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 U 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
Classification of Unmanned Aerial Vehicles

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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
Classification of Unmanned Aerial Vehicles

- Structure of airfoil and propulsion system
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- Application specified

- Micro Aerial Vehicles (MAVs)
- Small-UAVs (SUAVs)
- Medium-UAVs
- Large-UAVs

Source: www.airdomainintelligence.mil  

Source: www.af.mil
Classification of Unmanned Aerial Vehicles

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Source: defproac.com

Source: missiledefenseadvocacy.org
Classification of Unmanned Aerial Vehicles

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- Application specified

Aerial photography
Agriculture
Inspection
Remote sensing
Urban mobility
Military

Source: cfdflowengineering.com
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
Towards fully autonomous aerial robots - basic terms

**Position of the robot**

\[ \mathbf{r} = \begin{pmatrix} r_x \\ r_y \\ r_z \end{pmatrix} \]
- position of the robot

**Euler angles** (yaw, pitch and roll)

\[ \varphi, \theta, \psi \]

**Angular velocities**

\[ \omega_x, \omega_y, \omega_z \]

**Configuration (state) of the robot**

\[ \mathbf{x} = (r_x, r_y, r_z, \varphi, \theta, \psi) \]
- configuration (state) of the robot for planning (week 4)

**Configuration space (C-space)**

\[ C \]
- the space of all robot configurations

**Set of obstacles**

\[ O \]
- free space (the space, where the robot can move)

\[ A(\mathbf{x}) \subset W \]
- geometry of the robot at a configuration \( \mathbf{x} \) in the world \( W \)

**Set of configurations, where the robot is in a collision**

\[ C_{obs} = \{ \mathbf{x} \in C | A(\mathbf{x}) \cap O \neq \emptyset \} \]

**Free space**

\[ C_{free} = C \setminus C_{obs} \]

**Configuration (state) of the robot for state estimation (week 2)**

\[ \mathbf{x} = (\mathbf{r}^T, \dot{\mathbf{r}}^T, \ddot{\mathbf{r}}^T, \varphi, \theta, \psi, \omega_x, \omega_y, \omega_z) \]

**Configuration (state) of the robot for control (week 2)**

\[ \mathbf{x} = (\mathbf{r}^T, \dot{\mathbf{r}}^T, \ddot{\mathbf{r}}^T, \dddot{\mathbf{r}}^T, \varphi, \theta, \psi, \omega_x, \omega_y, \omega_z) \]

**Jerk and Snap**

Source: A. Civita’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)
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)

- UAV state: position, linear velocity, linear acceleration, orientation, angular velocity

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

- Various sources of sensory information
- Depending on the sensory setup and the surrounding environment

Source: A. Civita’s archive

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


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

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For 3D model see: https://myfei82.autodesk360.com/g/shares/SH35dfcQT936092f0e43ad283f586a8de440

Source: J. Shahmoradi 's archive

Source: mydronelab.com

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

Towards a Swarm of Nano Quadrotors

Alex Kushleyev, Daniel Mellinger, and Vijay Kumar
GRASP Lab, University of Pennsylvania


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: K. Pothuganti’s archive

Source: Q. Li’s archive

Source: Bitcraze (Crazyflie)
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

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**UAV sensors to achieve autonomy**

- **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
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)

✓ **Radar**: 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](image)


*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**.

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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: NVIDIA 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

UAV manipulators/arms

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https://youtu.be/QHpiXJzH5g
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).


