# Multi-Robot Systems

https://youtu.be/dT7b1j5Ij1I


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# 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**

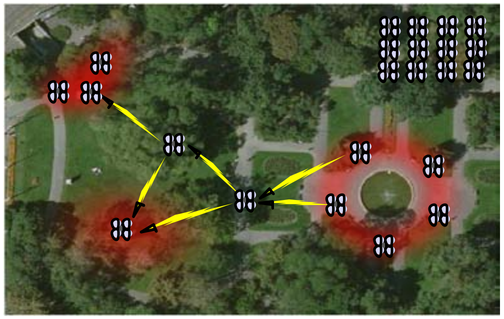

3/2017 – MBZIRC 3rd challenge:
1st place    $330.000


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*

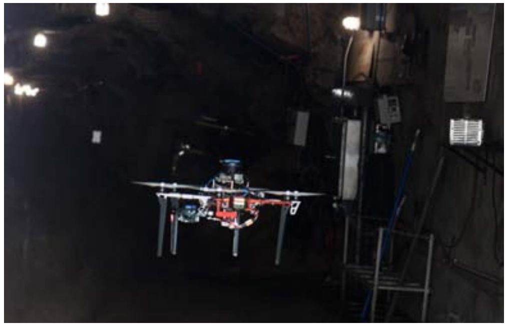

*Saska 2017 ETFA*

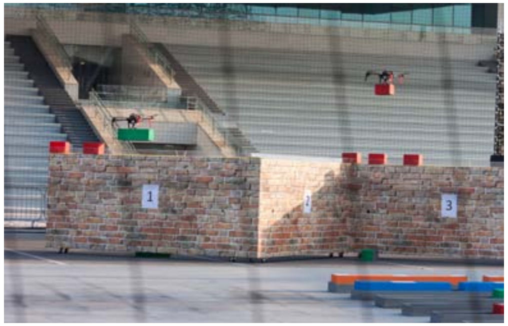
*Spurný 2019 ETFA*

# 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

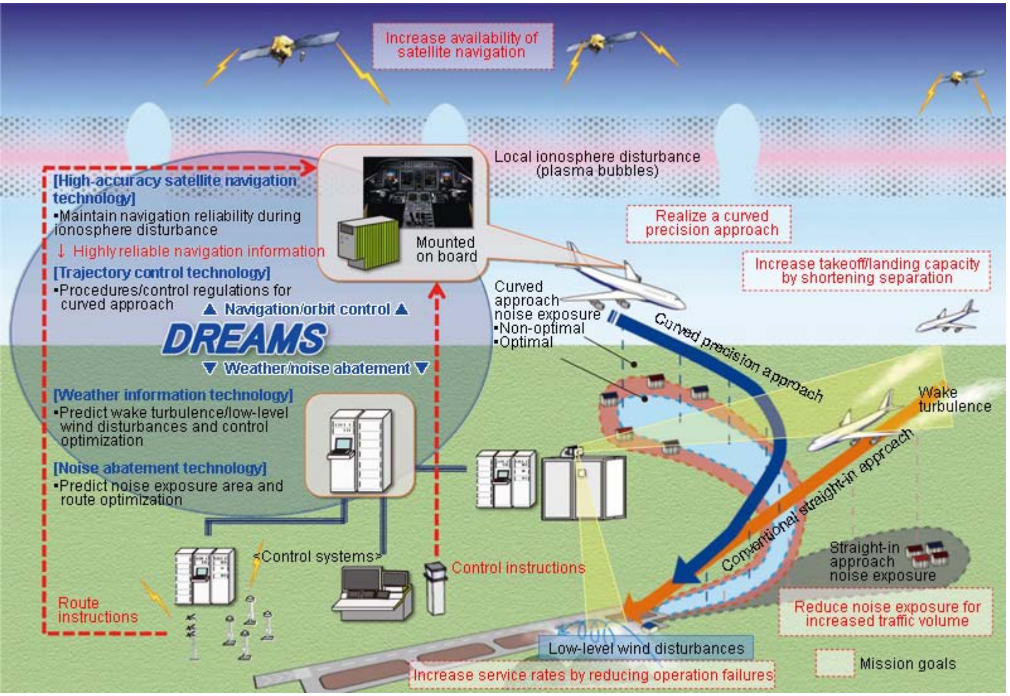
# Centralized vs. Decentralized (vs. Distributed)

- Decentralized control architecture

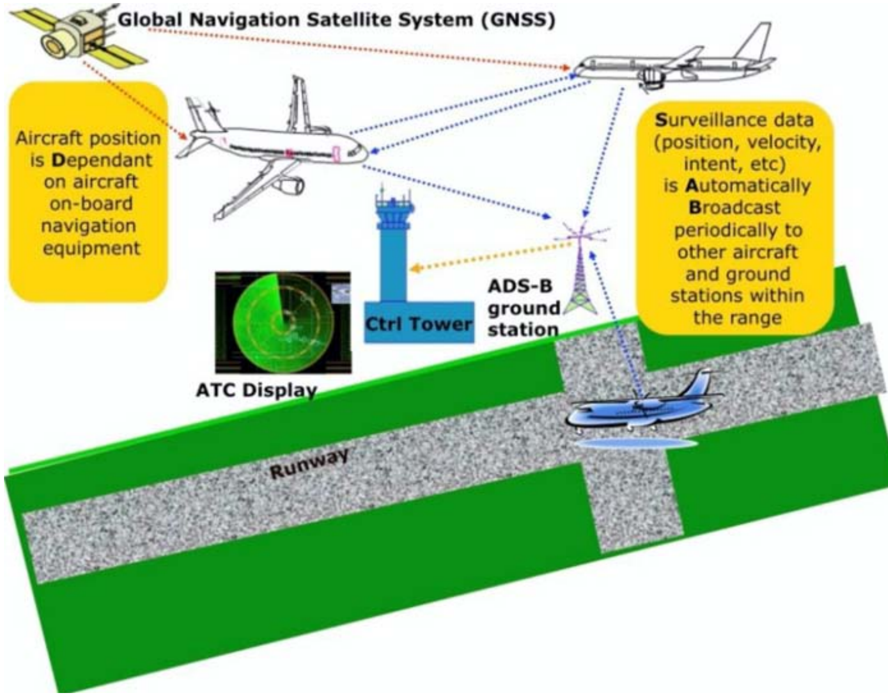
*Petráček 2020 B&B* https://youtu.be/slzlHtve3kY

# 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

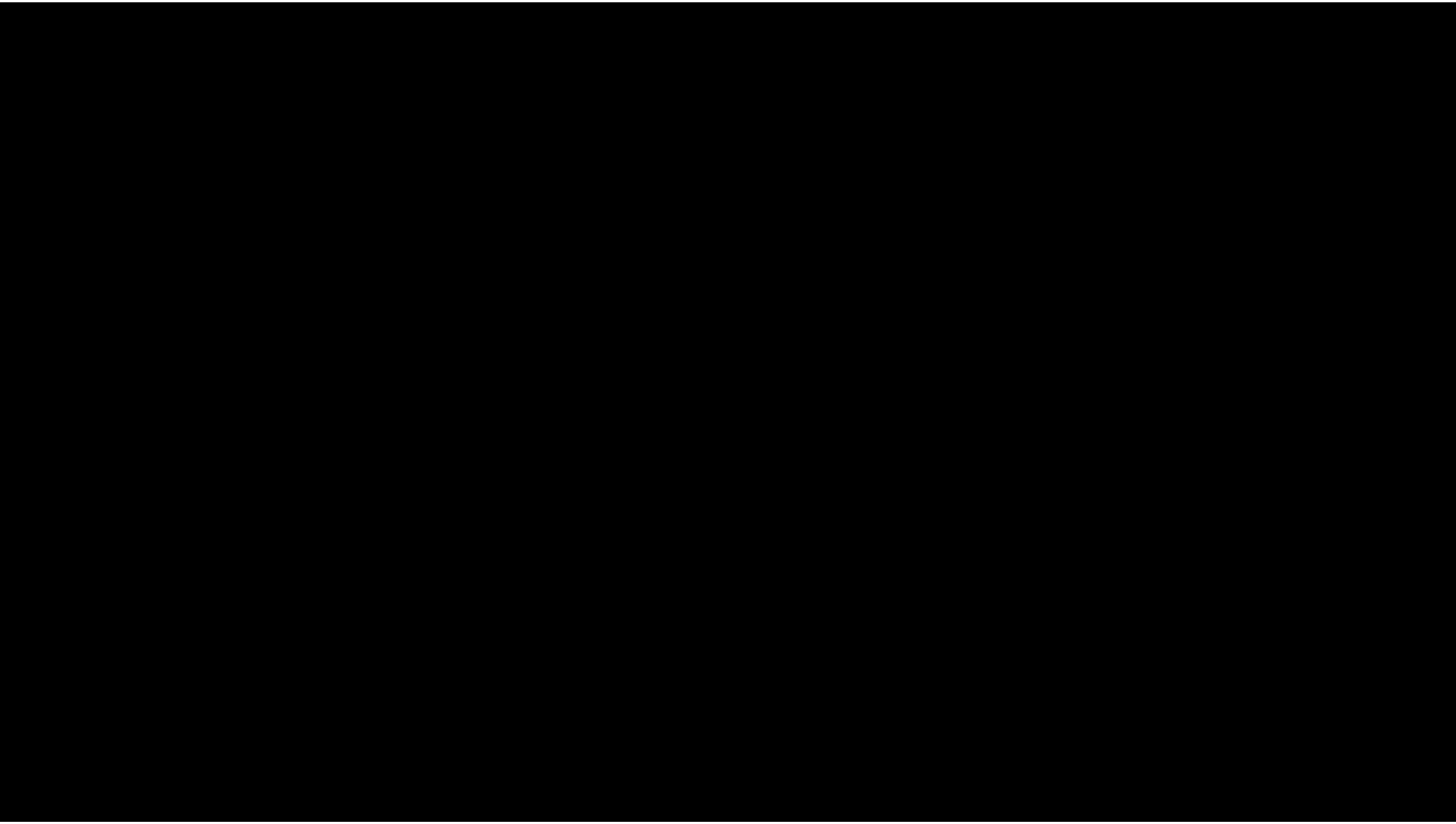
# Coordination vs. Cooperation vs. Collaboration

- 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

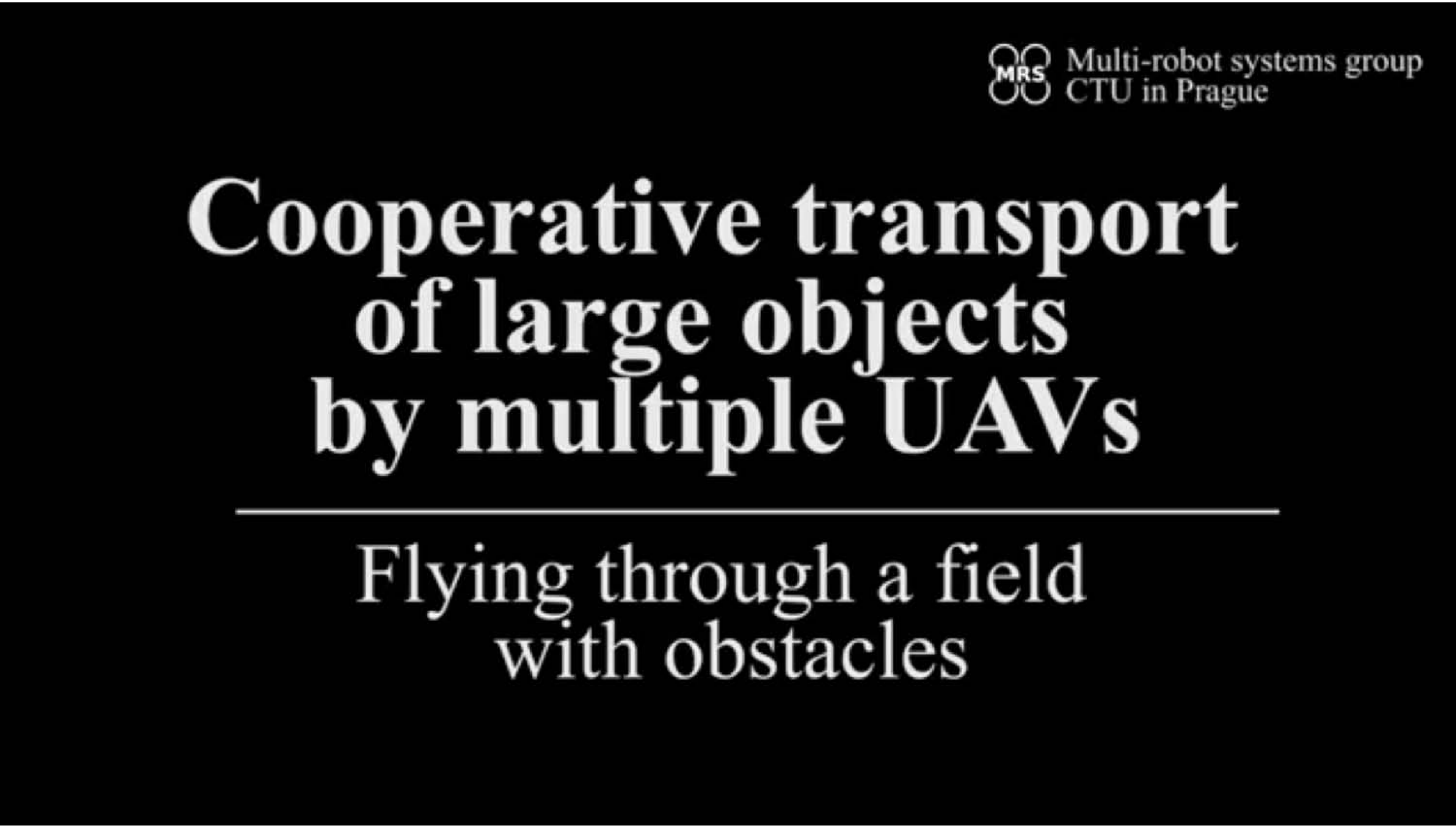
- Multi-UAV team collecting objects of unknown position – faster and more reliable



*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




*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*

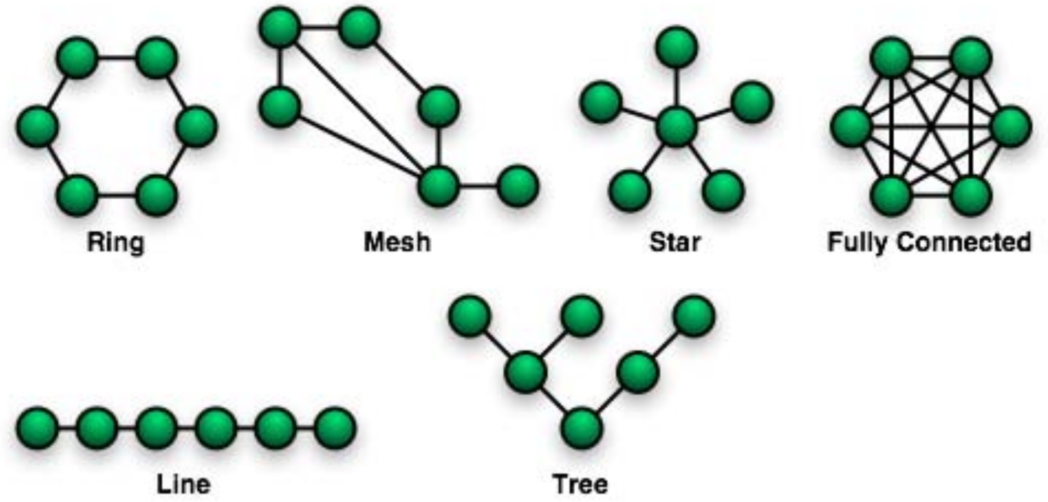
https://youtu.be/O8QBiAyP2c0

# 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*

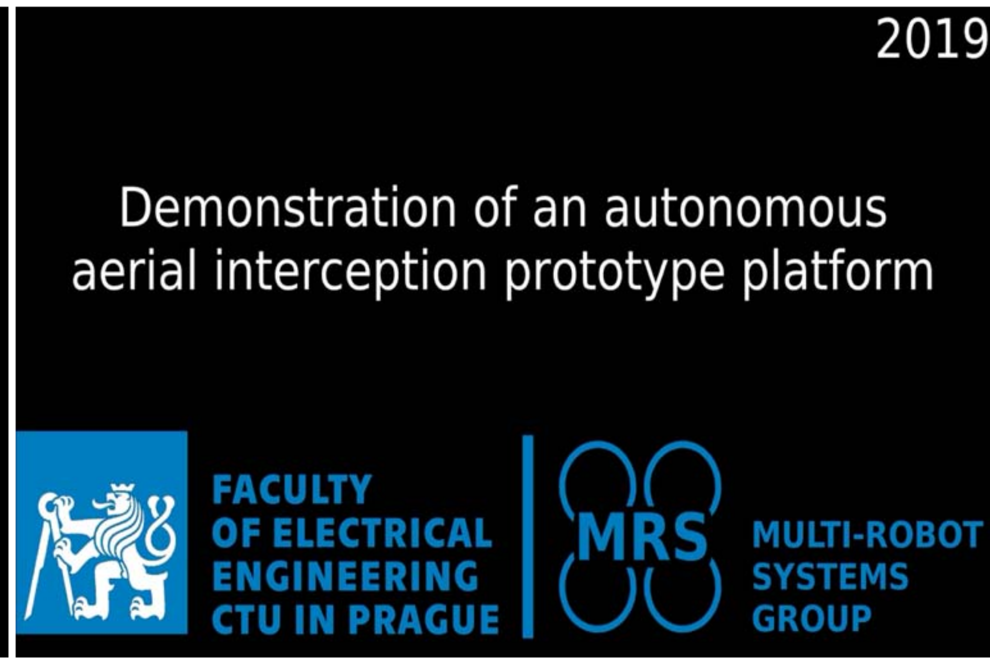
https://youtu.be/Nk7SUNGzo1k

# 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




*Vrba 2020 RAL*

https://youtu.be/mr4uqgBslHw

# Implicit communication – relative localization

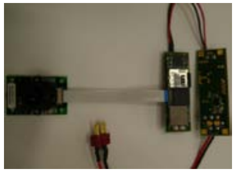
- MBZIRC 2020: Team of aerial robots hunting balloons and aerial target (RGB and Lidar)


*Vrba 2021 SMC, Stasinchuk 2021 ICRA*

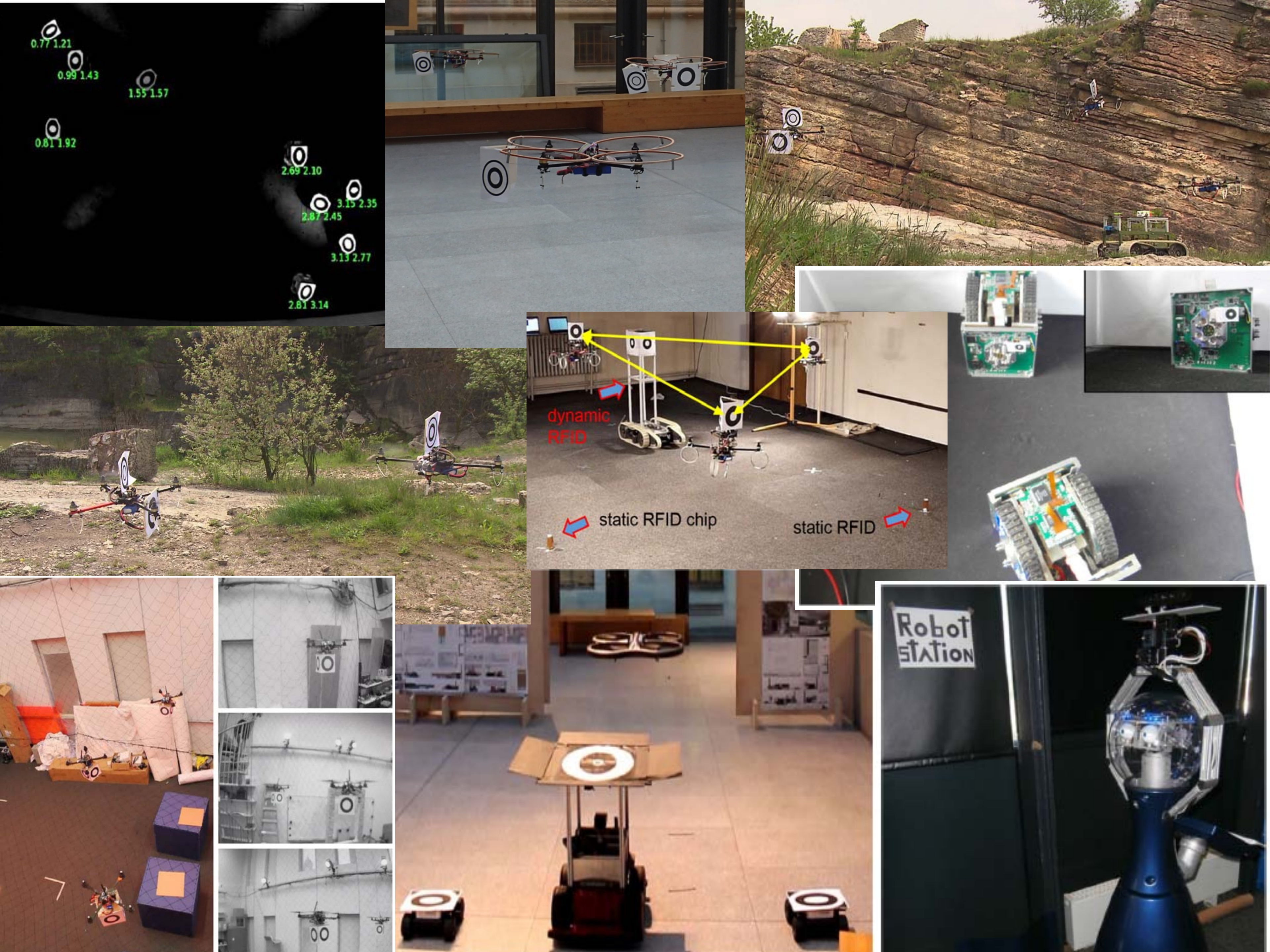
https://youtu.be/2-cLSjRCKDg

# Implicit communication – relative localization

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

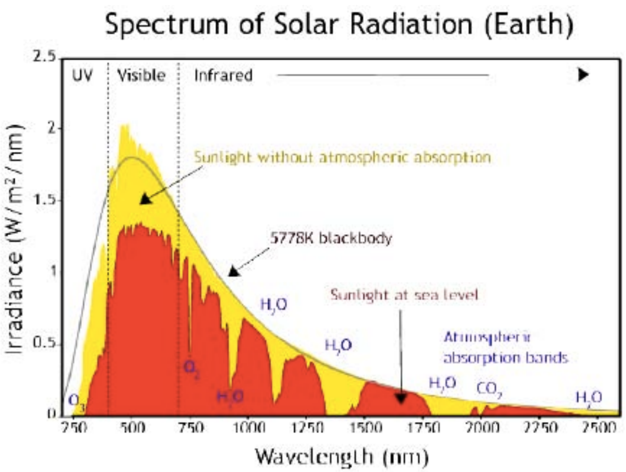


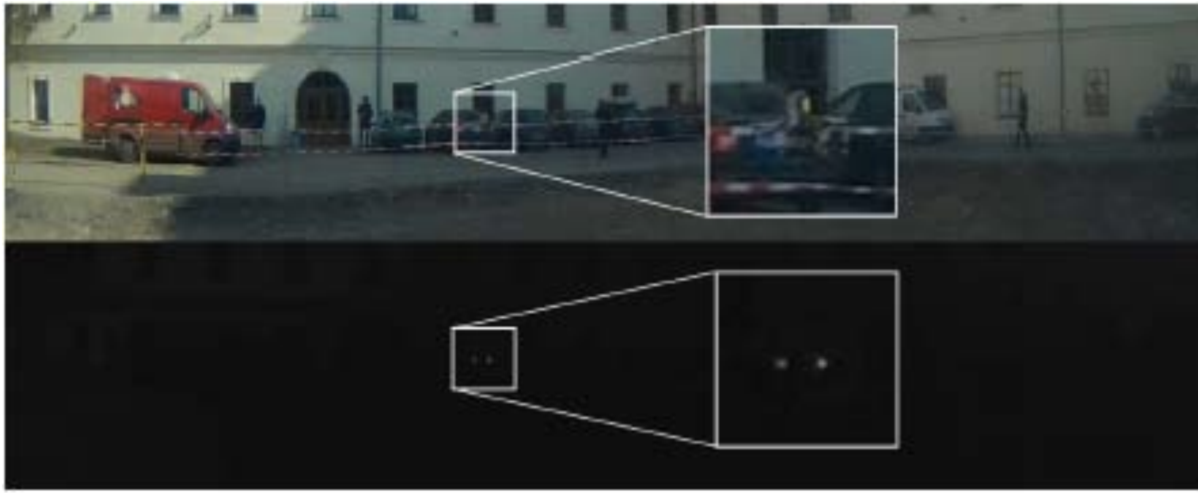
*Faigl 2013 ICRA, Krajnik 2014 JINT*

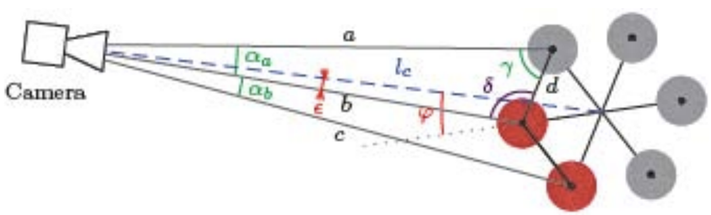

0.77 1.21
0.99 1.43
1.55 1.57
0.81 1.92
2.69 2.10
3.15 2.35
2.87 2.45
3.13 2.77
2.81 3.14
dynamic RFID
static RFID chip
static RFID
Robot STATION

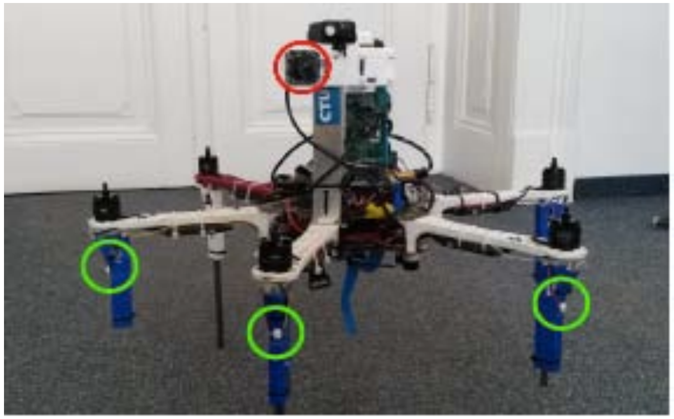
# Implicit communication – relative localization using active UV Markers

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



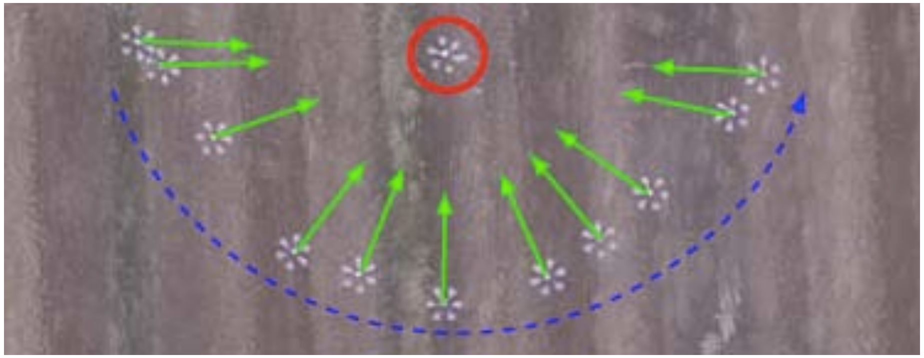


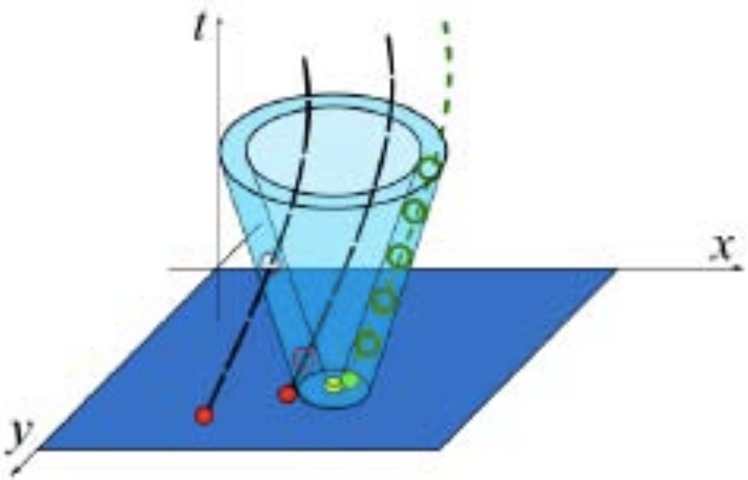



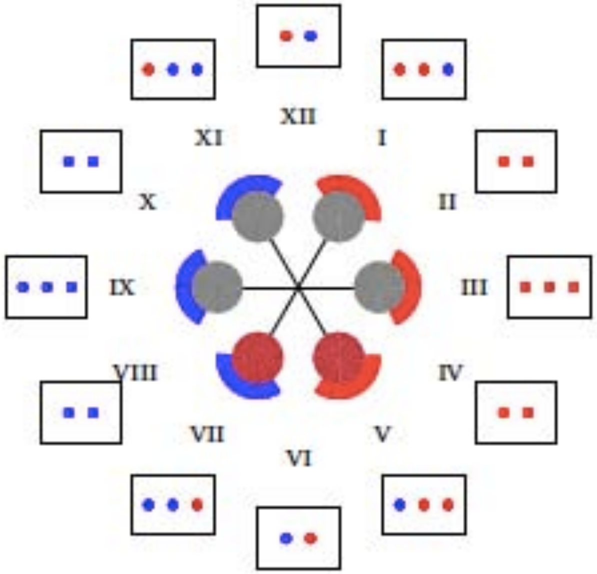
*Walter 2018 CASE, Walter 2018 ICUAS*

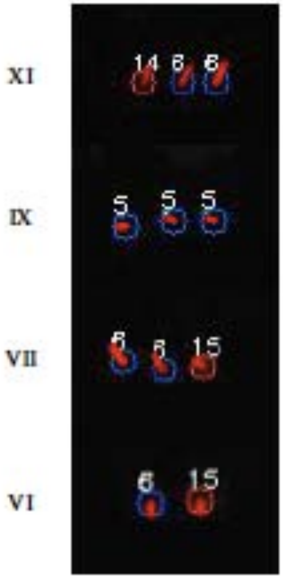
# Beyond implicit communication - Blinking UV markers

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





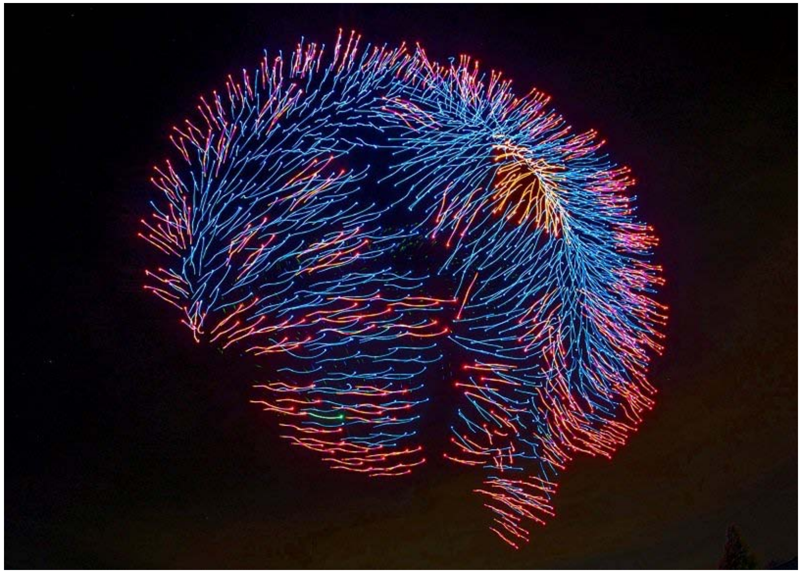




*Walter 2019 RAL*

# Collective Movement – swarms/flocks

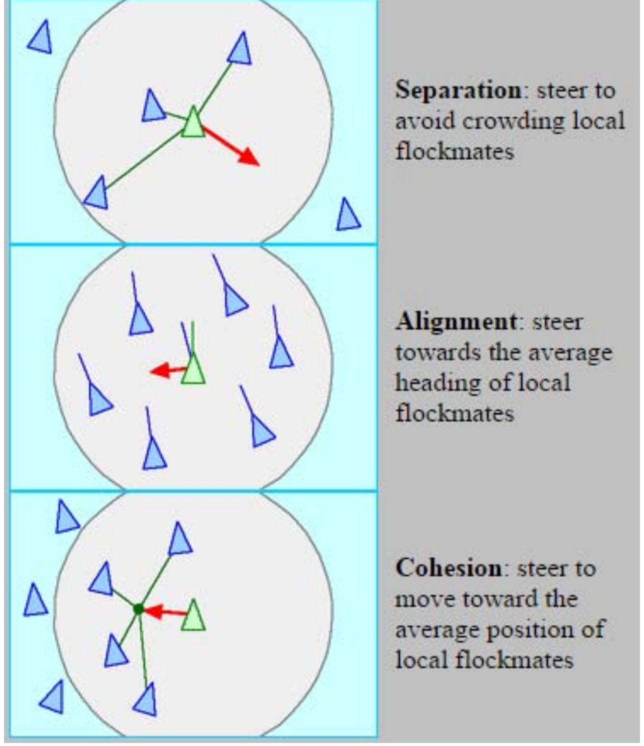
- Inspiration by nature
  - Completely decentralized (no leader), scalable, allows splitting, collective obstacle avoidance, escape ability (from predators), local interactions and relative localization
- Swarms of robots
  - Decentralized – e.g., Boids [Reynolds, 1997] or [Olfati-Saber, 2006]
  - Centralized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



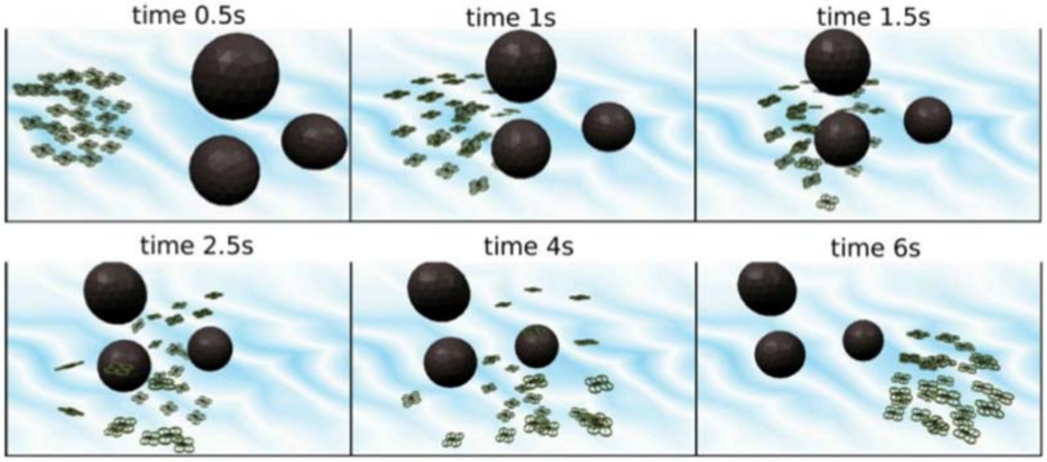
2,018 Intel Shooting Star drones

# Collective Movement – swarms/flocks

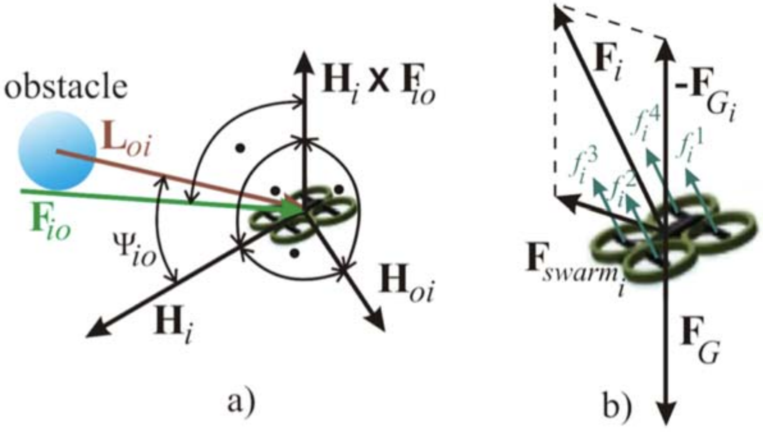
- Boids by Reynolds
  - Originally a computer graphic method to animate flocks
  - Each particle reacts to local neighborhood → complexity O(N)
  - 3 control rules in the primary method
  - For real-world swarms + *obstacle avoidance* and *common intention* rules
  - Local sensory system: (e.g., UVDAR)




Reynolds, 1997




*Saska 2015 ICUAS*




*Saska 2014 ICRA*

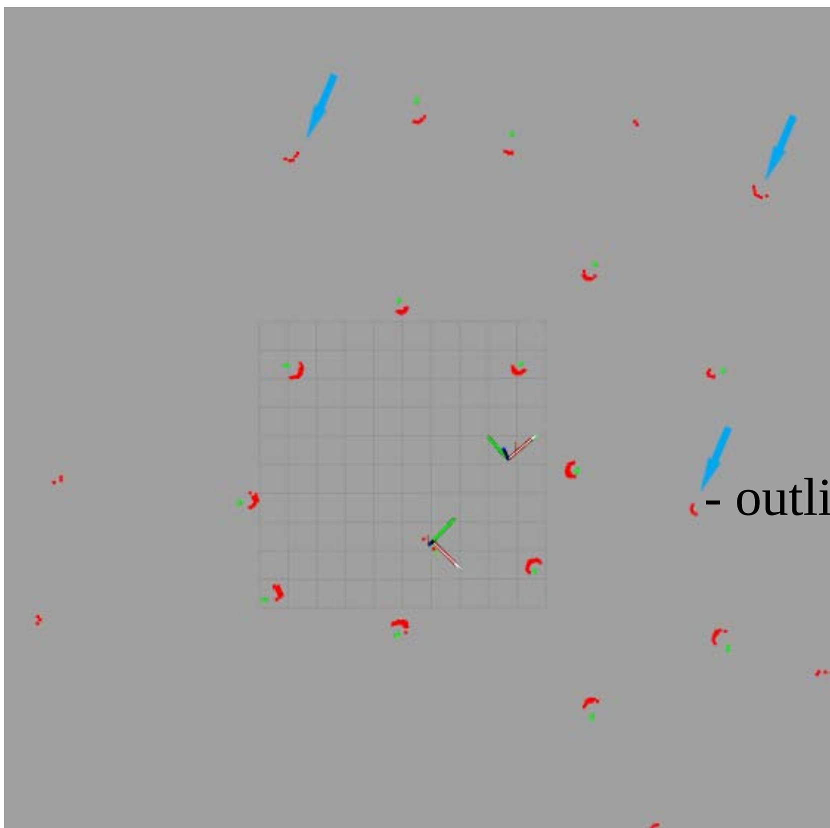
# Collective Movement – swarms in environments with obstacles

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

*Ahmad 2021 ICRA* https://youtu.be/nSIqyV0AlXU

# Implicit communication - undirect

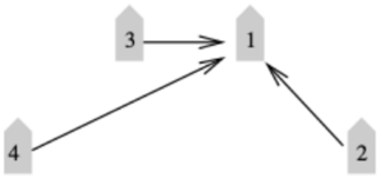
- Explicit communication
  - Undirect information exchange by observation of the workspace
  - Problem of matching features detected from different positions
  - Similar to ICP for SLAM



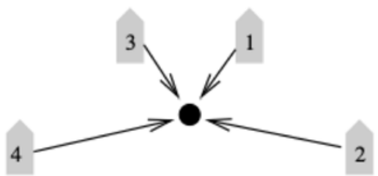
- outliers

# Collective movement - Formations

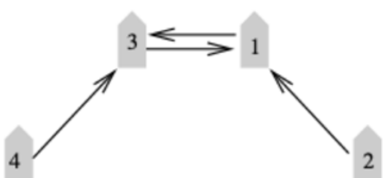
- Formations of cooperating robots
  - Specific geometric configurations
  - Knowledge of states of all robots required
- Formation driving and flying approaches
  - Virtual structures
  - Leader-follower
  - Virtual leader-follower (e.g. unite-center referenced)
  - Neighbor referenced



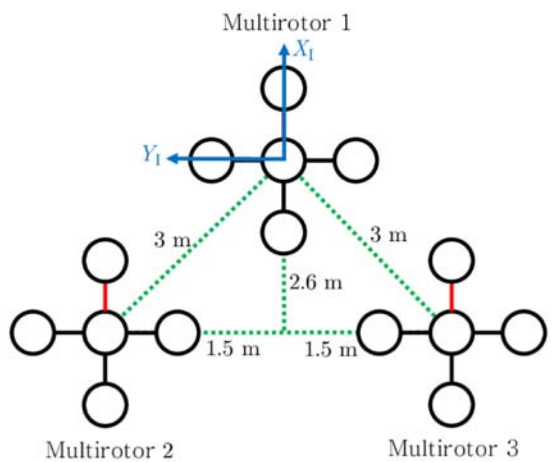
Leader-follower



Unite-center referenced



Neighbor referenced




*Viana 2015*

# Formations – Nonholonomic Leader-Follower model

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


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

$\bar{u}_j(t) = \left\{v_j(t), K_j(t)\right\}$ - 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)

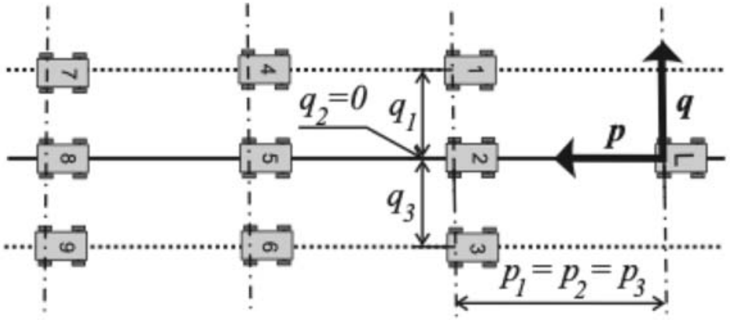
# Formations – Nonholonomic Leader-Follower model

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

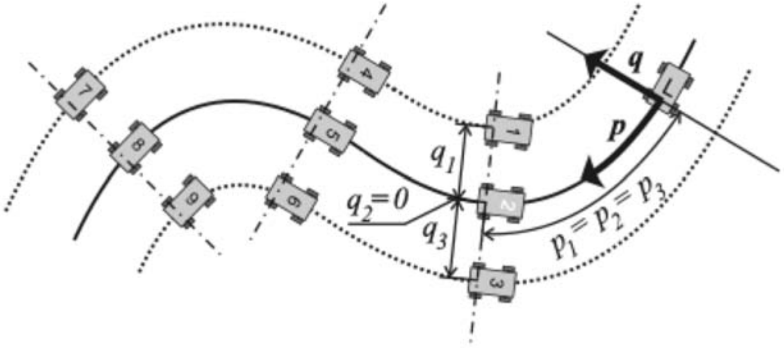
$p_i(t)$ - *traveled distance* between leader and follower *i*

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

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

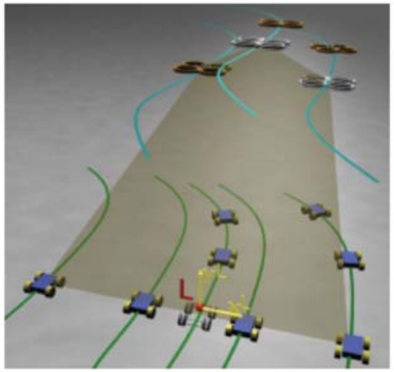


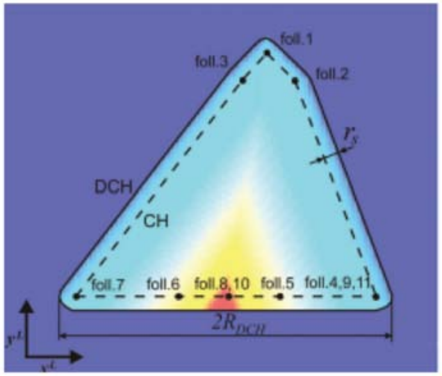

$$
\begin{aligned}
x_i(t) &= x_L(t_{p_i(t)}) - q_i(t_{p_i(t)}) \sin(\theta_L(t_{p_i(t)})) \\
y_i(t) &= y_L(t_{p_i(t)}) + q_i(t_{p_i(t)}) \cos(\theta_L(t_{p_i(t)})) \\
\theta_i(t) &= \theta_L(t_{p_i(t)})
\end{aligned}
$$



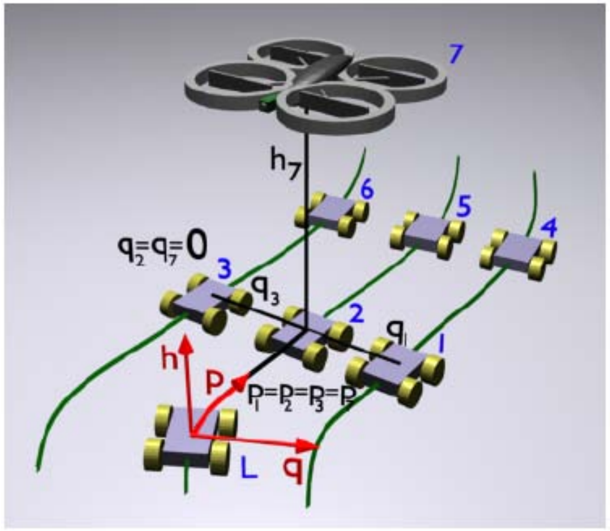
# Formations – Nonholonomic Leader-Follower model

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

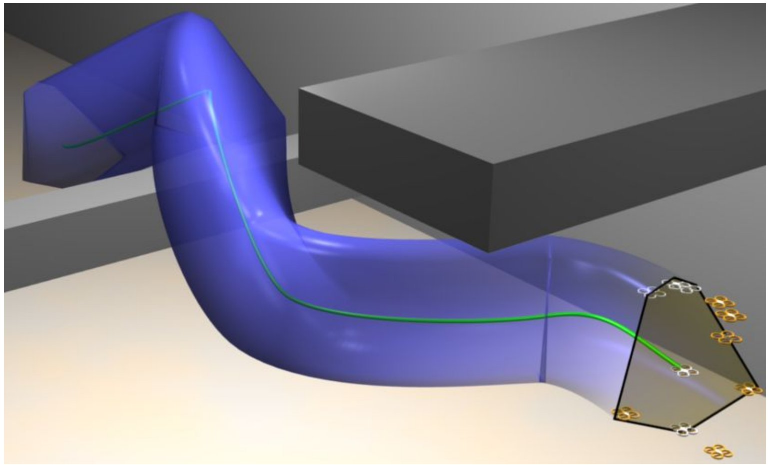





- Complex hull for obstacle avoidance



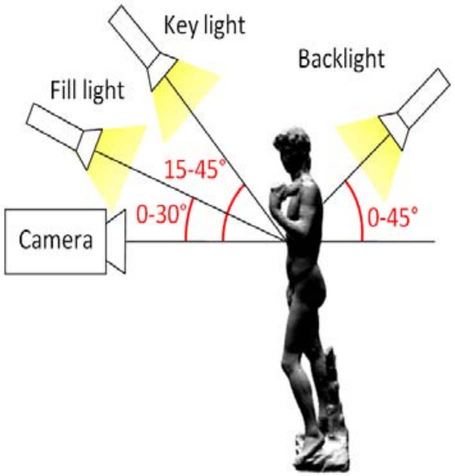

*Saska 2014 IJRR, Saska 2012 IROS*

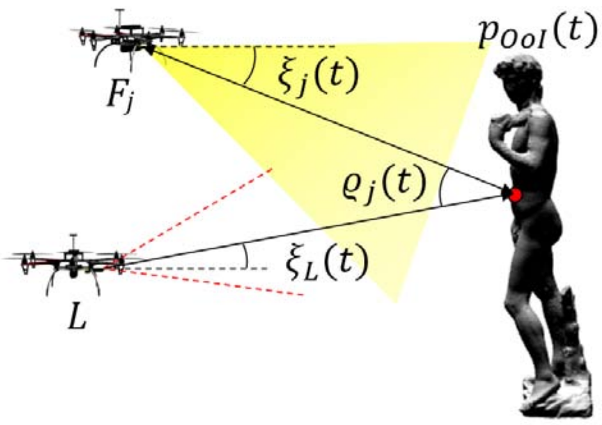


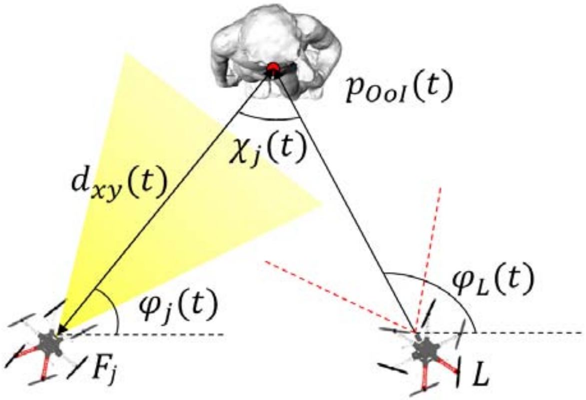
*Saska 2020 AURO, Saska 2014 IFAC*

# 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

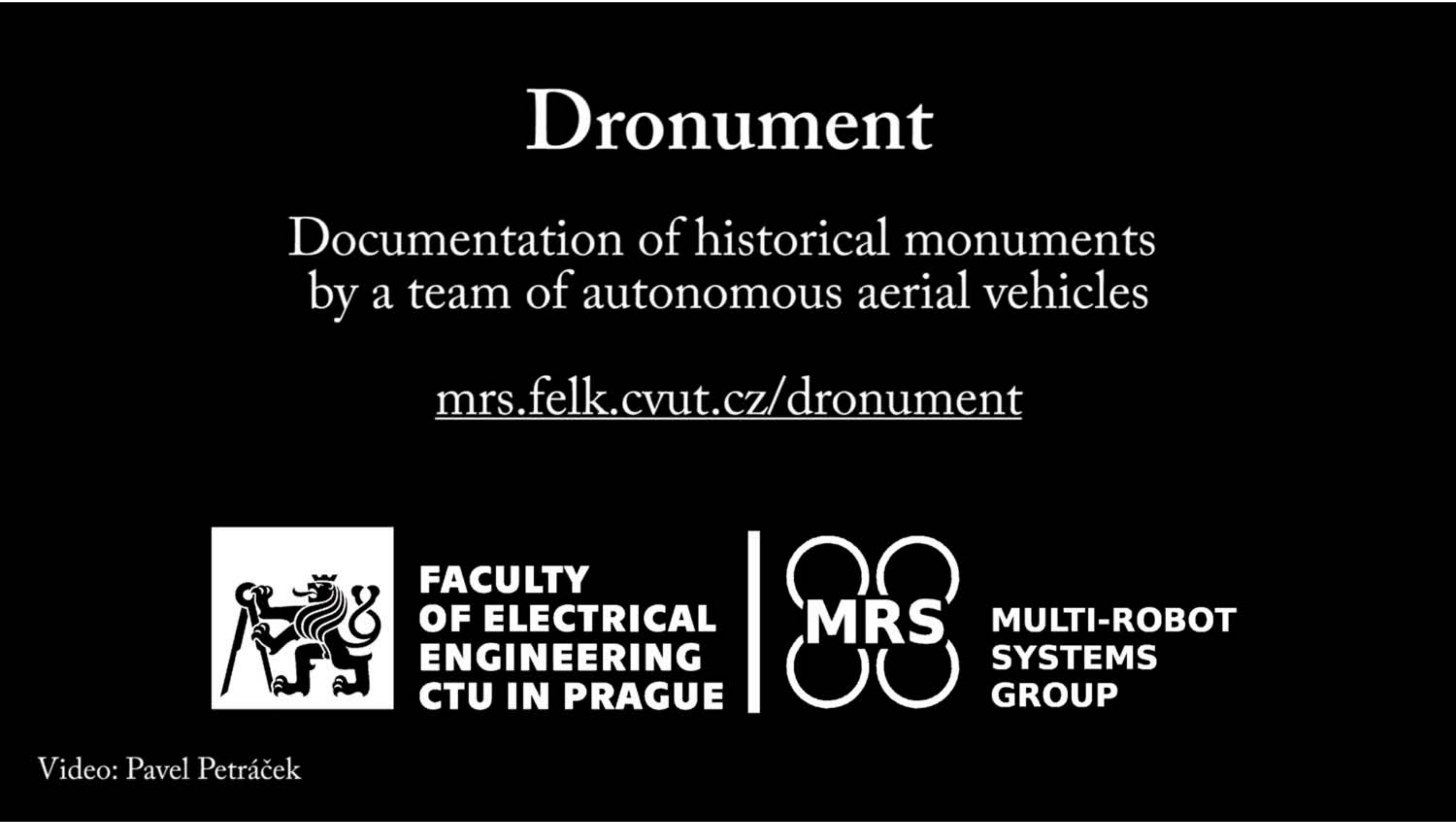



*Petráček 2020 RAL*
*Krátký 2020 RAL*
*Saska 2017 ETFA*

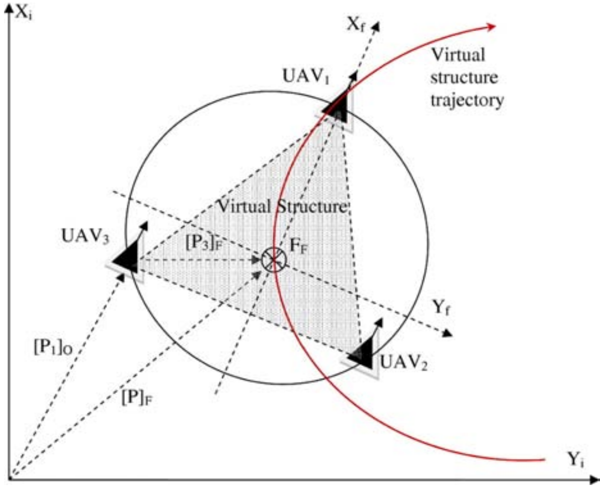
# Documentation of dark areas of large historical buildings by UAV formations



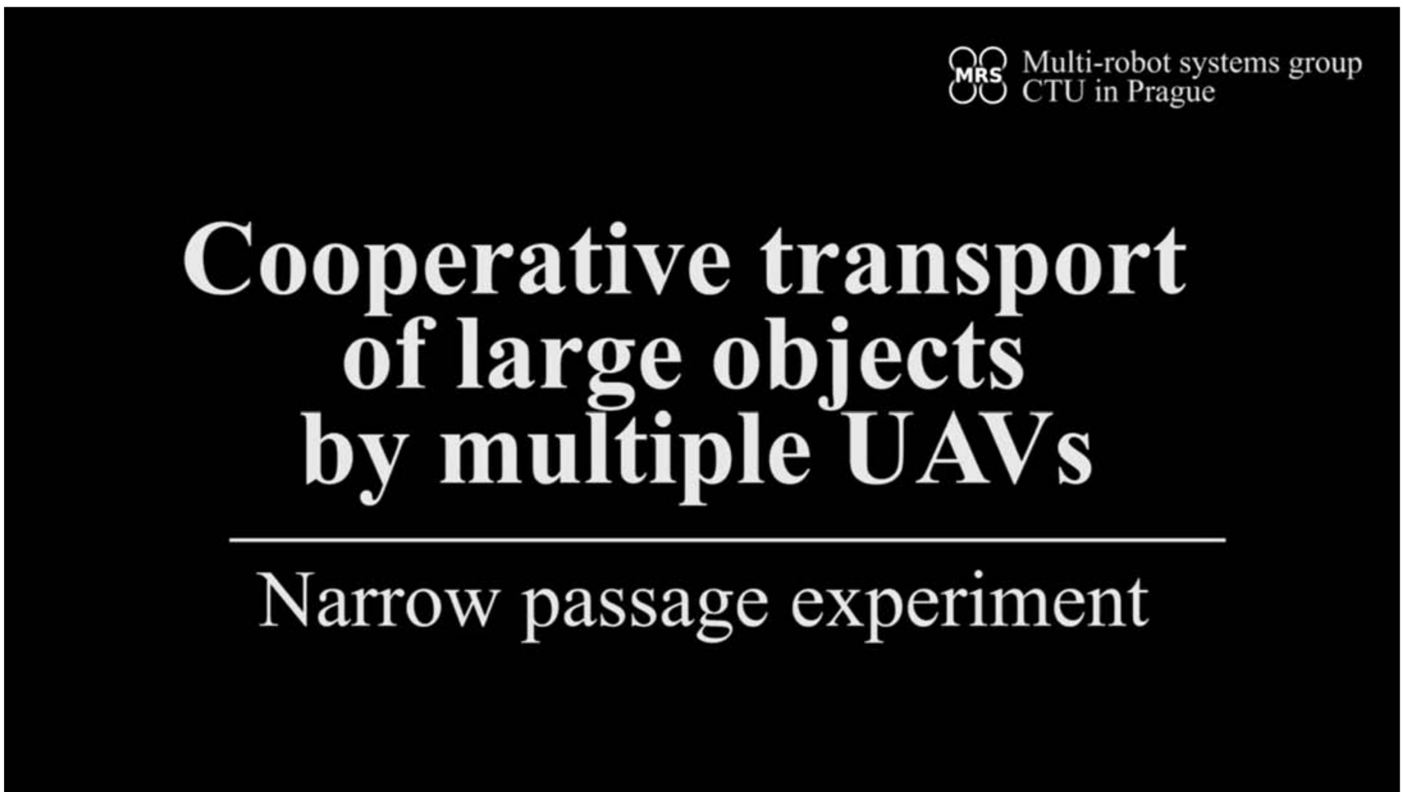

*Petráček 2020 RAL, Krátký 2020 RAL, Saska 2017 IEEE ETFA*

# 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*




*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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