Lecture 7: Formation Control

B3M33MRS — Aerial Multi-Robot Systems

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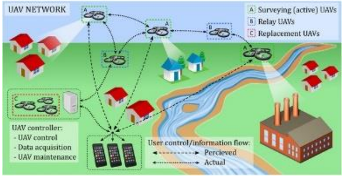
Formation control

- Coordination of robots moving/working together in a formation of a given shape – relative states (positions and angles) required between all robots in the team
- To achieve a global desired state of robots, while moving together in a shared workspace
- Time-varying shape (formation reshaping)
- Group size changed on demand (splitting and merging of sub-formations)
- Robot motion strongly depends on state and motion capabilities of the teammates – motion constraints of all team-members must be satisfied (e.g., velocities, acceleration limits, maneuvering ability)
- Mutual collision avoidance and obstacle avoidance included in the formation control strategies

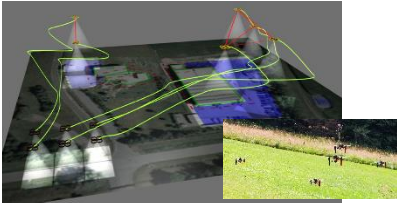
Formations - Motivation

- Motivation
  - ✓ Robotic problems are often naturally distributed

- Examples of applications: inspection, search end rescue, monitoring, construction, surveillance, data gathering



Source: M. Erdelj 's archive



M. Saska, et al. "Swarm Distribution and Deployment for Cooperative Surveillance by Micro-Aerial Vehicles," *JINT, 84(1):469–492, 2016.*

Formations - Motivation

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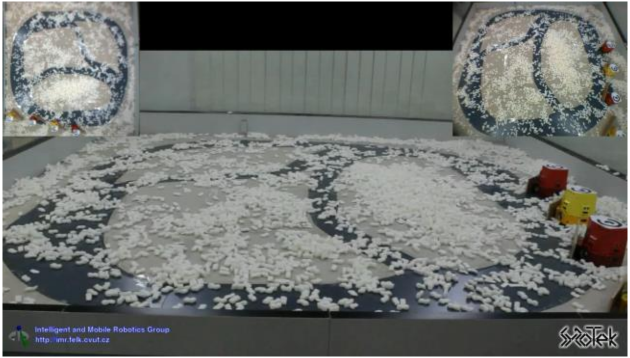

M. Saska, … L. Preucil, "Control and NAvigation in Manoeuvres of Formations of Unmanned Mobile Vehiclesf," *European Journal of Control, vol. 19, no. 2, pp.157 -171, 2013.*

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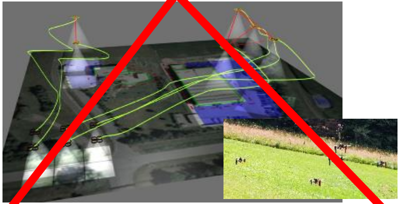

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Formations - Motivation

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  - ✓ Robotic problems are often naturally distributed
  - ✓ Redundancy and robustness vs. enlarged complexity of the system

- Examples of applications: search and rescue (price of a lost robot is less than human life), defense applications (one-way missions; smart “bullets”), swarming (robots can continue the mission in case of failures of some group member)

P. Petracek, … M. Saska, “Bio-Inspired Compact Swarms of Unmanned Aerial Vehicles without Communication and External Localization,” *Bioinspiration & Biomimetics 16(2):026009, December 2020.*

Formations - Motivation

- Motivation
  - ✓ Robotic problems are often naturally distributed
  - ✓ Redundancy and robustness vs. enlarged complexity of the system
  - ✓ Usually the problem of single-point of failure

- Examples of applications: search and rescue (price of a lost robot is less than human life), defense applications (one-way missions; smart "bullets"), swarming (robots can continue the mission in case of failures of some group member)

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Formations - Motivation

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  - ✓ Robotic problems are often naturally distributed
  - ✓ Redundancy and robustness vs. enlarged complexity of the system
  - ✓ Faster mission execution

- Examples of applications: search and rescue (time critical), inspection (shorter interruption of industrial processes), construction (faster execution), data gathering (old data are less useful), etc.

Q. Lindsey, D. Mellinger, V. Kumar, "Construction with quadrotor teams," *Autonomous Robots volume 33, pages 323–336, 2012.*

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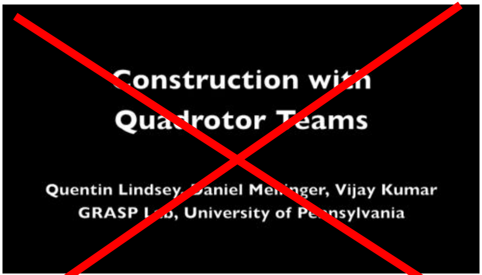

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Formations - Motivation

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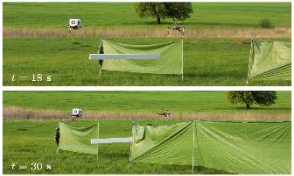
  - ✓ Several light-weight robots replace a large well-equipped and heavy robot

- Examples of applications: construction works and large payload transportation, data gathering by a heterogeneous team of MAVs equipped with different sensors

D. Mellinger,… V. Kumar "Cooperative Grasping and Transport using Multiple Quadrotors", *DARS, 2013.*



V. Spurny,… M. Saska, "Cooperative Transport of Large Objects by a Pair of Unmanned Aerial Systems using Sampling-based Motion Planning", *ETFA, 2019.*

Formations - Motivation

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  - ✓ Redundancy and robustness vs. enlarged complexity of the system
  - ✓ Faster mission execution
  - ✓ Several light-weight robots replace a large well-equipped and heavy robot
  - ✓ One of the most referred applications of formations

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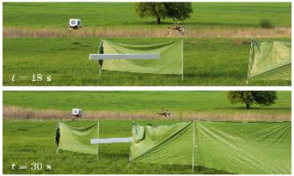

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Formations - Motivation

A. Ollero, … A. Franchi, "Past, Present, and Future of Aerial Robotic Manipulators", *IEEE Transactions on Robotics, vol. 38, no. 1, pp. 626-645, Feb. 2022*.

Formations - Motivation

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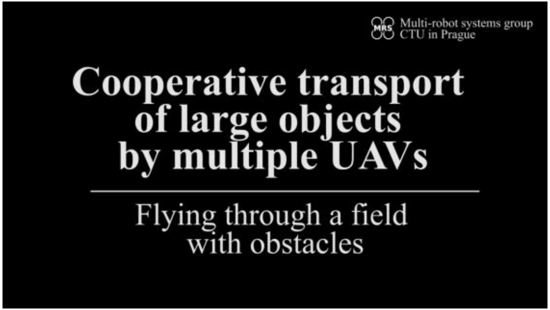
Formations - Motivation



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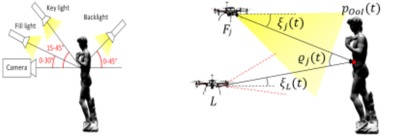
  - ✓ Faster mission execution
  - ✓ Several light-weight robots replace a large well-equipped and heavy robot
  - ✓ Many tasks not solvable by a single robot

- Examples of applications: smart lightening, moving radiation source detection, measuring of a unique phenomena simultaneously at different locations (volcano eruption)



V. Krátký,… M. Saska, "Autonomous Aerial Filming with Distributed Lighting by a Team of Unmanned Aerial Vehicles", *RAL, 2021*.

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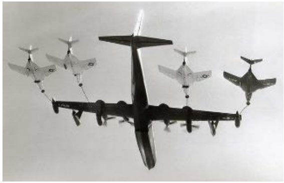

✓ These tasks often require formation-flying methods

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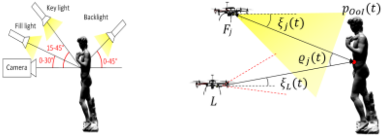

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Formations - Motivation

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Formation reshaping
Conclusion

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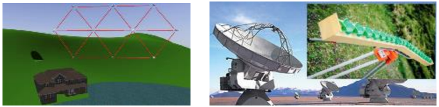
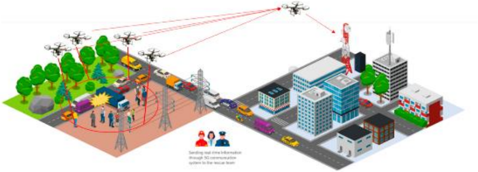
  - ✓ Redundancy and robustness vs. enlarged complexity of the system
  - ✓ Faster mission execution
  - ✓ Several light-weight robots replace a large well-equipped and heavy robot
  - ✓ Many tasks not solvable by a single robot
  - ✓ Actions realized in distance places in parallel

- Examples of applications: environment monitoring (to understand the complexity of time-variant phenomena), surveillance/ protection of long borderlines, communication relays (to connect points that are not reachable by available communication: under ground, long range outdoor operations)



M. Saska, “Large sensors with adaptive shape realised by selfstabilised compact groups of micro aerial vehicles”, *ISRR 2017.*



Source: J. Viana ‘s archive

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  - ✓ Formation needed in tasks requiring relative states of robots
  - ✓ E.g.: sensory arrays replacing a large measurement device (an antenna)

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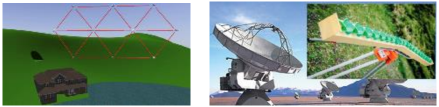

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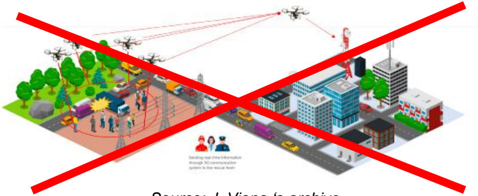

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  - ✓ Many tasks not solvable by a single robot
  - ✓ Actions realized in distance places in parallel
  - ✓ Formation flying looks impressive

- Examples of applications: drone light shows, commercials, acrobatic air shows

World record 50-ship formation flight over NASCAR. Source: bluestmuse.com

Formations - Motivation

Lecture 7
Formations

Martin Saska

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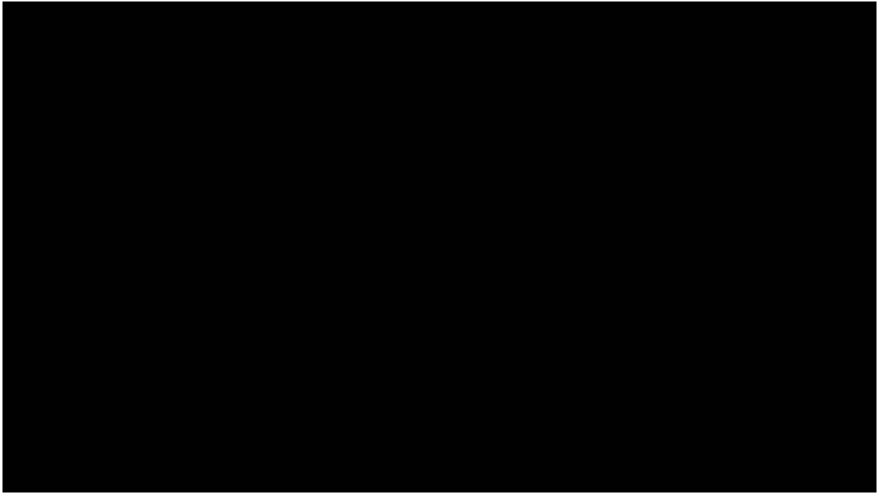
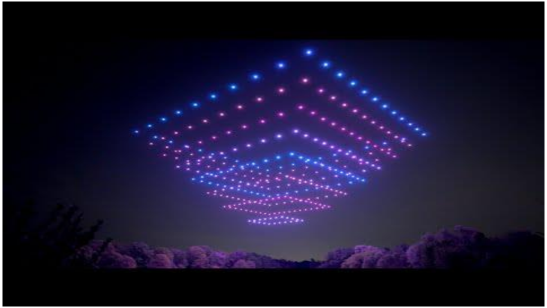


Source: Airbus 50-year anniversary

Drone shows vs. formations responding to dynamic real-world environment

- ✓ Scalable approach (thousands of agents)
- ✓ Pre-planned paths
- ✓ Relies on precise external localization system
- ✓ Completely independent agents unaware about the formation and other agents' states
- ✓ Cannot handle unexpected failures and changes in the environment



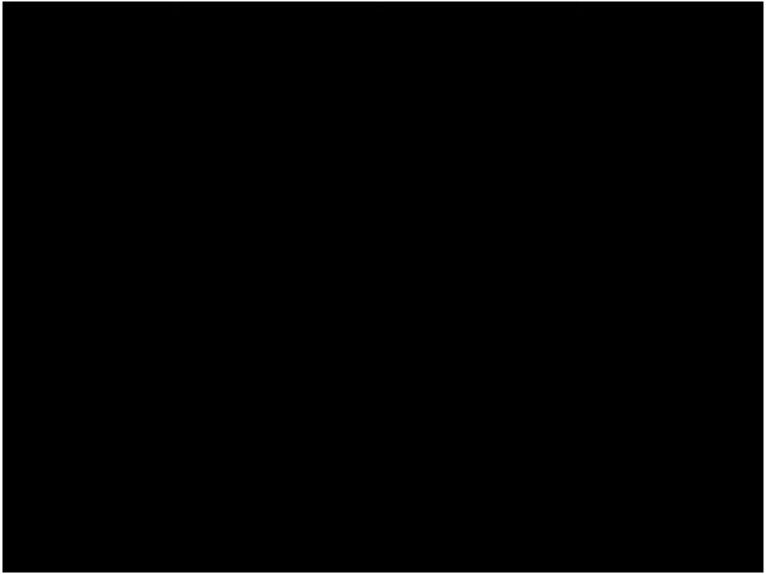
Source: *Firefly Drone Shows*

- ✓ Autonomous behavior based on perception
- ✓ Capability of failure detection and recovery
- ✓ Close cooperation among UAVs
- ✓ Complex algorithms running onboard
- ✓ Computational complexity increases with number of agents

Source: *Multi-robot Systems Group*

Issues and challenges related to UAV formations

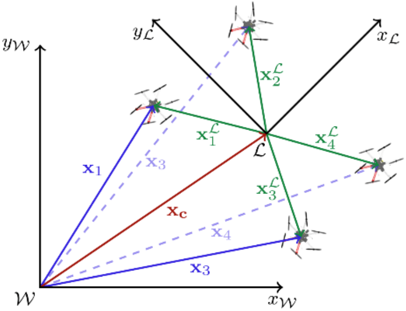
- ✓ Navigation in dynamic environment changed by the UAVs themselves
- ✓ Reliable communication required all the time
- ✓ Scalability of formation control approaches
- ✓ Failure detection and recovery
- ✓ Cooperative navigation and localization of closely flying UAVs
- ✓ Reliable formation shape changing – transition between required states
- ✓ Synchronization



Source: UFC UAV

Mathematical notation

- The formation can be described
  - ✓ by current configuration of n_r robots in world frame W as $\boldsymbol{F} = \{\boldsymbol{x}_1, \dots, \boldsymbol{x}_{n_r}, (\boldsymbol{x}_L)\}$
  - ✓ or using a central element (a leader) $\boldsymbol{x}_C$ in the world frame W. Then the current configurations of robots are given in the frame L with origin in $\boldsymbol{x}_C$ as $\boldsymbol{x}_i^L = \boldsymbol{x}_i$-$\boldsymbol{x}_C$, $\forall i \in \{1..n_r\}$



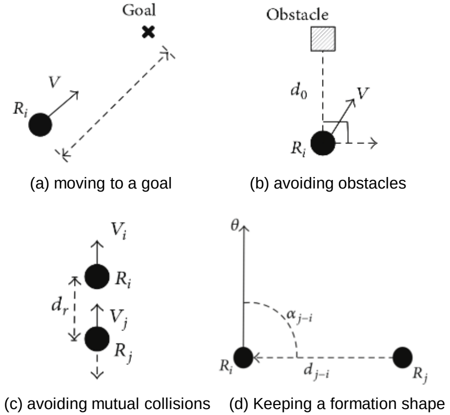
Formation control: approaches

- Behavior-based approach
- Virtual Structures (VS)
- Leader-follower (LF) approach

Behavior-based approach

- Control command as a combination of multiple behaviors, e.g.:
  - ✓ avoiding obstacles ($\boldsymbol{u}_o$)
  - ✓ moving towards a common goal ($\boldsymbol{u}_g$)
  - ✓ avoiding mutual collisions ($\boldsymbol{u}_m$)
  - ✓ keeping a formation shape ($\boldsymbol{u}_f$)

$$\boldsymbol{u} = \alpha \boldsymbol{u}_o + \beta \boldsymbol{u}_g + \gamma \boldsymbol{u}_m + \delta \boldsymbol{u}_f$$



Source: Xu's archive [4]

Behavior-based approach

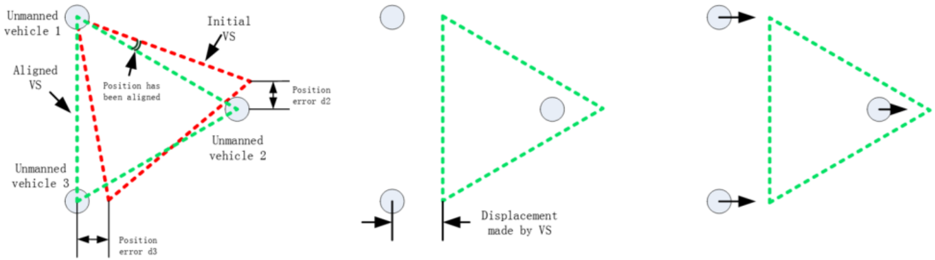
- Simple to implement – usually a sum of the vectors only
- Scalable – only a required shape is shared, the rest is decentralized
- Robust to failures of particular agents (except the entity that is sharing the goal)
- Difficult to analyze the behavior with respect to stability
- Optimal set of parameters can differ for various environments
- Problem of local minima and movement oscillations

✓ Details in the 8th presentation on “Behavior-based systems (swarm robotics, bio-inspired flocking algorithms)”

Virtual structure approach

- The formation defined as a rigid body
- The rotation and translation of the virtual structure (the rigid body) define motion of the robots
- Algorithm can be divided into three steps

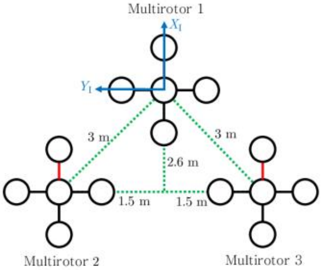
(1) VS position alignment (2) VS movement (3) formation movement



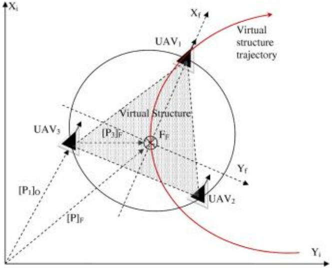
Y. Liu, and R. Bucknall, “A Survey of Formation Control and Motion Planning of multiple unmanned vehicles,” *Robotica*, vol. 36, no. 7, pp. 1019–1047, 2013.

Virtual structure approach

- Formation shape well defined and kept
- Proper for cooperative transportation
- Less sensitive to failures of particular agents than leader follower
- Low flexibility of formation -> complicated individual collision avoidance and transition between desired shapes
- Requires communication with low latency or precise synchronization

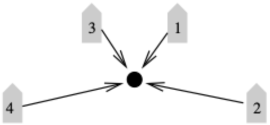


Source: Viana's archive



Source: Askari's archive

Unite-centre referenced



Virtual structure approach

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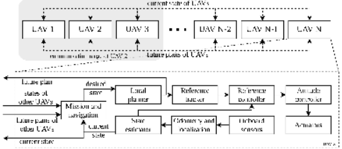
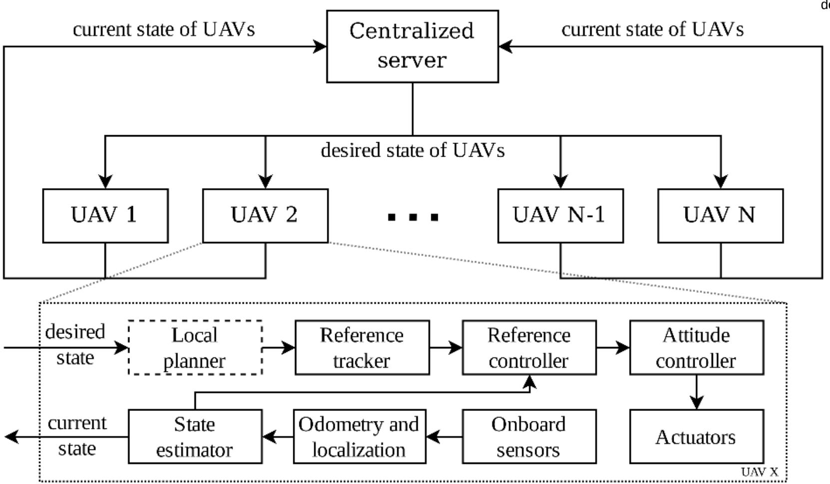
- Centralized approach – all robots controlled relatively to a leader state



decentralized approach for comparison



Leader-follower approach

- Required trajectory distributed for each robot of the formation
- Simple to interpret and analyze the behavior – possibility of stability/convergence analyses
- Requires efficient communication within the robots
- Sensitive to leader's failure or malfunction propagated to followers' behavior
- High flexibility - allows formation reshaping
- Practical applications: cooperative aerial filming, automated agriculture, military convoys and combat formations, automated re-fueling, cooperative snow shoveling, etc.
- Single point of failure problem (virtual leader concepts may partially solve it)

Leader-follower approach

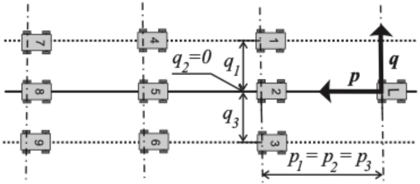
- Nonholonomic kinematic model
  - ✓ Motivation by UGV LF techniques
  - ✓ E.g. car-like vehicle model
  - ✓ Limited turning radius
- Virtual structure approaches do not provide feasible trajectories

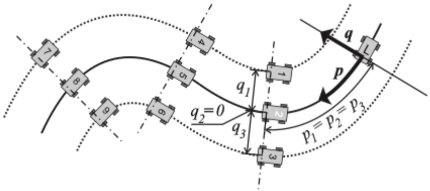
- For moving in a flat plane, position of the i –th follower may be determined by curvilinear coordinates p_i, q_i
- p_i - the traveled distance between the leader and follower i
- q_i - the offset distance between the leader and follower i
- t_{pi} - time when the leader was in traveled distance p_i

$$\boldsymbol{x}_i(t) = \boldsymbol{x}_L(t_{pi}) - q_i(t_{pi})\sin(\varphi_L(t_{pi}))$$

$$\boldsymbol{y}_i(t) = \boldsymbol{y}_L(t_{pi}) + q_i(t_{pi})\cos(\varphi_L(t_{pi}))$$

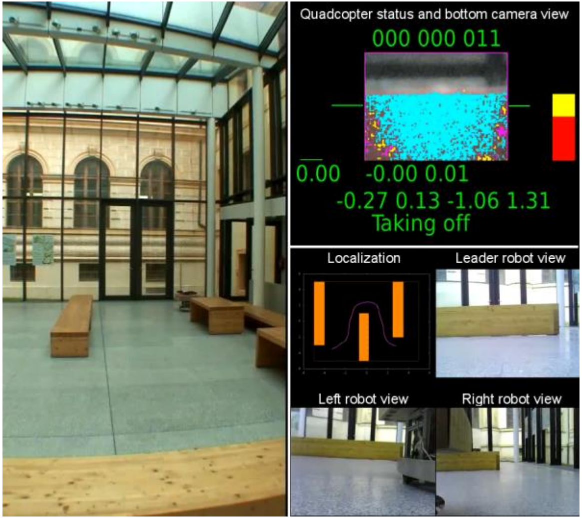
$$\varphi_i(t) = \varphi_L(t_{pi})$$





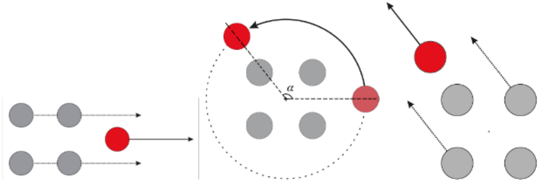
T.D. Barfoot and C. M. Clark, "Motion Planning for Formations of Mobile Robots", *Robotics and Autonomous Systems 46(2):65-78, 2004.*

Leader-follower approach



Virtual leader-follower

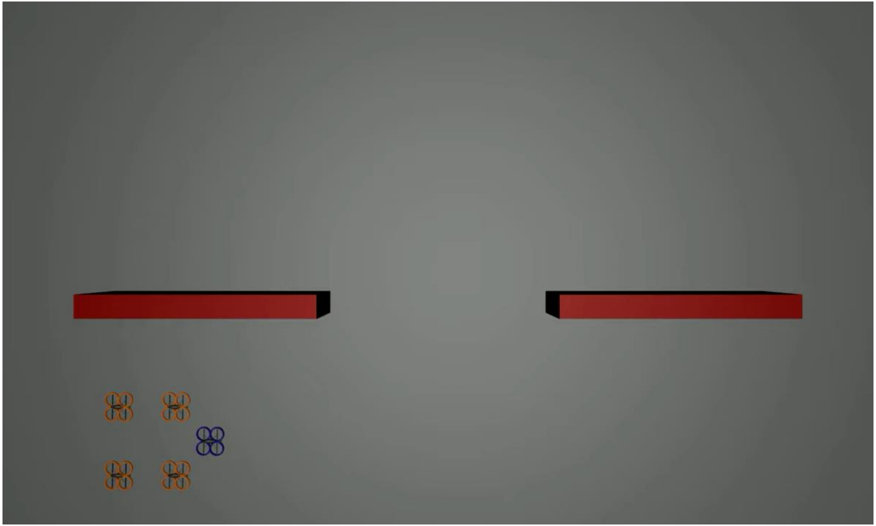
- Concept introduced to solve the single-point of failure problem (the leader's failure)
- The virtual leader (VL) is a disembodied version of a leader
- The same software of VL can run on all followers in parallel
- The control of VL itself is independent on the precision of localization, tracking, etc.
- The virtual leader does not have to conform dynamic constraints of real UAVs – it simplifies formation maneuvering



(a) Formation flying straight. (b) Virtual leader migration. (c) Flight in a new direction.

Source: MRS archive

Virtual Leader-follower



M Saska, at al. ,“Formation control of unmanned micro aerial vehicles for straitened environments.”, *Autonomous Robots 44:991-1008, 2020.*

Virtual Leader-follower

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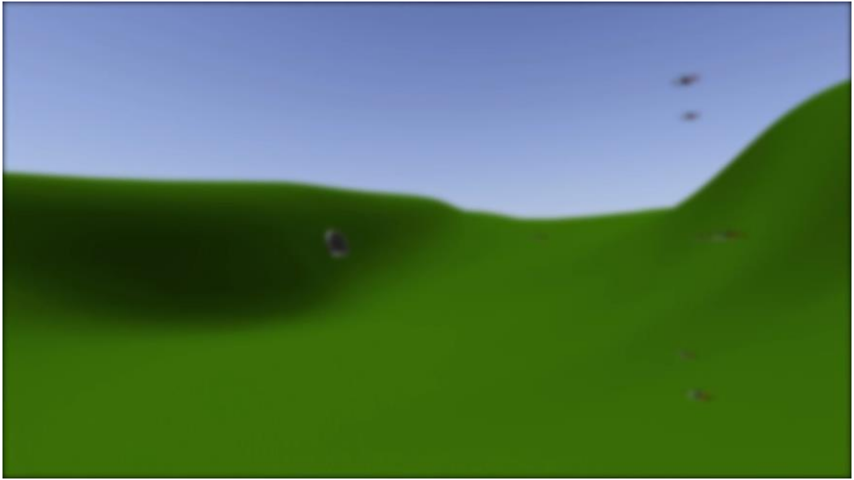


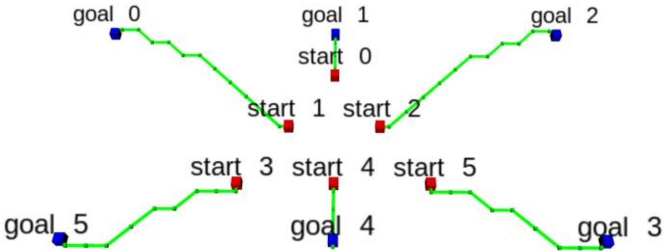
Distributed antenna array

Formation reshaping between different topologies

- Reasons for reshaping:
  - ✓ The desired shape usually depends on the assigned task
  - ✓ Obstacle avoidance – narrow corridors, windows, doors
  - ✓ Aerodynamic efficiency – depends on current wind conditions
  - ✓ Changing shape for data collection – multilateration
  - ✓ Optimizing the shape based on the workspace properties - area coverage, searching phalanx
- Possible topologies:
  - ✓ line
  - ✓ triangle
  - ✓ V-shape
  - ✓ circle
  - ✓ polygon
  - ✓ block

Formation reshaping - naive approach

- Applicable to static formations only (requires interruption of the formation movement)
- Includes four main phases:
  - ✓ Find matching between configurations in original formation shape and new formation shape
  - ✓ Find mutually collision-free paths leading UAVs from their current configuration to the new one
  - ✓ Navigate UAVs along the collision-free paths to new configuration
  - ✓ Return to the formation movement when desired shape is formed



✓ Applicable methods of multi-robot planning (6th lecture) and the task assignment (13th lecture)

Formation reshaping - integrated approach

- Transition between formation shapes handled by the formation control algorithm
- The formation reshaping integrated into the formation movement

- Leader-follower
  - ✓ Parameters describing positions of followers relatively to the leader are smoothly changed
  - ✓ The profile of the change of parameters must guarantee collision free transition
  - ✓ Or the parameters are suddenly changed
  - ✓ Equivalent to a sudden change of the reference trajectory
  - ✓ The low-level controller “should” solve collision free and smooth transition into a new equilibrium
  - ✓ Difficult to guarantee convergence
  - ✓ Oscillations due to often antagonistic objectives of local controllers can occur
  - ✓ Solution can be agent-based negotiation (goes beyond formation control)

Formation reshaping - integrated approach

- Behavior-based
  - ✓ Change of the action input $\boldsymbol{u}_f$ responsible for formation shape keeping
  - ✓ Input $\boldsymbol{u}_f$ continuously changed – smooth collision-free transition between required shapes
  - ✓ Input $\boldsymbol{u}_f$ suddenly changed – the entire local behavior rule (providing $\boldsymbol{u}$) may solve the collision-free transition (similar to the naïve approach, but the required global state of formation can move during transitioning)
  - ✓ Difficult (usually impossible) to guarantee convergence
  - ✓ Oscillations due to often antagonistic objectives of local rules often occur

- Virtual Structures
  - ✓ not possible with basic methods – require a modification (e.g. Virtual Rigid Body [Zhou 2018])

D. Zhou, Z. Wang, and M. Schwager, "Agile Coordination and Assistive Collision Avoidance for Quadrotor Swarms Using Virtual Structures," *IEEE Transactions on Robotics*, vol. 34, no. 4, pp. 916–923, 2018.

Conclusion

- Centralized vs. Decentralized control architecture

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  ✓ Single control unit: commands (a decision) are distributed to all robots from a central PC

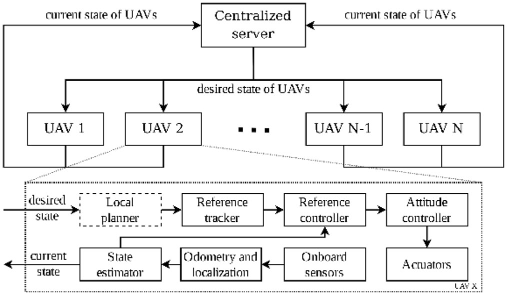
  ✓ Centralized state estimation of the entire MRS; knowledge of the global state required

  ✓ Usually simpler control design and better performance

  ✓ Requires synchronized and reliable communication

  ✓ Single-point of failure problem

  ✓ Less scalable



Conclusion

- Centralized vs. Decentralized control architecture
- Coordination vs. Cooperation vs. Collaboration

Conclusion

- Centralized vs. Decentralized control architecture
- Coordination vs. Cooperation vs. Collaboration

  - ✓ Coordination: Allows a group to complete a task more efficiently than a single robot by itself
  - ✓ For example, formation flying for drag reduction, compact flocking, convoys, platooning, air traffic management

  - ✓ Cooperation: Allows a group to complete a task that an individual robot could not complete on its own or to solve it more efficiently
  - ✓ Robots cooperate towards a common intention together
  - ✓ It usually requires synchronization and tight sharing of a workspace
  - ✓ For example, cooperative transportation, moving radiation source detection, search and rescue, construction

  - ✓ 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 – e.g. UAV-UGV formations and convoys

Conclusion

- Centralized vs. Decentralized control architecture
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- Explicit vs. Implicit communication

Conclusion

- Centralized vs. Decentralized control architecture
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- Explicit vs. Implicit communication

  - ✓ Explicit communication: mainly for centralized systems
  - ✓ States of neighbors are unobservable
  - ✓ Communication infrastructure required

  - ✓ Implicit communication : Directly through observation of neighbor states using onboard sensors
  - ✓ Relative localization – e.g. vision-based leader-follower

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