Multi-Robot Systems

https://youtu.be/dT7b1j5Ij1I

Martin Saska

Multi-robot Systems group,
Czech Technical University in Prague

http://mrs.felk.cvut.cz   martin.saska@fel.cvut.cz

Multi-Robot Systems at CTU in Prague

http://mrs.felk.cvut.cz/

http://mrs.felk.cvut.cz/available-student-projects

- **UAV localization, mapping, SLAM and perception**
- **UAV stabilization and fast collision mutual avoidance**
- **Model Predictive Control**
- **Vision-based techniques**
- **UAV formation coordination**
- **Safety-critical & robust applications**
- **Decentralized control of swarms of aerial vehicles**
- **Cooperative sensing and data collection by a group of UAVs**
- **Mutual localization of neighboring vehicles in swarms**
- **High-level planning, communication and coordination**
- **Indoor navigation and exploration**

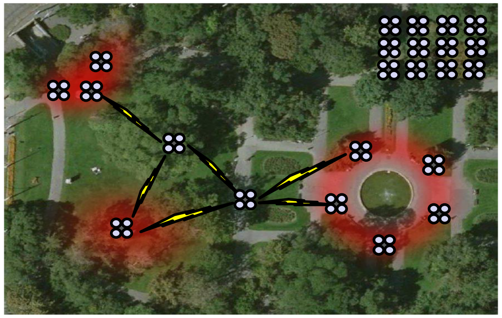
3/2017 – MBZIRC 3rd challenge:
1st place $330.000

2/2020 – MBZIRC 2rd challenge:
1st place $250.000, TOTAL WINNERS

2019-2020 - DARPA SubT: 2x 1st place among self-funded teams. $200k & $500k

Multi-Robot Systems

- Single-Robot → Multi-Robot Systems
  - Multiple mobile robots → Multi-Robot System
  - Coordination using communication
- Motivation
  - Robotic problems are often naturally distributed
  - Redundancy and robustness vs. enlarged complexity of the system
  - Faster mission execution (e.g., search and rescue)
  - Several light-weight robots replace a large well-equipped and heavy robot
  - Many tasks not solvable by a single robot
  - Actions realized in distance places in parallel



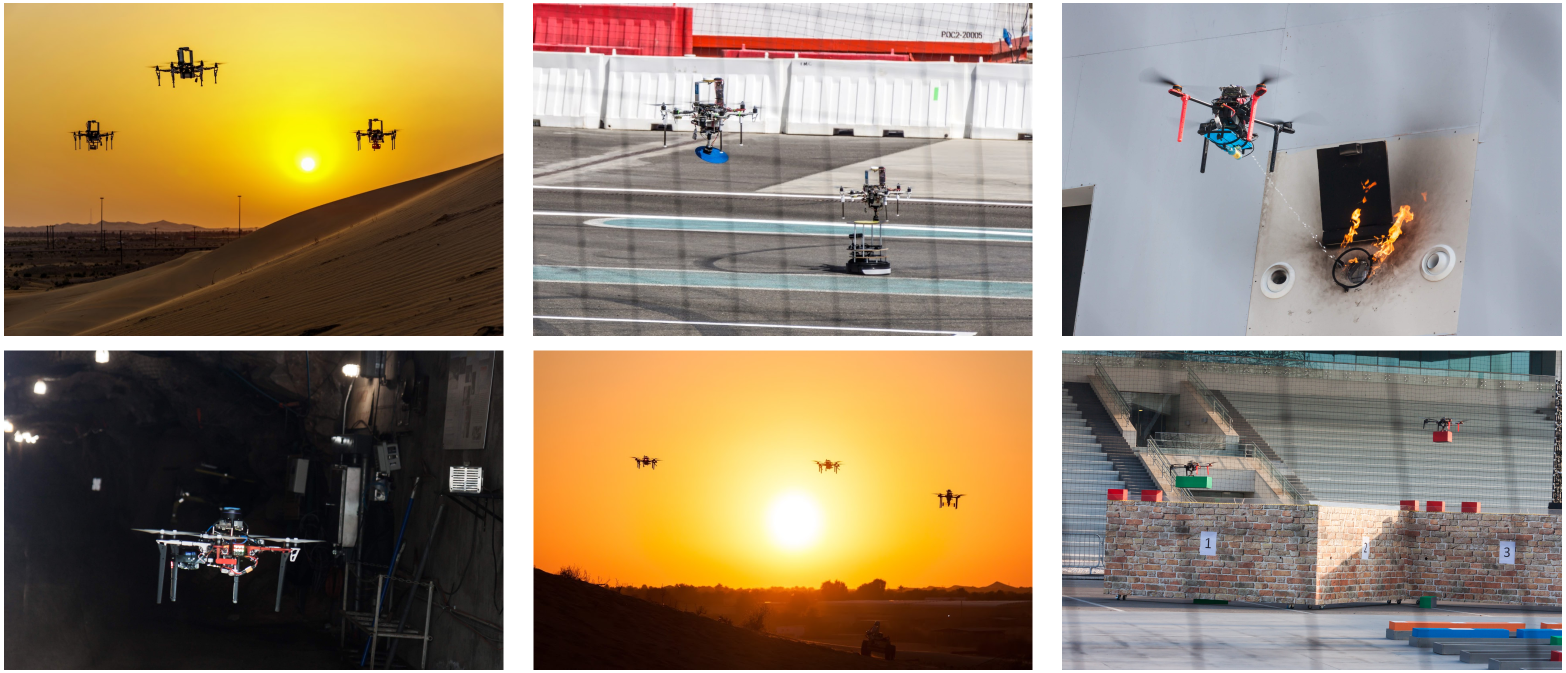
Saska 2017 AURO

Saska 2017 ETFA

Spurný 2019 ETFA

Multi-Robot Systems

- Taxonomy and essential terms
  - Centralized vs. Decentralized control architecture
  - Coordination vs. Cooperation vs. Collaboration
  - Explicit vs. Implicit communication
  - Homogeneous vs. Heterogeneous robots
  - Collective movement - Swarms vs. Formations



Centralized vs. Decentralized (vs. Distributed)

- Centralized control architecture
  - ▪ Single control unit (a decision/commands are distributed to all robots from a central PC)
  - ▪ Centralized state estimation of the entire MRS; knowledge of the global state
  - \+ Usually simpler control design and better performance
  - \- Requires synchronized and reliable communication
  - \- Single-point of failure problem
  - \- Less scalable

Centralized vs. Decentralized (vs. Distributed)

- Centralized control architecture

Saska 2020 AuRo https://youtu.be/slzlHtve3kY

Centralized vs. Decentralized (vs. Distributed)

- Decentralized control architecture
  - Each robot equipped with onboard processing unit makes and executes its own decision obtained based on interactions with other robots
  - Decentralized state estimation (each robot estimates its state and relative states of teammates)
  - \+ Scalability
  - \+ Robust to failures
  - \- Difficult to achieve optimal performance (sub-optimal performance)
  - \- Difficult to prove optimality

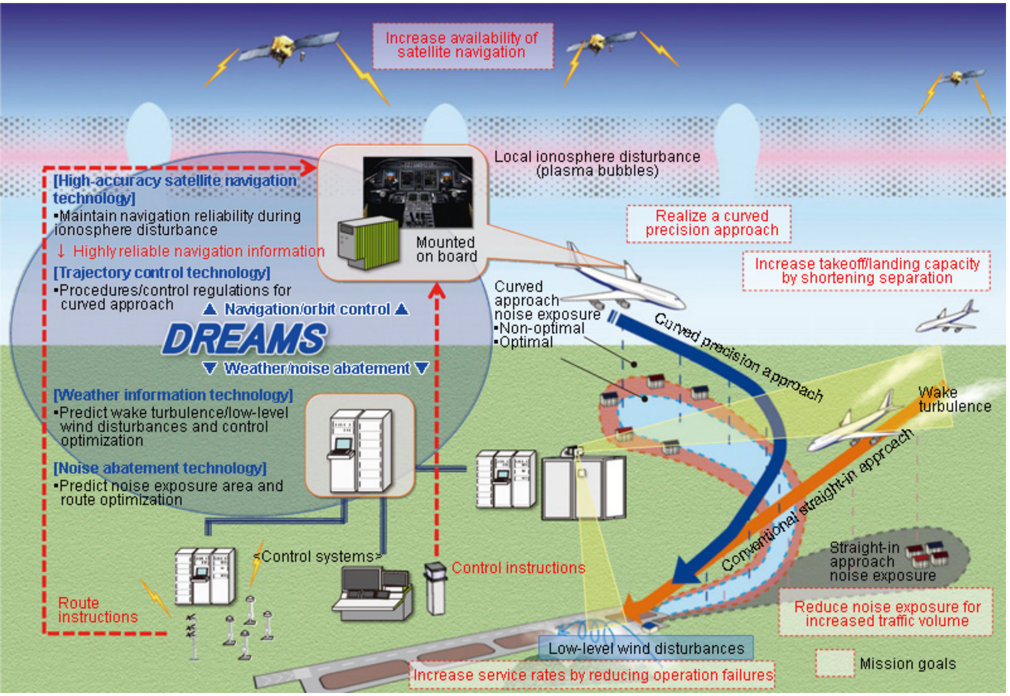
Centralized vs. Decentralized (vs. Distributed)

- Decentralized control architecture

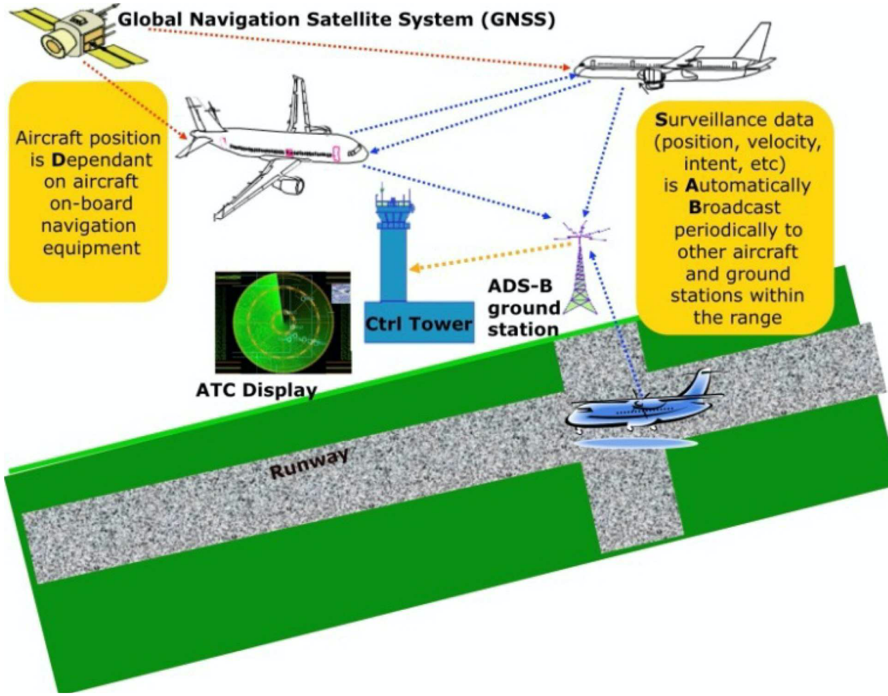
Petráček 2020 B&B https://youtu.be/slzlHtve3kY

Centralized vs. Decentralized (vs. Distributed)

- Distributed control architecture
  - The decision is made by a negotiation process between the robots
  - For example autonomous air and car traffic management
  - \+ Scalability and robust to failures
  - \- Requires reliable communication



DREAMS (Distributed and Revolutionarily Efficient Air-traffic Management System)



Air traffic management by Imperial College London

Coordination vs. Cooperation vs. Collaboration

- Coordination
  - Allows a group to complete a task more efficiently than a single robot by its self (according to Vijay Kumar, UPENN)
  - Usually motion coordination and alignment (e.g., to keep a cohesive swarm)
- Cooperation
  - Allows a group to complete a task that an individual robot could not complete on its own at all.
  - Robots cooperate towards a common intention together (e.g., cooperative transportation)
  - It usually requires synchronization and tight sharing workspace
- Collaboration
  - Allows a group of different types of robots with diverse capabilities to complete a task that cannot be completed using just one type of robots

https://soundcloud.com/robohubpodcast/coordination-cooperation-and-collaboration

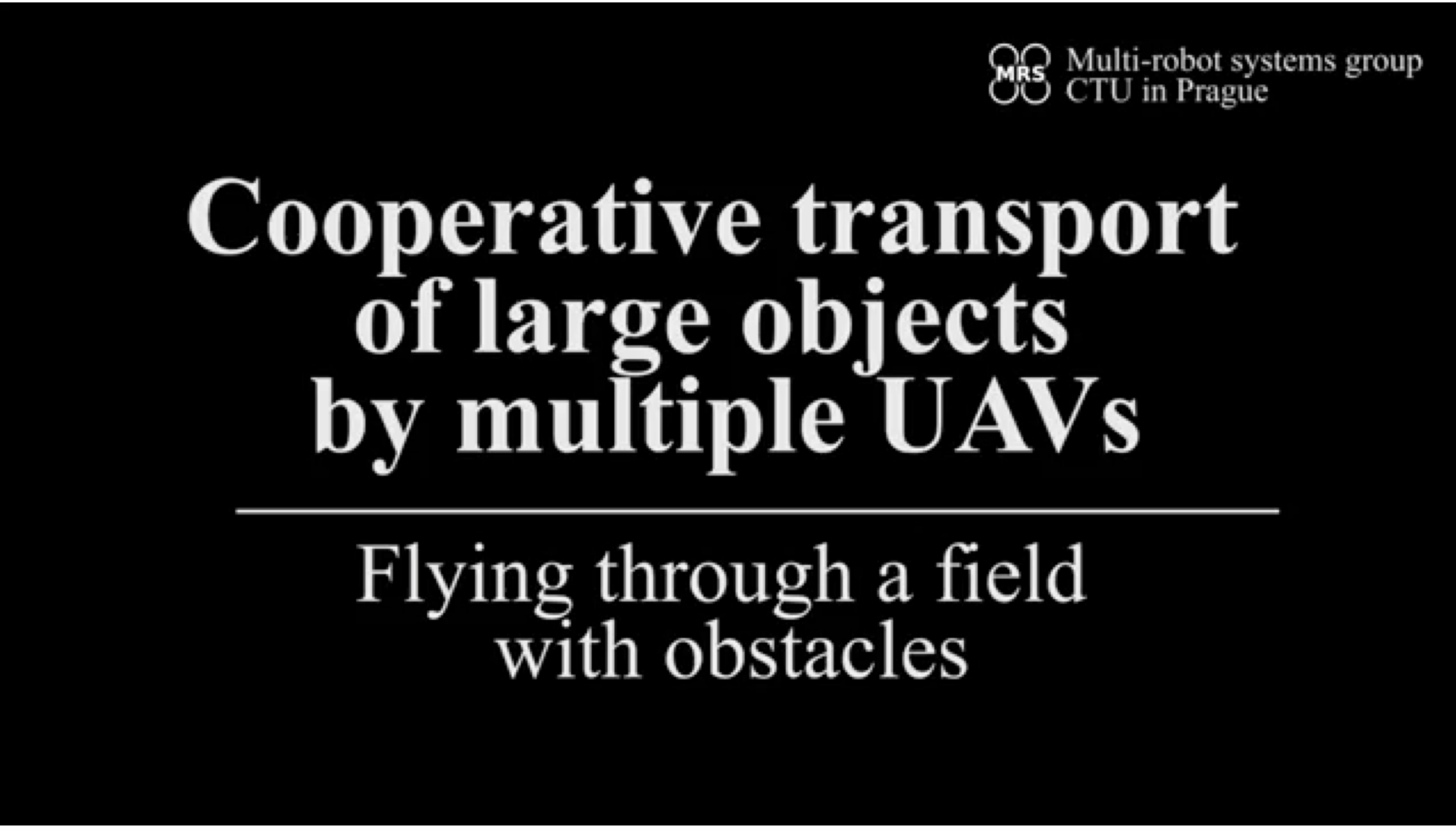
Coordination – e.g. Treasure hunt at MBZIRC 2017

- Multi-UAV team collecting objects of unknown position – faster and more reliable

Spurný 2019 JFR https://youtu.be/ogmQSjkqqp0

Cooperation – e.g. heavy object transportation

- The object is too heavy or large to be transported by a single UAV with a payload



Multi-robot systems group
CTU in Prague

Cooperative transport
of large objects
by multiple UAVs

Flying through a field
with obstacles

Spurný 2019 ETFA https://youtu.be/FQH769AnYbQ

Collaboration – e.g. complex fire extinguishing or smart lightening

- MBZIRC 2020: Different robots for different fire locations (ground floor, top floor, outdoor)

Spurný 2020 JINT, Stibinger 2020 RAL

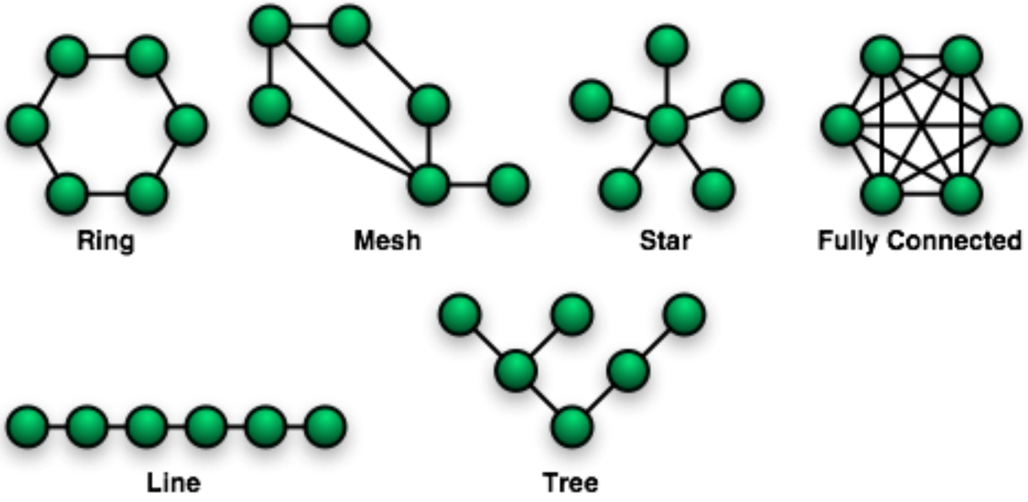
https://youtu.be/O8QBiAyP2c0

Explicit vs. Implicit communication

- Explicit communication
  - States of neighbors are unobservable
  - Communication infrastructure required
- Implicit communication
  - Directly through observation of neighbor states (relative or mutual localization)
  - Undirect information exchange by observation of the workspace

Explicit communication - Topologies

- Range of communication
  - A disc model (only in a simple environment)
- Communication for centralized control/coordination
  - **Fully connected**
  - **Star**, Line, Ring, Tree, Hierarchical topology
- Communication for decentralized control/coordination
  - Mesh
  - Random mesh



Explicit communication – Line and Mesh topology

- DARPA SubT: Team of ground and aerial robots deployed in underground tunnels

Roucek 2019 MESAS, Petrlik 2020 RAL

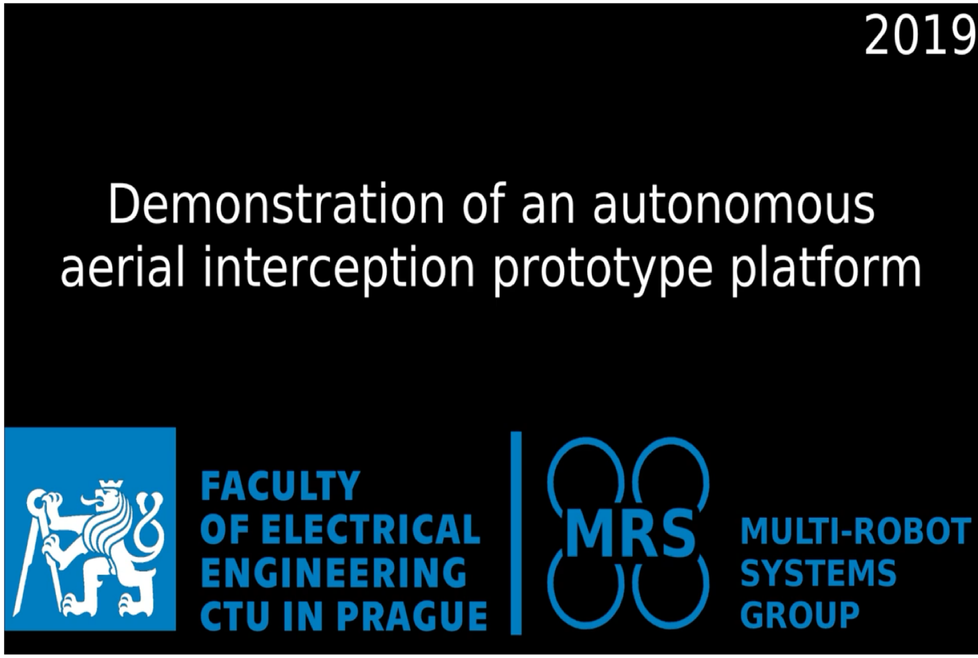
https://youtu.be/Nk7SUNGzo1k

Implicit communication – relative localization

- Marker-Less Detection and Localization
  - Vision-based (CNN), Lidars, 3D cameras
  - None-cooperating robots, humans, vehicles

Vrba 2019 RAL

https://youtu.be/r_qou0pFMn4



2019

Demonstration of an autonomous aerial interception prototype platform

FACULTY OF ELECTRICAL ENGINEERING CTU IN PRAGUE

MRS MULTI-ROBOT SYSTEMS GROUP

Vrba 2020 RAL

https://youtu.be/mr4uqgBslHw

Implicit communication – relative localization

- MBZIRC 2020: Team of aerial robots hunting balloons and aerial target (RGB and Lidar)

MBZIRC 2020 Summary

Challenge #1

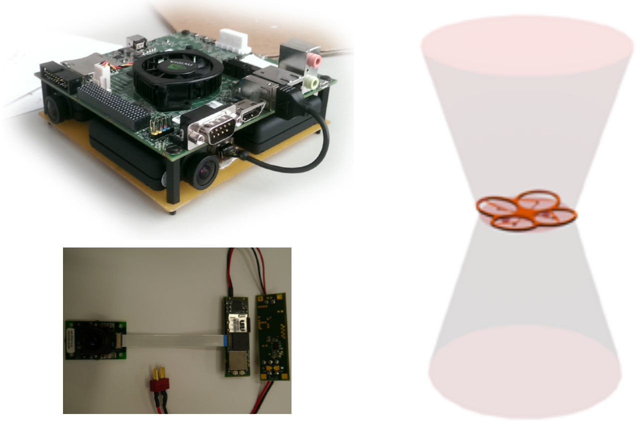
CTU in Prague, UPenn, NYU

Vrba 2021 SMC, Stasinchuk 2021 ICRA

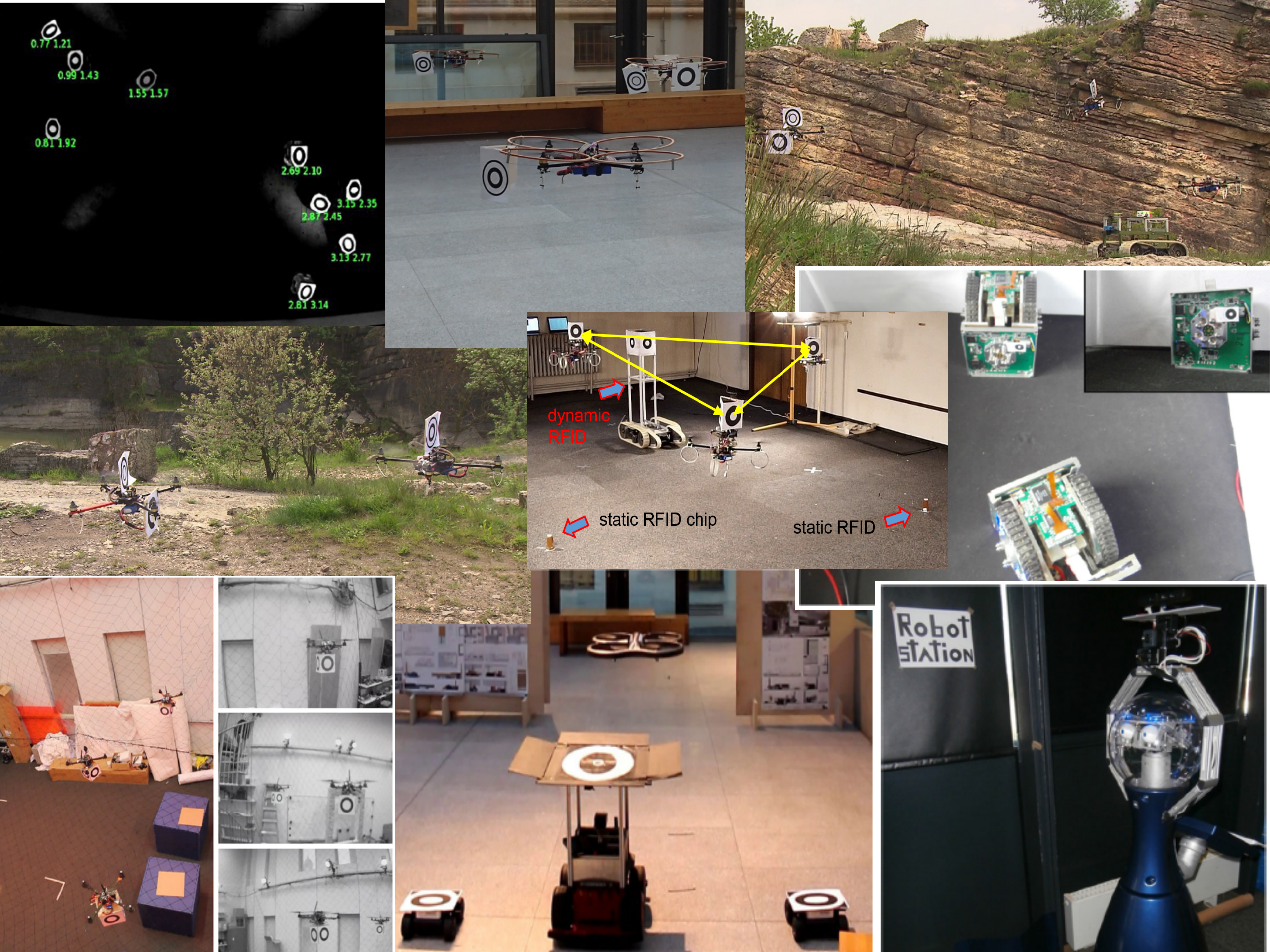
https://youtu.be/2-cLSjRCKDg

Implicit communication – relative localization

- Marker-based relative localization
  - Passive markers – color and B&W patterns
  - Active markers – RGB and UV lights

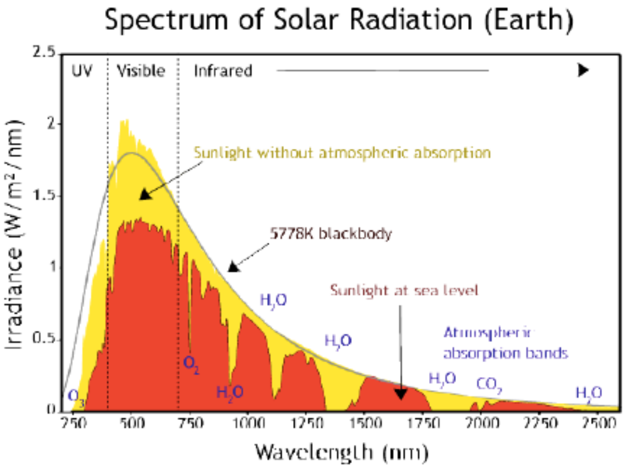


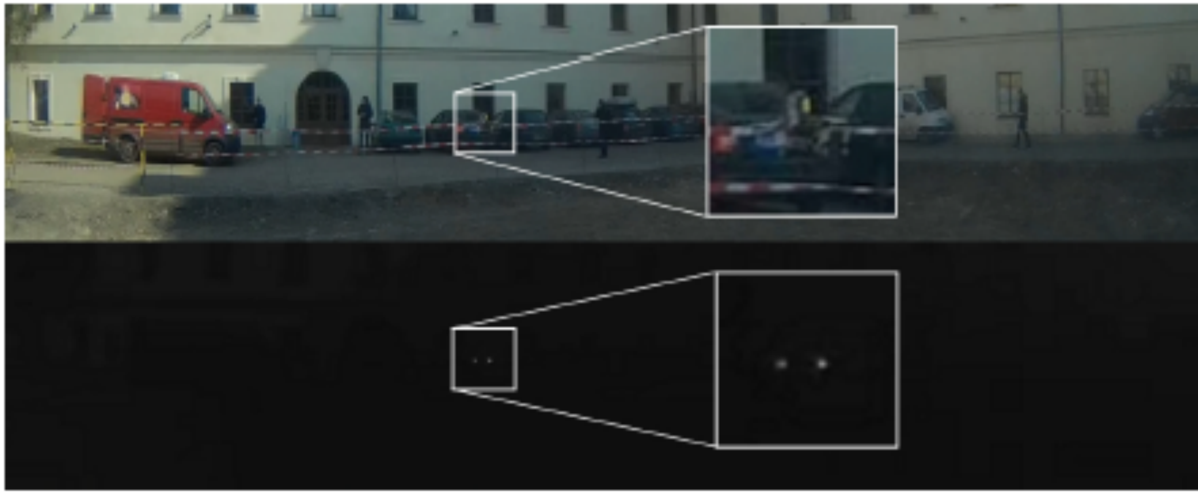
Faigl 2013 ICRA, Krajnik 2014 JINT

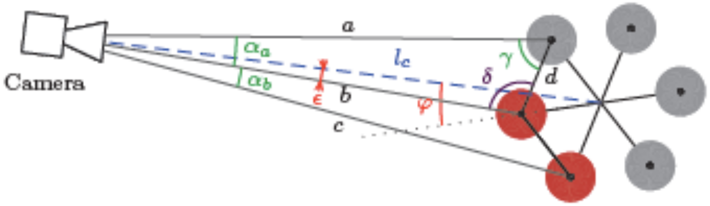

0.77 1.21
0.99 1.43
1.55 1.57
0.81 1.92
2.69 2.10
3.15 2.35
2.87 2.45
3.13 2.77
2.81 3.14
dynamic RFID
static RFID chip
static RFID
Robot STATION

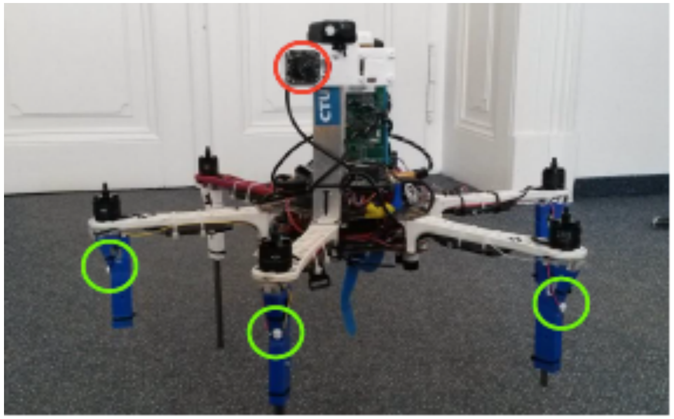
Implicit communication – relative localization using active UV Markers

- Reduced size of markers, low computational complexity
- Increased reliability





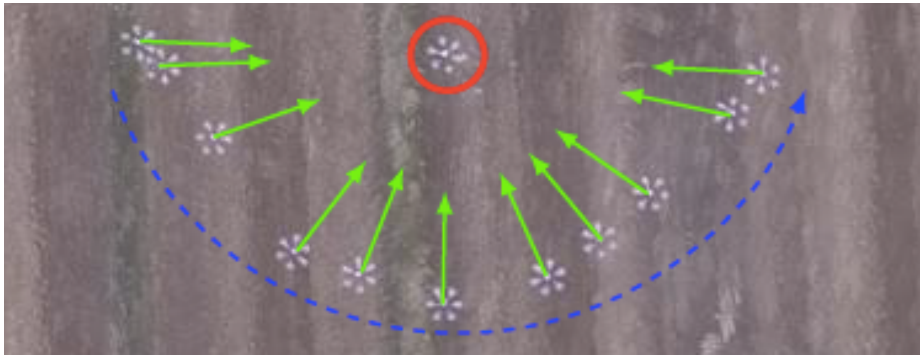


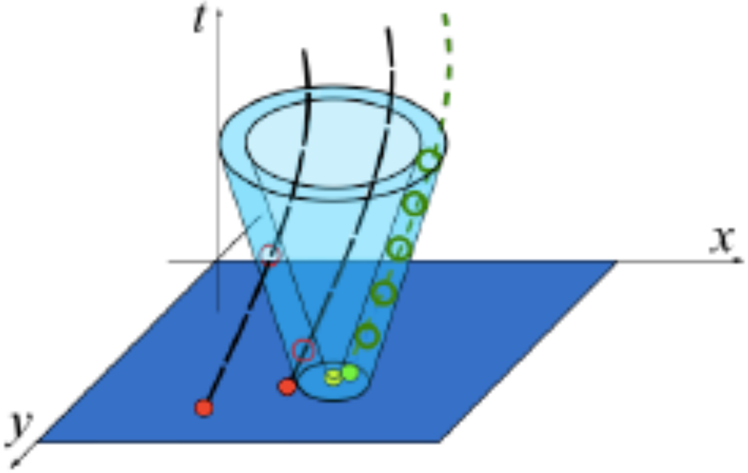


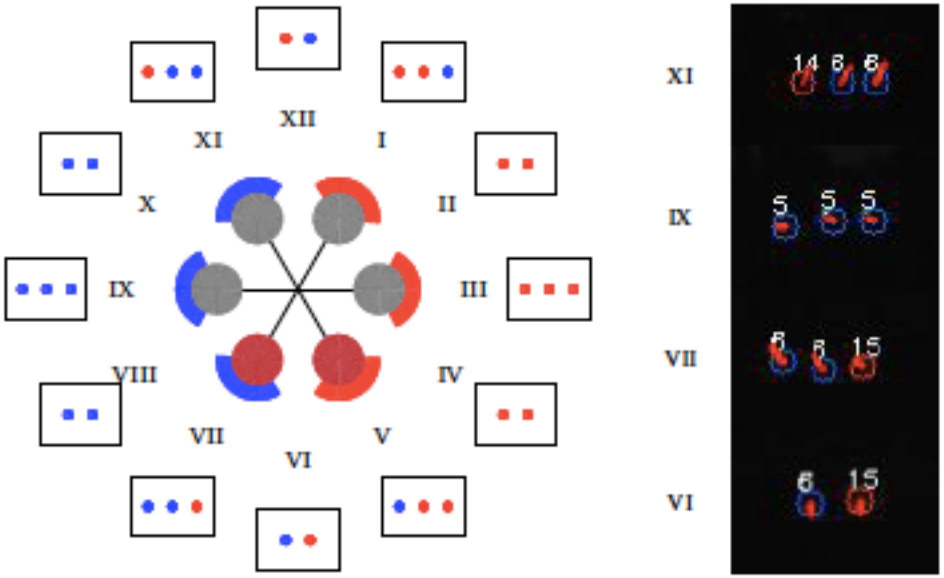
Walter 2018 CASE, Walter 2018 ICUAS

Beyond implicit communication - Blinking UV markers

- ID encoding and observation
- Relative orientation estimation
- 3D time-position Hough transform
- Robustness increase



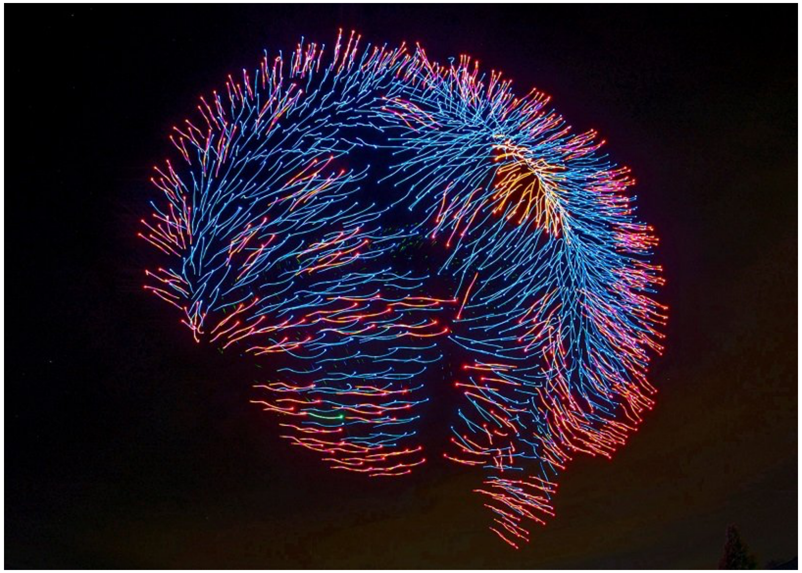




Walter 2019 RAL

Collective Movement – swarms/flocks

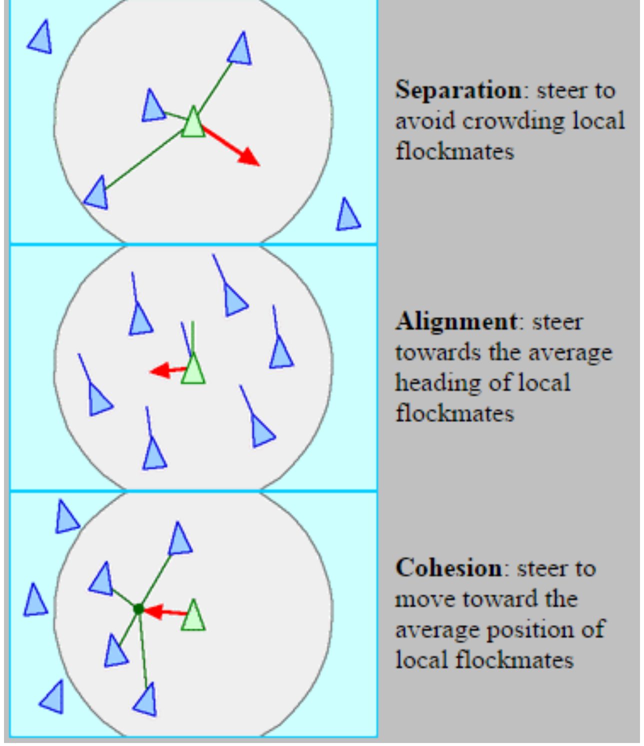
- Inspiration by nature
  - Completely decentralized (no leader), scalable, allows splitting, collective obstacle avoidance, escape ability (from predators), local interactions and relative localization
- Swarms of robots
  - Decentralized – e.g., Boids [Reynolds, 1997] or [Olfati-Saber, 2006]
  - Centralized – drone shows, stochastic optimization methods: PSO, Fish school



2,018 Intel Shooting Star drones

Collective Movement – swarms/flocks

- Boids by Reynolds
  - Originally a computer graphic method to animate flocks
  - Each particle reacts to local neighborhood → complexity O(N)
  - 3 control rules in the primary method
  - For real-world swarms + *obstacle avoidance* and *common intention* rules
  - Local sensory system: (e.g., UVDAR)

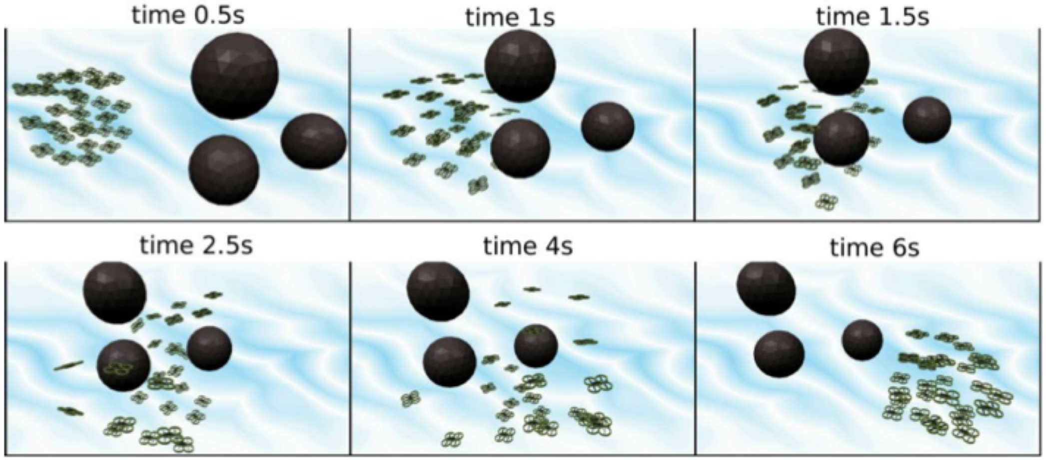


Separation: steer to avoid crowding local flockmates

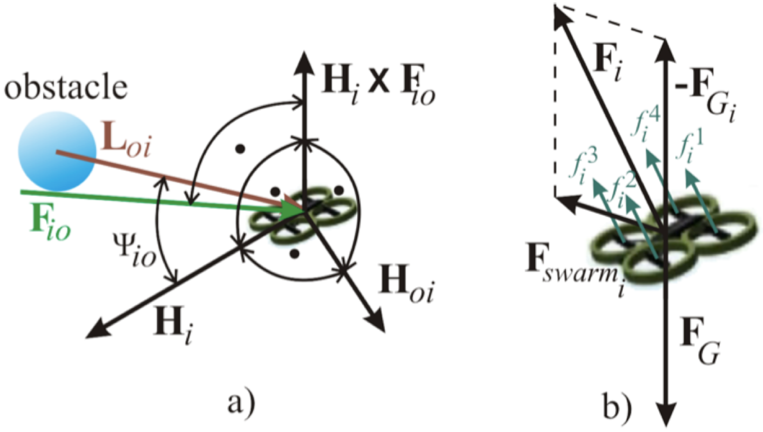
Alignment: steer towards the average heading of local flockmates

Cohesion: steer to move toward the average position of local flockmates

Reynolds, 1997



Saska 2015 ICUAS



Saska 2014 ICRA

Collective Movement – swarms in environments with obstacles

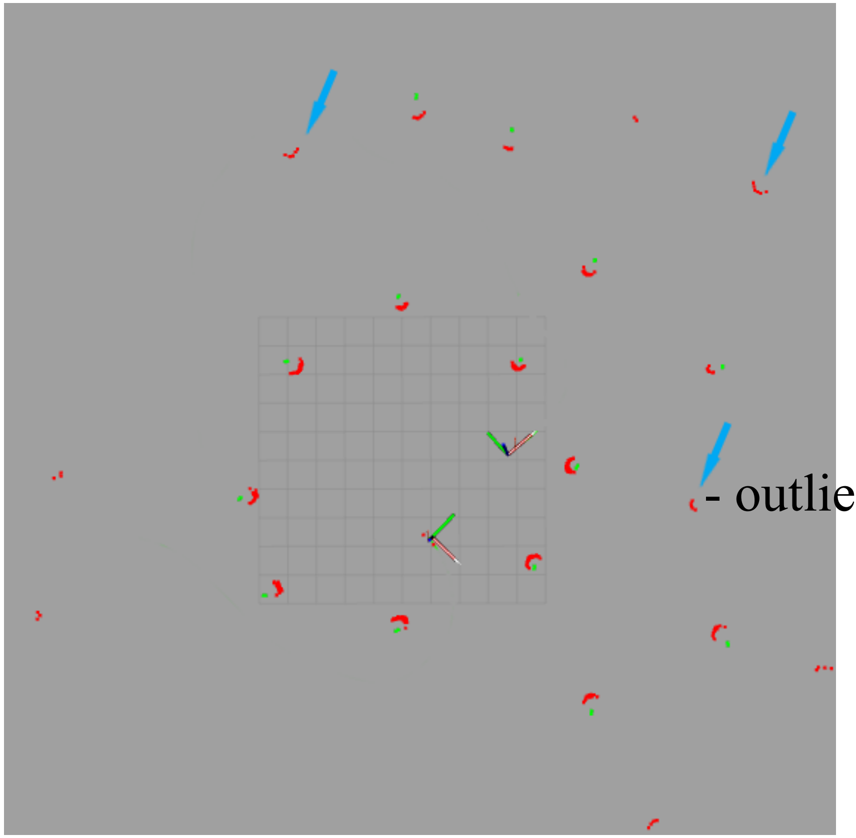
- No GNSS, no explicit communication, fully decentralized, implicit UV-based com.

Ahmad 2021 ICRA

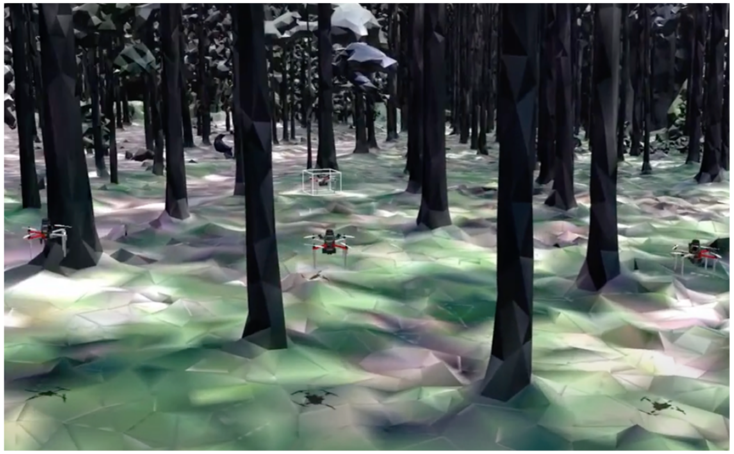
https://youtu.be/nSIqyV0AlXU

Implicit communication - undirect

- Explicit communication
  - Undirect information exchange by observation of the workspace
  - Problem of matching features detected from different positions
  - Similar to ICP for SLAM

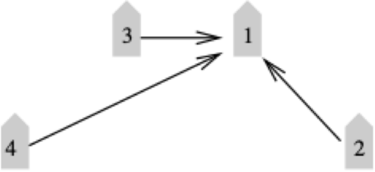


- outliers

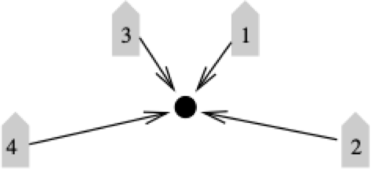


Collective movement - Formations

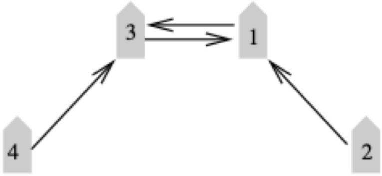
- Formations of cooperating robots
    - Specific geometric configurations
    - Knowledge of states of all robots required
- Formation driving and flying approaches
    - Virtual structures
    - Leader-follower
    - Virtual leader-follower (e.g. unite-center referenced)
    - Neighbor referenced



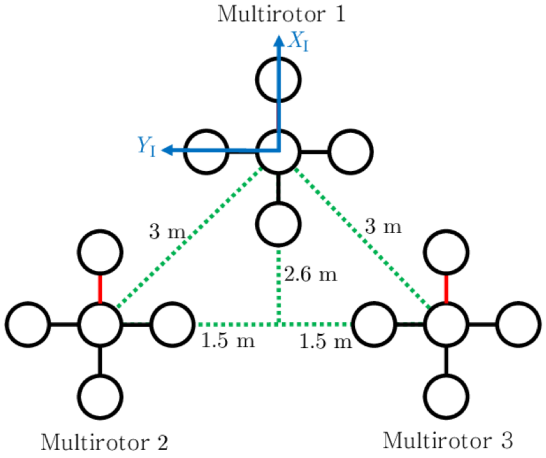
Leader-follower



Unite-center referenced



Neighbor referenced



Viana 2015

Formations – Nonholonomic Leader-Follower model

- Nonholonomic kinematic model
  - Car-like vehicle
  - Limited turning radius

$$\dot{x}_j(t) = v_j(t)\cos\theta_j(t)$$
$$\dot{y}_j(t) = v_j(t)\sin\theta_j(t)$$
$$\dot{\theta}_j(t) = K_j(t)v_j(t) \qquad j \in \{1, \ldots, n_r, L\}$$

$\bar{u}_j(t) = \left\{v_j(t), K_j(t)\right\}$ - control inputs (velocity + curvature)

$\bar{p}_j(t) = \left\{x_j(t), y_j(t)\right\}$ - position

$\psi_j(t) = \left\{p_j(t), \theta_j(t)\right\}$ - system state (position + heading)

Formations – Nonholonomic Leader-Follower model

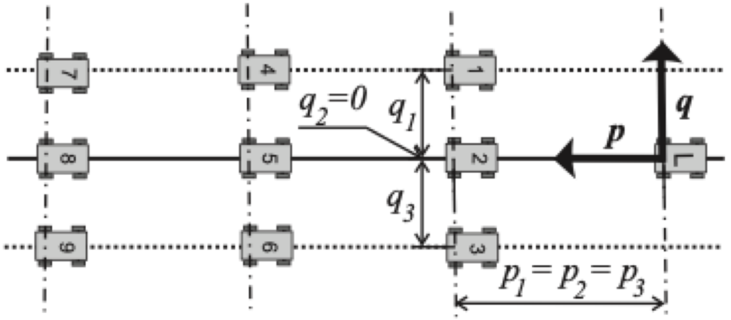
- Position of the followers determined by curvelinear coordinates $p_i(t), q_i(t)$

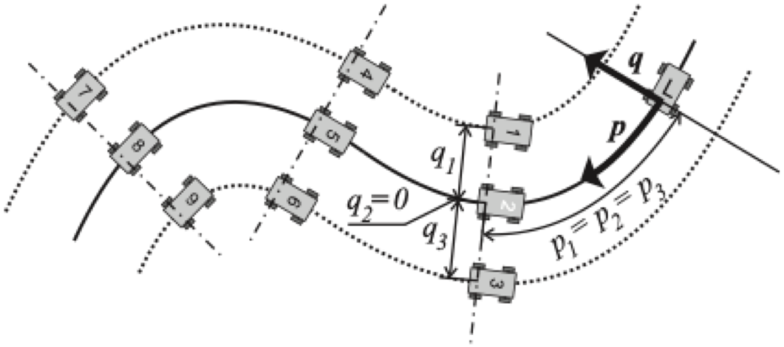
$p_i(t)$ - *traveled distance* between leader and follower *i*

$q_i(t)$ - *offset distance* between leader and follower *i*

$t_{p_i(t)}$ - time when the leader was in traveled distance $p_i(t)$

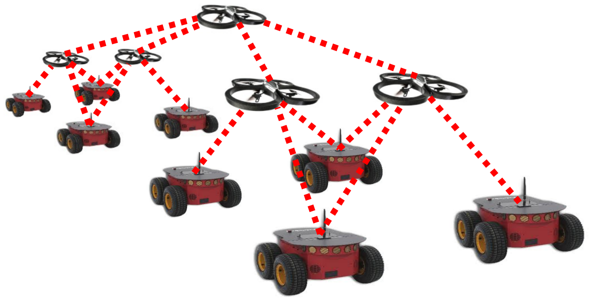
$$
\begin{aligned}
x_i(t) &= x_L(t_{p_i(t)}) - q_i(t_{p_i(t)}) \sin(\theta_L(t_{p_i(t)})) \\
y_i(t) &= y_L(t_{p_i(t)}) + q_i(t_{p_i(t)}) \cos(\theta_L(t_{p_i(t)})) \\
\theta_i(t) &= \theta_L(t_{p_i(t)})
\end{aligned}
$$

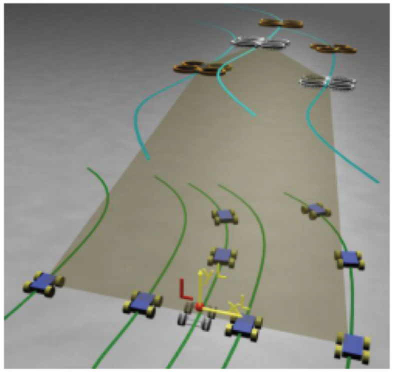


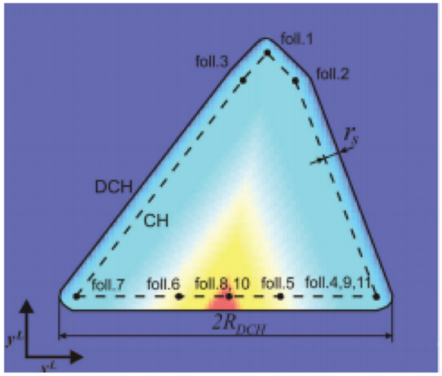


Formations – Nonholonomic Leader-Follower model

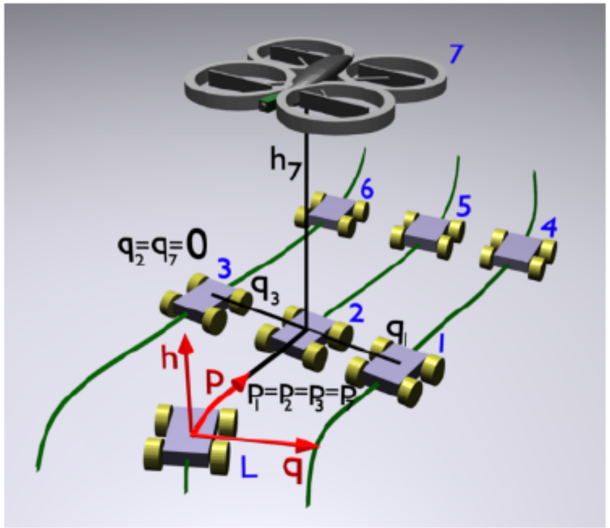
- Heterogenous UAV-UGV formations and 3D UAV formations
- MAV-UGV teams with a "hawk-eye" relative localization

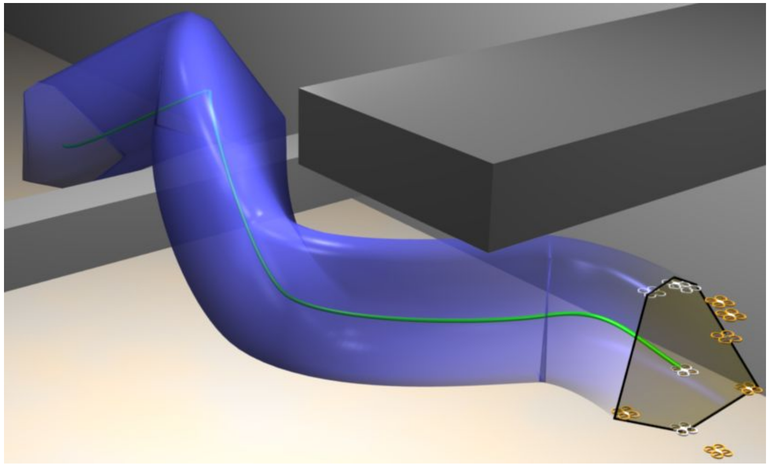






- Complex hull for obstacle avoidance



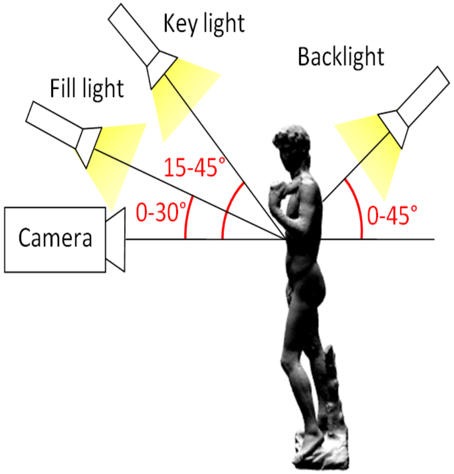


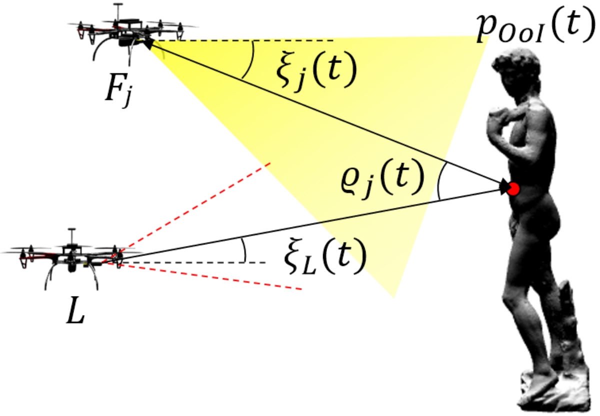
Saska 2014 IJRR, Saska 2012 IROS

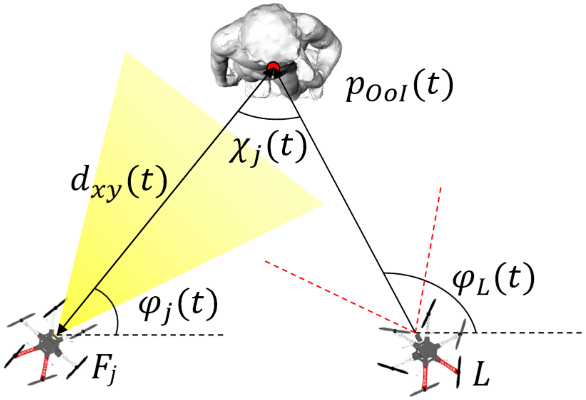
Saska 2020 AURO, Saska 2014 IFAC

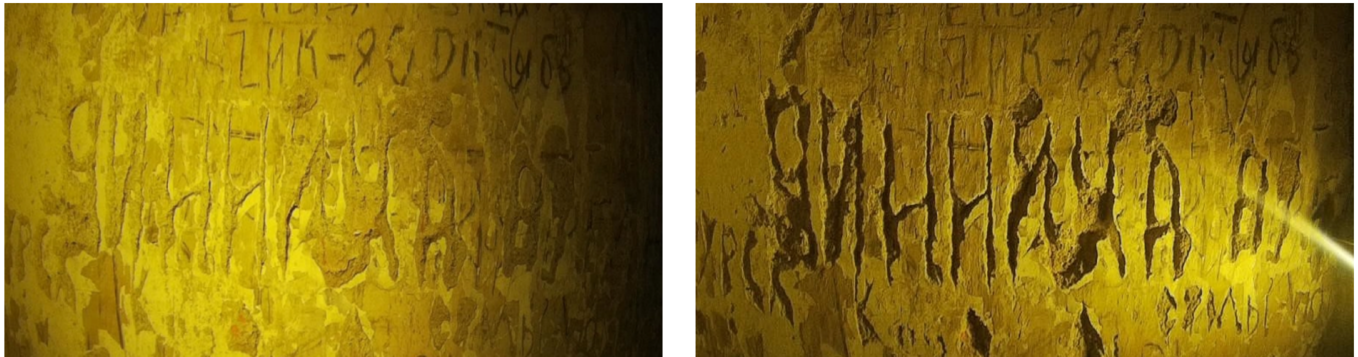
Formations –Leader-Follower Applications

- Documentation of dark areas of large historical buildings by a formation of unmanned aerial vehicles
  - Three points lighting technique
  - Cannot be solved by a single robot



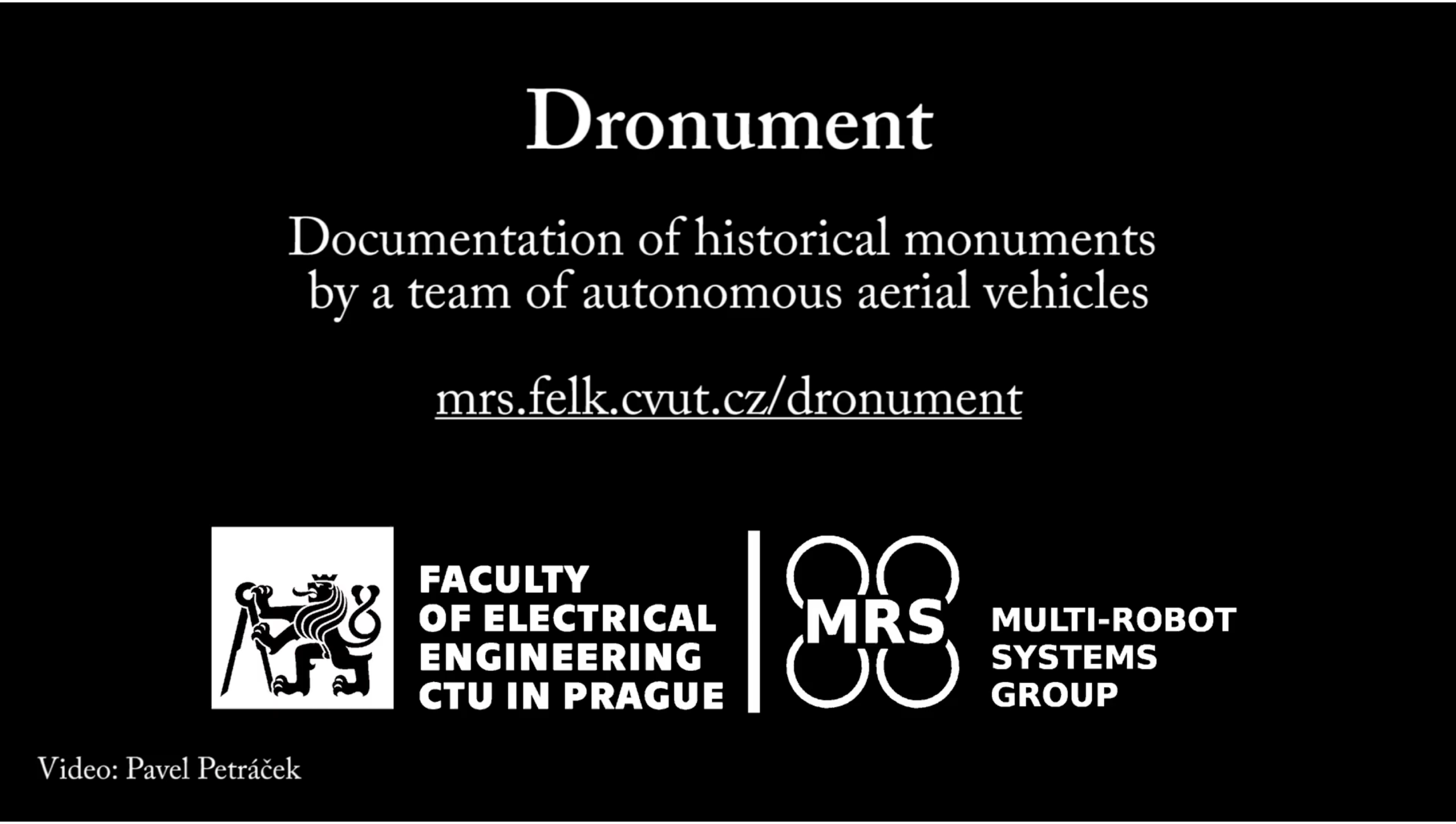






Petráček 2020 RAL
Krátký 2020 RAL
Saska 2017 ETFA

Documentation of dark areas of large historical buildings by UAV formations



Dronument

Documentation of historical monuments
by a team of autonomous aerial vehicles

mrs.felk.cvut.cz/dronument

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MRS

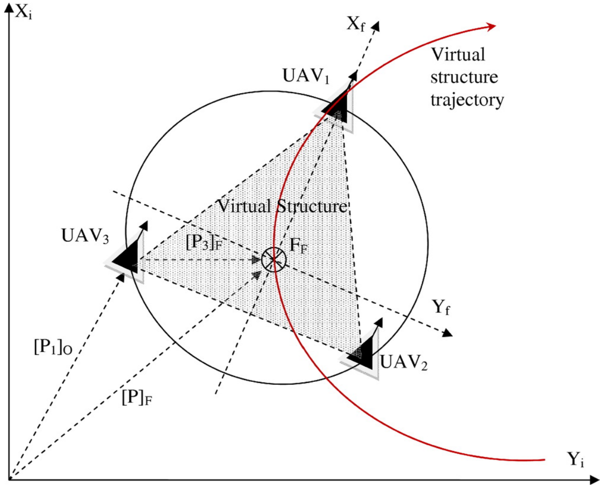
MULTI-ROBOT
SYSTEMS
GROUP

Video: Pavel Petráček

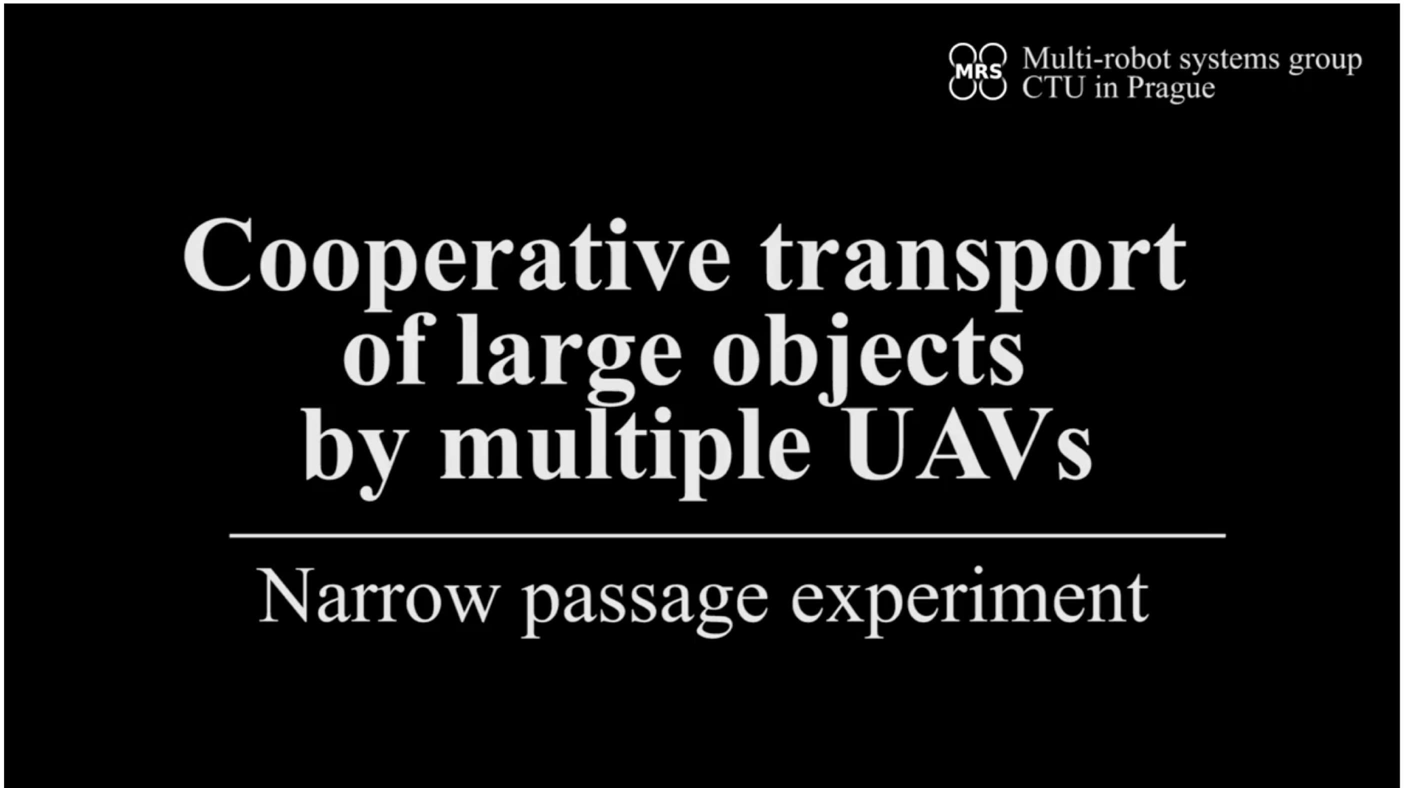
Petráček 2020 RAL, Krátký 2020 RAL, Saska 2017 IEEE ETFA

Formations – Virtual Structures

- Virtual structures approach
  - + Fixed relative positions between vehicles
  - + Cooperative manipulation with large objects
  - - Limited motion constraints
  - - Unfeasible for nonholonomic car-like vehicles



Askari 2015



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Cooperative transport of large objects by multiple UAVs

Narrow passage experiment

Spurný 2019

https://youtu.be/Pdg3j791I9c

Further reading

- Classical graph-based approaches designed for multi-robot systems can be found in:
  - Mesbahi, M. & Egerstedt, M. (2010) Graph theoretic methods in multiagent networks. Princeton University Press.
- Topics related directly to multirotor aerial platforms may be studied from:
  - Franck Cazaurang Kelly Cohen Manish Kumar (2020) Multi-rotor Platform Based UAV Systems. Elsevier.
- An overview of swarming approaches can be found in:
  - Heiko Hamann (2018) Swarm Robotics: A Formal Approach. Springer.

References

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- Reynolds, C.: Flocks, herds and schools: A distributed behavioral model. In: Proc. of the 14th annual conference on Computer graphics and interactive techniques, pp. 25–34. ACM Press, New York, 1987.
- M Saska. MAV-swarms: unmanned aerial vehicles stabilized along a given path using onboard relative localization. In International Conference on Unmanned Aircraft Systems (ICUAS). 2015.
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