Multi-Robot Systems

https://youtu.be/dT7b1j5lj1I

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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 2nd 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 $\rightarrow$ Multi-Robot Systems
  ▪ Multiple mobile robots $\rightarrow$ 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
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
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
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
Cooperation – e.g. heavy object transportation

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

Cooperative transport of large objects by multiple UAVs

Flying through a field with obstacles
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
Implicit communication – relative localization

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

- MBZIRC 2020: Team of aerial robots hunting balloons and aerial target (RGB and Lidar)
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
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)
Collective Movement – swarms in environments with obstacles

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

Ahmad 2021 ICRA  https://youtu.be/nSlqyV0AlXU
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

Viana 2015
Formations – Nonholonomic Leader-Follower model

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

\[
\begin{align*}
\dot{x}_j(t) &= v_j(t) \cos \theta_j(t) \\
\dot{y}_j(t) &= v_j(t) \sin \theta_j(t) \\
\dot{\theta}_j(t) &= K_j(t)v_j(t) \quad j \in \{1, \ldots, n_r, L\}
\end{align*}
\]

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

\[
\bar{p}_j(t) = \left\{x_j(t), y_j(t)\right\} \quad \text{- position}
\]

\[
\psi_j(t) = \left\{p_j(t), \theta_j(t)\right\} \quad \text{- system state (position + heading)}
\]
Formations – Nonholonomic Leader-Follower model

- Position of the followers determined by curvilinear 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 $p_i(t)$

$x_i(t) = x_L(t_{p_i}(t)) - q_i(t_{p_i}(t)) \sin(\theta_L(t_{p_i}(t)))$

$y_i(t) = y_L(t_{p_i}(t)) + q_i(t_{p_i}(t)) \cos(\theta_L(t_{p_i}(t)))$

$\theta_i(t) = \theta_L(t_{p_i}(t))$
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
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

Video: Pavel Petráček

Petráček 2020 RAL, Krátký 2020 RAL, Sask 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

Cooperative transport of large objects by multiple UAVs

Narrow passage experiment

Askari 2015

Spurný 2019

https://youtu.be/Pdg3j791I9c
Further reading

• Classical graph-based approaches designed for multi-robot systems can be found in:

• Topics related directly to multirotor aerial platforms may be studied from:

• An overview of swarming approaches can be found in:
References


References


• Vrba, Matouš; Stasinchuk, Yurii; Baca, Tomas; Spurny, Vojtech; Petrlik, Matej; Heřt, Daniel; Zaitlík, David; Saska, Martin. Autonomous Capturing of Agile Flying Objects using MAVs: The MBZIRC 2020 Challenge. Submitted to IEEE Transactions on Systems, Man and Cybernetics: Systems, 2021
References


