Transportation and manipulation by aerial vehicles

B(E)3M33MRS — Aerial Multi-Robot Systems

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What have we learnt so far?

UAV State estimation

- Estimation and filtering of system's states.
- **notable techniques**: LKF, EKF, UKF.

UAV Localization

- Measuring of UAV's position or velocity.
- **Techniques**: GNSS, Optic Flow, VIO, SLAM.

UAV Dynamics model

- Motor dynamics, propeller model, Attitude dynamics, Translational dynamics.

UAV Control

- Tracking the required states with the UAV.
- **Techniques**: PID, SO(3), Feed forward, MPC.

Methods required for stable flight.

What have we learnt so far?

Methods required for moving through the environment.

Path planning

- Finding collision-free path with waypoints.
- **Techniques**: Search-based methods. PRM

Motion planning

- Generating feasible trajectories.
- **Techniques**: Polynomial methods, MPC.

Mapping

- Building maps from sensory input.
- **Techniques**: Grid maps, OcTree, Point clouds.

Exploration

- Populating maps, planning in the unknown.
- **Techniques**: Frontier exploration.

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Interaction with the environment?

So far — everything except interaction

- All the efforts went into avoiding interaction with the environment:
  - defying gravity,
  - not crashing,
  - avoiding obstacles,
  - avoiding neighboring Unmanned Aerial Vehicles (UAVs),
  - finding collision-free paths through known/unknown environments.
- Interaction is *hard* because it must be *gentle*.
- Interaction is *hard* because it introduces disturbance.

"How not to land a drone"

Video: `https://youtu.be/GoEqMj4nZ7A`

Interaction with the environment

Tier 1 — Counteracting external disturbances

- Counteracting external disturbances:
  - wind,
  - air drag,
  - ground effect.
- Measuring or estimating the disturbances.
- Changing the dynamic model of the UAV:
  - change in mass, battery performance, propeller efficiency, center of gravity

Tier 2 — Admitting forces from the environment

Tier 3 — UAV carrying objects, exerting forces

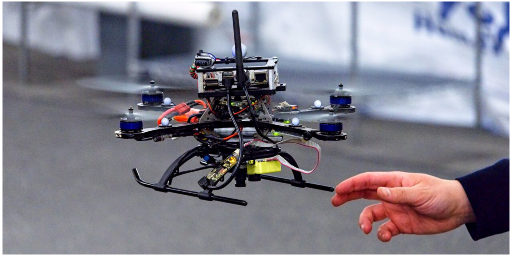
Tier 4 — Multi-UAV manipulation and transportation

Interaction with the environment

Tier 1 — Counteracting external disturbances

Tier 2 — Admitting forces from the environment

- Admitting forces from the environment.
- Takeoff and landing.
  - UAV can get stuck while taking off.
  - UAV can tip over while landing on uneven ground.
- Human-UAV interaction.
- Contact with the environment.



Tier 3 — UAV carrying objects, exerting forces

Tier 4 — Multi-UAV manipulation and transportation

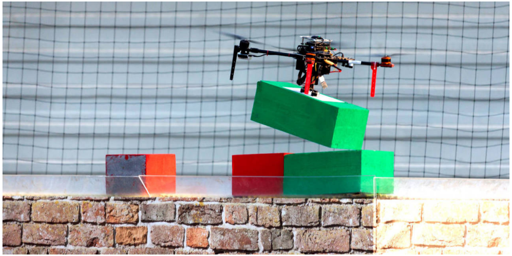
Interaction with the environment

Tier 1 — Counteracting external disturbances

Tier 2 — Admitting forces from the environment

Tier 3 — UAV carrying objects, exerting forces

- Carrying objects by underactuated UAV.
- How to grasp the object?
- The suspended load problem:
  - flying with a "pendulum" under the UAV.
- Exerting forces by underactuated UAV.
- Exerting forces by fully-actuated UAV.



Tier 4 — Multi-UAV manipulation and transportation

Interaction with the environment

Tier 1 — Counteracting external disturbances

Tier 2 — Admitting forces from the environment

Tier 3 — UAV carrying objects, exerting forces

Tier 4 — Multi-UAV manipulation and transportation

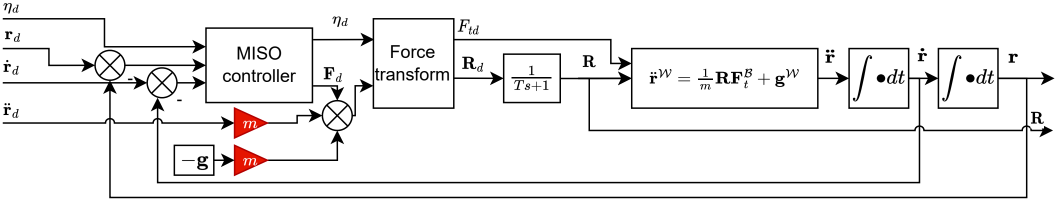
- **Planning-wise**: constrained formation planning for solving the *piano-mover's problem* (when the effects on the UAVs are negligible).
- **Control-wise**: coupled control of multiple UAVs carrying a payload (when the effects on the UAVs are too large to be compensated individually).

Tier 1 — Counteracting external disturbances — mass estimation

UAV Mass in feedforward control

- UAV mass (m) appears as a variable in feedforward control:
  - in transforming desired acceleration to desired force,
  - in counteracting the force of gravity.

Mass as a variable in control



UAV mass estimation

In an estimator

- Requires a nonlinear estimator for:

$$\ddot{\mathbf{r}}^{\mathcal{W}} = \frac{1}{m}\mathbf{R}\mathbf{F}_t^{\mathcal{B}} + \mathbf{g}^{\mathcal{W}}. \tag{1}$$

- Commonly EKF, UKF.
- Requires a close compatibility of estimators and controllers.
- Preferred in all-in-one solution (DJI).
- Recommended for agile flight and extreme manoeuvres.

Pros

- Will supply the estimate with any controller (even a human).
- Might be very accurate and precise.

Cons

- Sensitive to the UAV dynamics model.
- Requires good propulsion thrust curve model + battery model.
- Difficult to correct its bias.
- Requires controller's output.

UAV mass estimation

In a controller (Implemented in the MRS pipeline [1])

- Integral term for z-axis expressed as mass.
- **Premise**: PID controller for z-axis (as defined in the tutorial Task 01)

$$\ddot{r}_{\mathrm{zd}} = P_{\mathrm{z}} e_z + D_{\mathrm{z}} \frac{de_{\mathrm{z}}}{dt} + I_{\mathrm{z}} \int_0^t e_z d\tau \tag{2}$$

integrates the controller error e_z. The integral can be interpreted as **acceleration**, since it is part of a sum creating desired acceleration command $\ddot{r}_{\mathrm{zd}}$.

- **Alteration**: let's remove the integral term from the controller's output:

$$\ddot{r}_{\mathrm{zd}} = P_{\mathrm{z}} e_{\mathrm{z}} + D_{\mathrm{z}} \frac{de_{\mathrm{z}}}{dt}, \tag{3}$$

and use the integral term $I_{\mathrm{z}} \int_0^t e_{\mathrm{z}} d\tau$ as the difference from nominal mass (m) in the force transform:

$$m_e = m + I_{\mathrm{z}} \int_0^t e_{\mathrm{z}} d\tau, \tag{4}$$

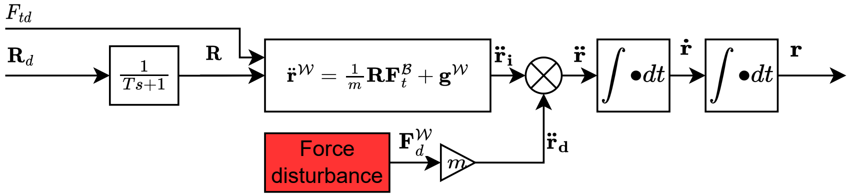
$$\mathbf{F}_{\mathrm{des}} = m_e(\ddot{\mathbf{r}}_{\mathrm{d}} + \ddot{\mathbf{r}}_{\mathrm{f}} - \mathbf{g}). \tag{5}$$

Counteracting external disturbances — world frame

External disturbances in the world frame

- Invariant in rotation (2D) of the UAV.
- **Wind** is the one and only typical world disturbance.
- Can be estimated by a Kalman filter.

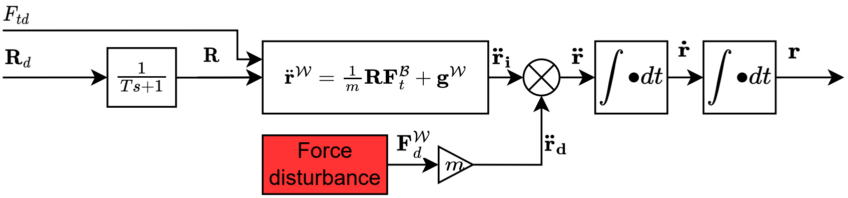
Dynamics with the external disturbance



External disturbances in the world frame

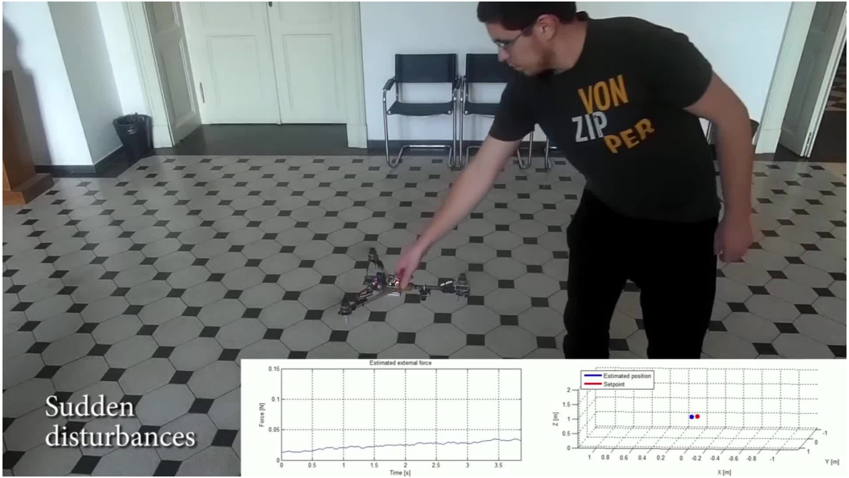
Translation Linear Time Invariant (LTI) subsystem

$$\mathbf{x} = \begin{bmatrix} r_x \\ \dot{r}_x \\ \ddot{r}_x \\ \ddot{\mathbf{r}}_{\mathbf{xd}} \\ \ddot{r}_{xi} \end{bmatrix}, \mathbf{u} = \begin{bmatrix} \ddot{r}_{xu} \end{bmatrix}, \mathbf{A} = \begin{bmatrix} 1 & \Delta t & \frac{1}{2}\Delta t^2 & 0 & 0 \\ 0 & 1 & \Delta t & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0.99 \end{bmatrix}, \mathbf{B} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0.01 \end{bmatrix}. \quad (6)$$



External disturbances in the world frame

LKF estimating external force

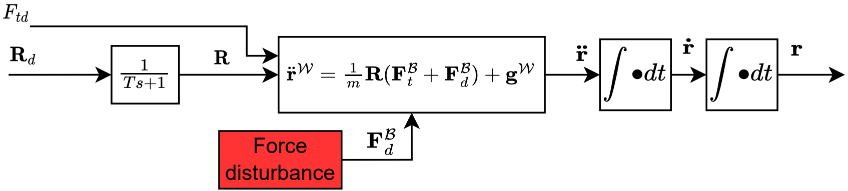


Video: `https://youtu.be/S-0qX9xLP-E`

External disturbances in the body frame

- Air drag (when flying front-first).
- Imprecise attitude horizon calibration (accelerometers).
- Can be estimated with nonlinear Kalman filter (EKF, UKF).

Dynamics with the body-frame external disturbance

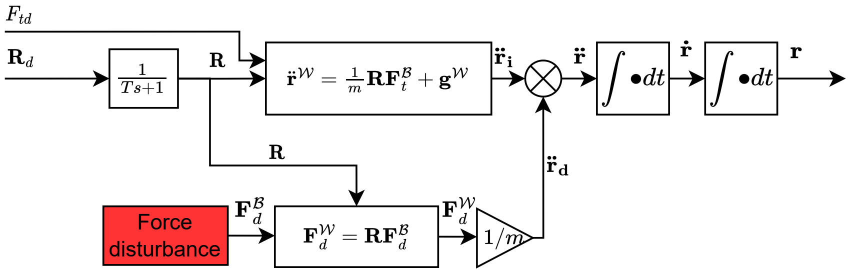


Counteracting external disturbances — body frame

External disturbances in the body frame

- Air drag (when flying front-first).
- Imprecise attitude horizon calibration (accelerometers).
- Can be estimated with nonlinear Kalman filter (EKF, UKF).

Compensating for the body-frame external disturbance



Separating body and world disturbances

Feedback with disturbance compensation

$\mathbf{a} \circ \mathbf{b}$: piecewise product of $\mathbf{a}$, $\mathbf{b}$

$$\mathbf{F}_d = \overbrace{\mathbf{k}_p \circ \mathbf{e}_p}^{\text{position feedback}} + \overbrace{\mathbf{k}_v \circ \mathbf{e}_v}^{\text{velocity feedback}} + \overbrace{m_e \ddot{\mathbf{r}}_d}^{\text{reference feedforward}} + \overbrace{m_e g \hat{\mathbf{e}}_3}^{\text{gravity compensation}} + \overbrace{-\mathbf{d}_w \circ \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix}}^{\text{world disturbance compensation}} + \overbrace{-\mathbf{d}_b \circ \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix}}^{\text{body disturbance compensation}} \quad (7)$$

World disturbance integration

$$\mathbf{d}_w = \sum_{n=0}^{N} \mathbf{k}_{iw} \circ \mathbf{e}_{p[n]} \, \Delta t_{[n]} \quad (8)$$

Mass estimation

$$m_e = m + (\mathbf{d}_w + \mathbf{H}\mathbf{d}_b)^\intercal \, \hat{\mathbf{e}}_3, \quad (9)$$

Body disturbance integration

$$\mathbf{d}_b = \mathbf{H}_{[N]} \sum_{n=0}^{N} \mathbf{k}_{ib} \circ (\mathbf{H}_{[n]}^\intercal \, \mathbf{e}_{p[n]}) \, \Delta t_{[n]} \quad (10)$$

$$\mathbf{H}_{[n]} = \begin{bmatrix} \cos\ \eta_{[n]} & -\sin\ \eta_{[n]} & 0 \\ \sin\ \eta_{[n]} & \cos\ \eta_{[n]} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (11)$$

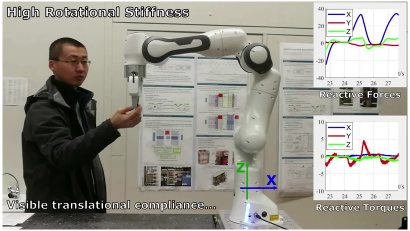
Tier 2 — Admitting forces from the environment

Admittance control

- Allowing control error to occur.
- Outer loop controller that modifies nominal control reference.
- Commonly used with robotic manipulators:
  - direct control by pushing the robot around.

Takeoff and Landing

- Part of every flight.
- The most dangerous part of a normal flight.
- Requires admittance for safety.
- Takeoff:
  - UAV can get stuck.
  - Control errors due to *clean initialization*.
- Landing:
  - UAV can be landing on uneven ground.
  - Touchdown detection is often based on admittance control.



Video: `https://youtu.be/XwiX2vv14Qs`

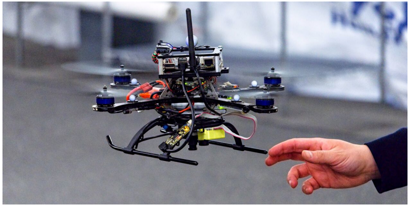


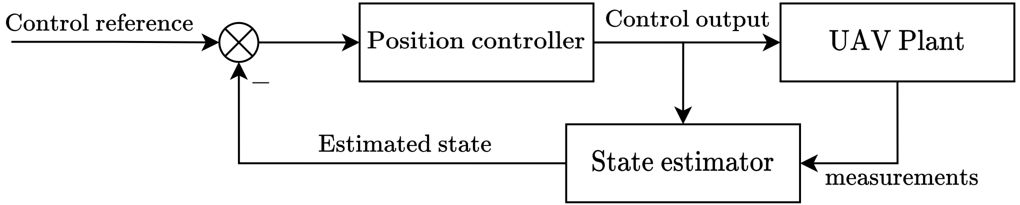
Figure 1: UAV being pulled by a person.

Admitting forces from the environment

Normal control loop

- The *Position controller* makes all the effort to minimize the *Control error*.
- This can lead to dangerous manoeuvres, if disturbed artificially by human.

Standard control loop

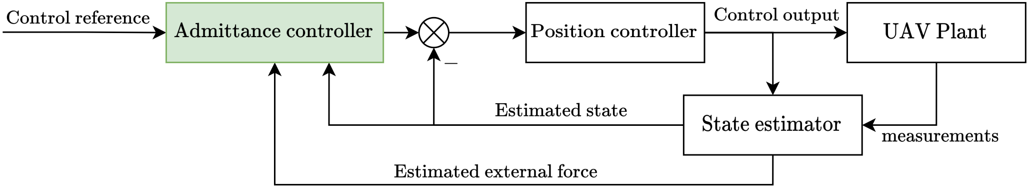


Admitting forces from the environment

Admittance control loop

- Additional outer control loop.
- The *Admittance controller* modified the reference such that some control errors are allowed.

Admittance control



Admitting forces from the environment

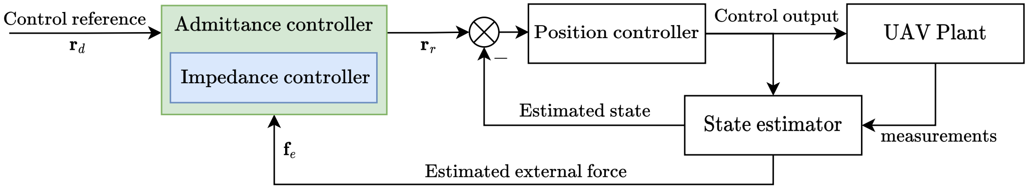
Impedance control loop

- The admittance controller is governed by an *artifical dynamics*.
- Typically, 2nd-order mass-spring-damper dynamics:

$$\mathbf{M}(\ddot{\mathbf{r}}_d - \ddot{\mathbf{r}}_r) + \mathbf{D}(\dot{\mathbf{r}}_d - \dot{\mathbf{r}}_r) + \mathbf{K}(\mathbf{r}_d - \mathbf{r}_r) = -\mathbf{f}_e \quad (12)$$

- $\mathbf{r}_d \in \mathbb{R}^3$ — reference from the *user*.
- $\mathbf{r}_r \in \mathbb{R}^3$ — reference from the *admittance cont.*
- $\mathbf{M} \in \mathbb{R}^{3\times3}$ — inertia (diagonal).
- $\mathbf{D} \in \mathbb{R}^{3\times3}$ — damping (diagonal).
- $\mathbf{K} \in \mathbb{R}^{3\times3}$ — stiffness (diagonal).

Admittance + Impedance control



Admittance control — Human-machine interaction

Video: `https://youtu.be/w2itwFJCgFQ`

[2] F. Augugliaro and R. D'Andrea, "Admittance control for physical human-quadrocopter interaction," in *2013 European Control Conference (ECC)*, IEEE, 2013, pp. 1805–1810

Tier 3 — Aerial manipulation

Carrying a physical payload by a UAV

- Aspects and Problems:
  - The nature of the payload attachment?
  - The way of *attaching* the payload?
  - Where to attache the payload?
  - How will it influence the system dynamics and control?
  - How will it influence the air dynamics and air flow?

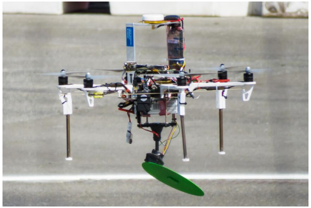
Attaching the payload

Rigidly

Figure 2: Source: Matternet

- Simpler mechanism.
- Needs precision while attaching.
- Changes rotational inertia.
- Ideally placed along body-z axis.

Semi-rigidly



- Allows some movement of the payload.
- Gives leeway for attachment precision.
- More complex and heavier mechanism.
- Can be robotized: a manipulator.

Suspended

- Allows for large payloads.
- Introduces *suspended pendulum* problem.
- Subject of research.
- Challenging when mass of the payload ≈ mass of the UAV.

Under-actuated manipulation — robotic arms onboard UAVs

Individually-controlled

- Naive approach.
- The manipulator and the UAV controller are independent.
- The manipulator driven only by sensory input.

Half-coupled

- The manipulator controller is given the UAV and control actions.
- Compensation of the UAV motion.

Fully-coupled

- A single controller drives both: the UAV and the manipulator.
- The UAVs motion adjusts to the motion of the manipulator.

Figure 3: 7-DOF robotic arm under a UAV [3].

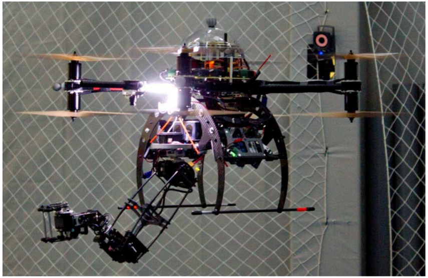


Figure 4: Servo robot arm onboard UAV [4].

Exerting forces on the environment

Why?

- Pushing objects around.
- Inspecting objects by touch:
  - material inspection,
  - contact sampling.
- Installing devices in the surrounding
  - IOT sensors,
  - markers and beacons.
- Aerial painting.
- Stabilization of the UAV *at location*.
  - *perching*.

Pipe inspection by a multirotor UAV

Figure 5: Fully-actuated multirotor UAV applying force to a pipe.

UAV-Wall interaction

Video: `https://youtu.be/nv9UzNkVEGI`

[5] D. Smrcka, T. Baca, T. Nascimento, and M. Saska, "Admittance Force-Based UAV-Wall Stabilization and Press Exertion for Documentation and Inspection of Historical Buildings,", 2021, 2021 International Conference on Unmanned Aircraft Systems (ICUAS)

Fully-actuated multirotor UAVs

Video: `https://youtu.be/22Q9dxS6QfM`

[6] R. Rashad, D. Bicego, R. Jiao, S. Sanchez-Escalonilla, and S. Stramigioli, "Towards vision-based impedance control for the contact inspection of unknown generically-shaped surfaces with a fully-actuated UAV," in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, IEEE, 2020, pp. 1605–1612

Fully-actuated multirotor UAVs

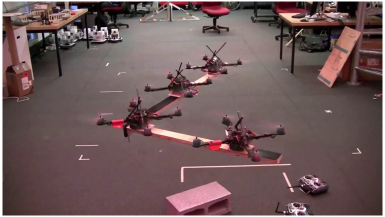
Video: `https://youtu.be/-RCQmaKvsL0`

[7] K. Bodie, M. Brunner, M. Pantic, S. Walser, P. Pfandler, U. Angst, *et al.*, "Active interaction force control for contact-based inspection with a fully actuated aerial vehicle," *IEEE Transactions on Robotics*, vol. 37, no. 3, pp. 709–722, 2020

Tier 4 — Multi-robot manipulation and transportation

Rigid attachment

- With perfect localization:
  - Leads to a specific control problem.
  - The structure creates a single multirotor vehicle.
- Needs centralized control.
- Needs fast communication.
- Impractical in the real world.



Video: `https://youtu.be/YBsJwapanWI`, [8]

Semi-rigid attachment

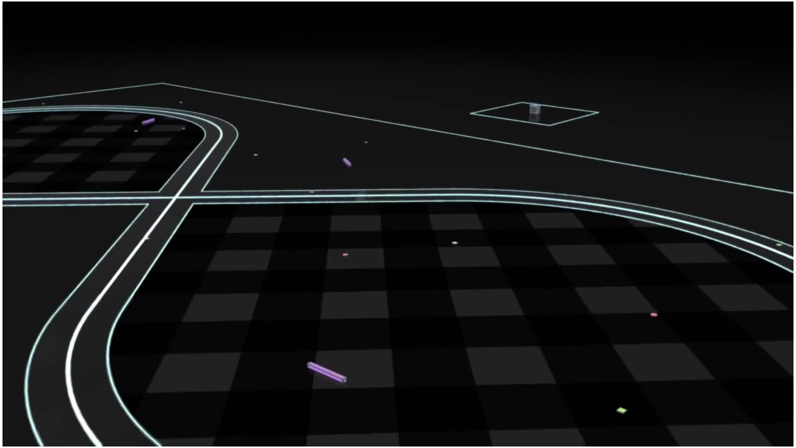
- With perfect localization:
  - Leads to centralized formation control problem.
- With real-world localization:
  - Leads to a difficult control problem.

Rope-suspended payload

- Possible even with imprecise localization.
- The grasping is challenging.
- The problem then reduces to formation planning (Lecture 07).

Case-study — MBZIRC 2017 Challenge

Introductory video (by organizers)



Video: `https://youtu.be/u106Vy-XJ7c`

Case-study — MBZIRC 2017 Challenge

Methodology

- Visual object detection.
- Mapping of objects in the global GPS frame.
- Motion estimation for moving objects.
- RTK GPS fused (if available).
- Robust grasping state machine.
- Banning of unpickable objects from the map:
  - to avoid deadlocks.
- Sharing of the pickup locations between UAVs:
  - to avoid conflicts while grasping.

[9] V. Spurny, T. Baca, M. Saska, R. Penicka, T. Krajnik, J. Thomas, *et al.*, "Cooperative Autonomous Search, Grasping and Delivering in a Treasure Hunt Scenario by a Team of UAVs," *Journal of Field Robotics*, vol. 36, no. 1, 125–148, 2019

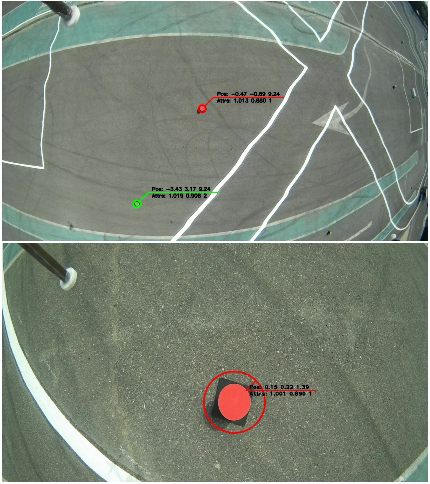


Figure 6: Visual object detection.

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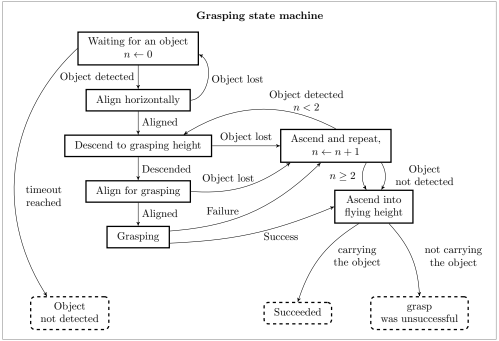

Figure 6: Grasping state machine.

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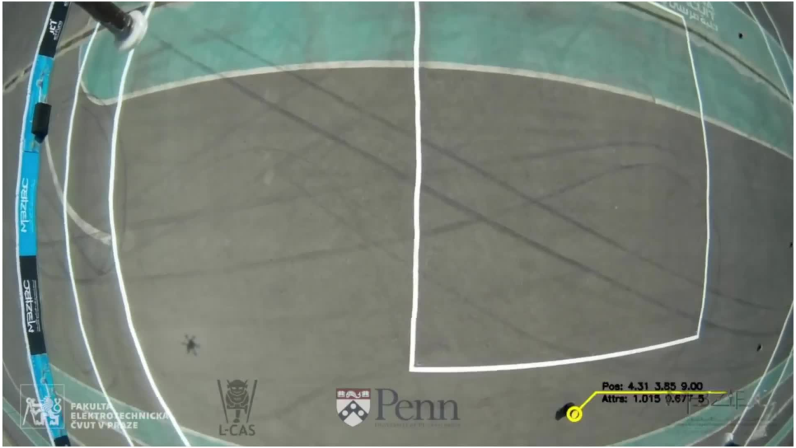
Figure 6: MRS UAVs during the competition.

Performance of the MRS team in the competition



Video: `https://youtu.be/-PTk_tnh7tU`

Case-study — MBZIRC 2020 Challenge

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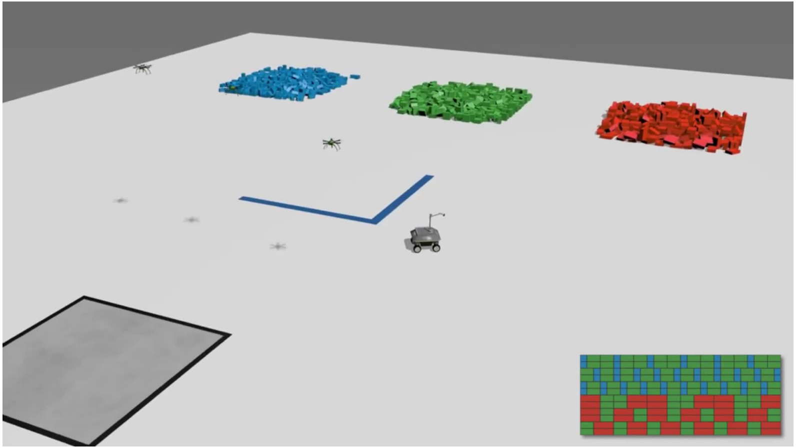

Video: `https://youtu.be/u106Vy-XJ7c`

Grasping objects with imprecise UAV localization

Problems with Global Navigation Satellite System (GNSS) localization

- Estimating objects' position in GNSS world is inaccurate.
- Random walk and drift in UAV localization causes apparent random walk of the objects.
- This limits the precision and accuracy of possible interaction.

Solution: Visual servoing

- UAV is localized relatively to the object.
- Closing the control loop directly using the relative localization.
- Requires tracking of the objects in the GNSS frame for their unique identification.

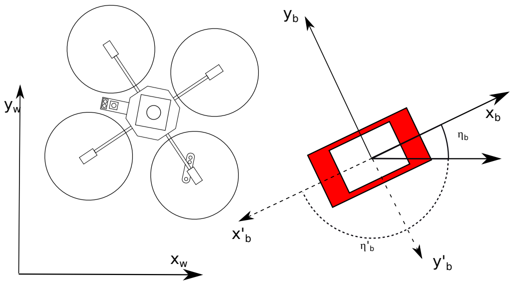

Figure 7: Coordinate frames defined by the object.

Case-study — MBZIRC 2020 Challenge

Methodology

- Visual and 3D detection of bricks and the wall.
- Mapping and filtration of bricks and walls.
- Operation in multiple frames of reference:
  - GNSS, Optic flow, Brick
- Magnetic gripper with feedback and damping.
- Visual servoing against the grasped brick.
- Admittance control for the final grasping manoeuvre.
  - Risk of the UAV tipping over.
  - Risk of hitting other bricks.
- Admittance control for laying the brick.

[10] T. Baca, R. Penicka, P. Stepan, M. Petrlik, V. Spurny, D. Hert, *et al.*, "Autonomous Cooperative Wall Building by a Team of Unmanned Aerial Vehicles in the MBZIRC 2020 Competition," *Robotics and Autonomous Systems*, vol. 167, p. 104 482, Sep. 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/

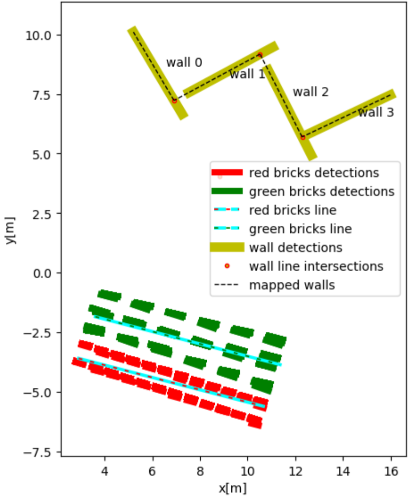

Figure 8: Map of bricks and wall segments.

Methodology

- Visual and 3D detection of bricks and the wall.
- Mapping and filtration of bricks and walls.
- Operation in multiple frames of reference:
  - GNSS, Optic flow, Brick
- Magnetic gripper with feedback and damping.
- Visual servoing against the grasped brick.
- Admittance control for the final grasping manoeuvre.
  - Risk of the UAV tipping over.
  - Risk of hitting other bricks.
- Admittance control for laying the brick.

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Figure 8: Magnetic gripper.

Case-study — MBZIRC 2020 Challenge

Methodology

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Figure 8: Grasping in action.

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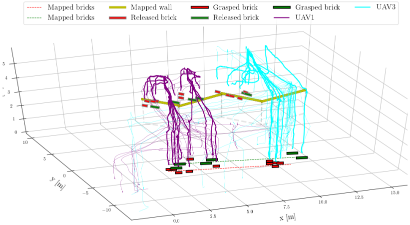
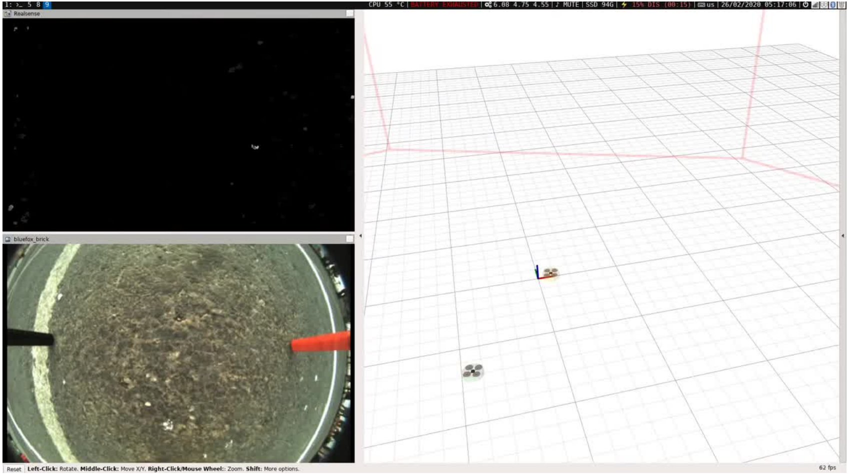


Figure 8: All UAVs trajectories.

Case-study — MBZIRC 2020 Challenge



Video: `https://youtu.be/Fb8kSxgVopU`

Collaborative transportation in the real world

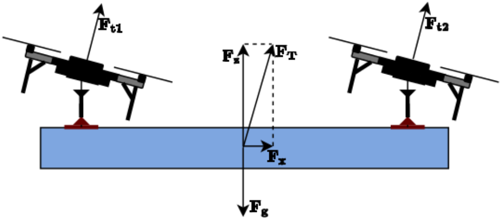
Problems to be solved.

- Relative localization of the UAVs.
- Mutual communication.
- Grasping mechanism and grasping manoeuvre.
- Time synchronization.

Solution

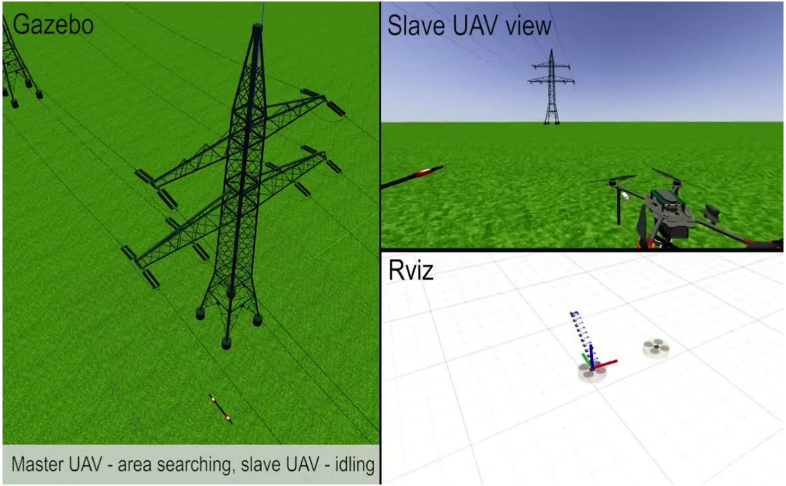
- Master-slave control scheme.
- Each UAV acts as a tiltable propeller.
- Semi-rigid gripper: rigid for grasping, ball-joint for carrying.

Formation diagram



Formation

Collaborative transportation in the real world



Video: `https://youtu.be/5jSwKbBZwP4`

Collaborative transportation in the real world

Video: `https://youtu.be/qSvCNqfmNCI`

Current state of drone delivery?

Amazon Prime Air

- Announced in 2013
- Offices closed in 2021.
- Theoretically feasible, but impractical.

Implementation problems

- Safety:
  - securing the delivery location,
  - safety of the recipients,
  - safety of the UAV,
  - safety in the common airspace.
- Package hand-over.
- Multicopter are energy inefficient.
- Navigating obstacles.
- Economic viability? Not good in general.
- Very-location specific.


abc NEWS VIDEO LIVE SHOWS 2022 MIDTERM ELECTIONS JAN. 6

Amazon Prime Air: Delivery by Drones Could Arrive As Early as 2015

Drones soon might be dropping off your toothpaste and underwear.

By JOANNA STERN
December 2, 2013, 3:43 AM

Amazon Plans Drone-Delivery Service
The online retailer says the vehicles are ready to go, but they need approval from the FAA.

Figure 9: Amazon Prime Air announcement, source ABC news.

Current state of drone delivery?

Where could it work?

- Remote locations, e.g., archipelago.
- Controlled environments: warehouses.
- Low population density.
- Far from important infrastructure.
- Delivery of medical goods.
- Delivery between **dedicated boxes**.

Success stories

- **Matternet** (Multirotor)
  - Delivery of medical goods.
  - Custom *launch station*
  - Pilot project in Berlin.
- **Zipline** (Plane)
  - Delivery of medical goods.
  - Deployed in Rwanda.

More to watch: Why did drone delivery fail?

Wendover Productions:
`https://youtu.be/J-M98KLgaUU`.

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Conclusion

- Aerial manipulation and transportation is **hard**.
- Its practicality is very **limited**.
- It is currently subject of **research**.