180, 2020.*

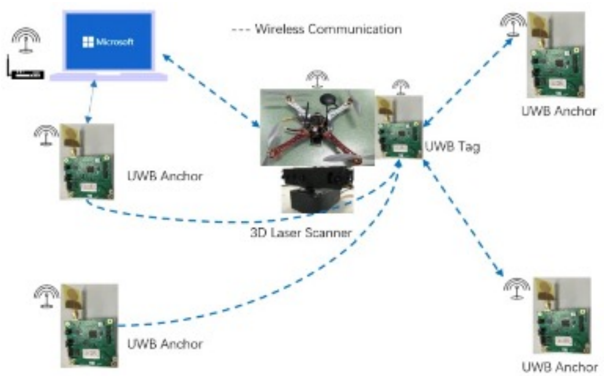
UAV with a Multi-spectral camera.
Source: A. Lucier's archive

UAV sensors to achieve autonomy

- Frame, airframe
- Sensors
- Onboard computers
- Flight controllers
- Actuators (motors, manipulators)

✓ **UWB**: Ultra wideband beacons in the environment or onboard of robots. Short range, small operational space. Indoor localization, mutual localization in multi-robot systems – week 9.

✓ **Vision with active markers:** requires onboard omnidirectional cameras and light sources, onboard processing, reliable detection. Mutual localization in multi-robot systems. **UVDAR**.



K. Li, …., Y. Liao, "Self-positioning for UAV indoor navigation based on 3D laser scanner, UWB and INS," *IEEE ICIA, 2016.*

V. Walter, …., M. Saska, "UVDAR System for Visual Relative Localization With Application to Leader–Follower Formations of Multirotor UAVs.," *IEEE RAL, 2019.*

UAV onboard computers

- Frame, airframe
- Sensors
- Onboard computers
- Flight controllers
- Actuators (motors, manipulators)

✓ GNSS available - microcontroller inside a flight-controller: state estimation and control using low bandwidth sensors (IMU, GNSS…)

✓ GNSS denied – sensors processing (images, 3D LiDARs), mapping (filtering and fusing sensory data), control and motion planning, trajectory planning, high-level planning, processing for applications

More powerful PC. Often with Linux, e.g. Intel NUC, raspberry, odroid (embedded computers). Image processing: NVIDA Jetson, AI modules for depth NN

Source: docs.px4.io

Source: Intel

Source: NVIDIA

UAV flight controllers

- Frame, airframe
- Sensors
- Onboard computers
- Flight controllers (autopilots)
- Actuators (motors, manipulators)

✓ Provides low level control inputs (a speed reference signal) for ESCs (Electronic Speed Controller) attached to each motor

✓ Direct control by a remote radio controller, planning and navigation through a set of GNSS points (e.g. QGroundControl), interface with the onboard computer (e.g. MAVLink – MAV communication protocol)

✓ Open-source: Pixhawk (PX4, ArduPilot), Paparazzi, OpenPilot, Betaflight

✓ Commercial (closed) solutions: DJI, … all commercially available UAVs

✓ Integration with low bandwidth sensors - IMU, GPS, Range finder

Source: ardupilot.org

Source: docs.px4.io

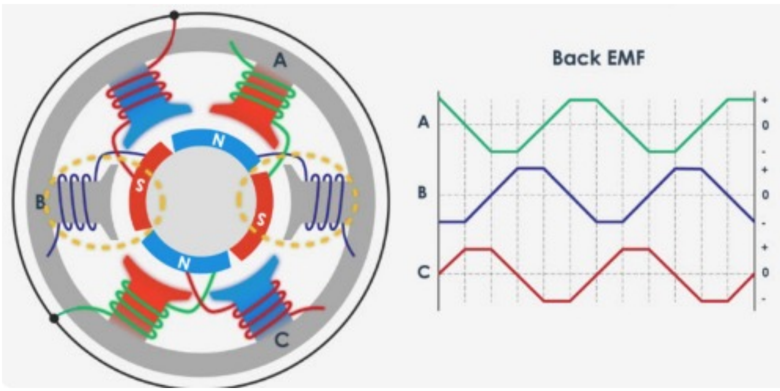
ESC with a brushless motor

Source: Racestar

UAV propulsion system

- Frame, airframe
- Sensors
- Onboard computers
- Flight controllers
- Actuators (motors, manipulators)

✓ Propulsion system: motor- propeller sets
✓ Larger propellers - more thrust, better efficiency, bigger payload
✓ Smaller propellers - compact design
✓ Motors: BLDC (BrushLess DC) design
✓ DC from a battery is converted in ESC into three-phase alternating current with a variable frequency. ESC is actively tracking the motor rotations and setting the required throttle of each motor



Source: https://howtomechatronics.com/how-it-works/how-brushless-motor-and-esc-work/

UAV manipulators/arms

- Frame, airframe
- Sensors
- Onboard computers
- Flight controllers
- Actuators (motors, manipulators)

✓ Manipulators: to enable physical interaction with environment

✓ Robotic arms, dual arms, tactile force sensors, grippers, launchers

Source: prodrone.com

Source: M. Kim's archive

T. Baca, …., M. Saska, "Autonomous Cooperative Wall Building by a Team of Unmanned Aerial Vehicles in the MBZIRC 2020 Competition," *In arXiv, 2020.* https://arxiv.org/abs/2012.05946

UAV manipulators/arms

Lecture 1 Introduction

Martin Saska

Basic terminology

Classification of UAVs

Towards autonomous UAVs

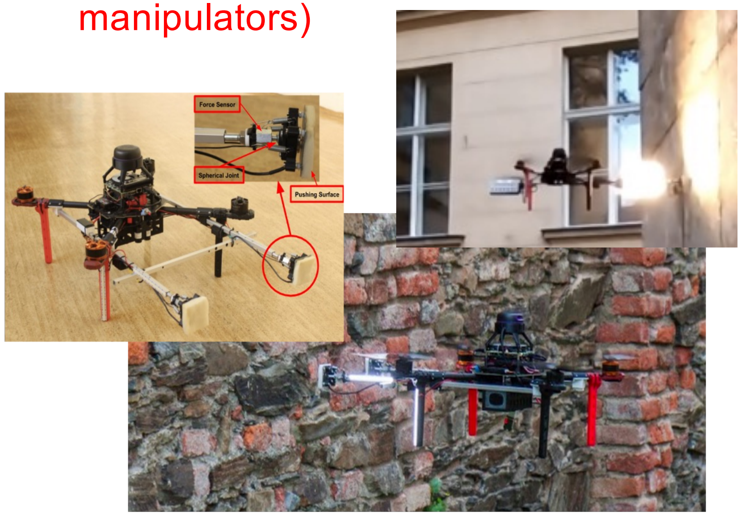
Autonomous UAV structure

Conclusion

- Frame, airframe
- Sensors
- Onboard computers
- Flight controllers
- Actuators (motors, manipulators)

✓ Manipulators: to enable physical interaction with environment.

✓ Robotic arms, dual arms, tactile force sensors, grippers, launchers



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https://youtu.be/QHpifXJzH5g

Conclusion

- The main software components that need to be designed for achieving a full autonomy are: State estimation and localization, control and motion planning, mapping, and planning.
- The real-world deployment may require much more: High-level planning and reasoning, task assignment, environment exploration, fully actuated control, human-robot interaction, image processing, reinforcement learning, communication, failure detection and recovery, and multi-robot coordination.
- The main hardware components of an autonomous vehicle are: Frame (size~payload), sensors (for the autonomy and for the mission), onboard computers, flight controller, and actuators (motors, manipulators).
- But there is many more onboard of UAVs: power source (batteries, petrol engine, hybrid), communication module, parachute, lights, responder (for sense and avoid and traffic management).

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