Distributed Lloyd-based Algorithm for Uncertainty-Aware Multi-Robot Under-Canopy Flocking

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Three UAVs flocking under the forest canopy — no GNSS, no communication, only on-board sensing.

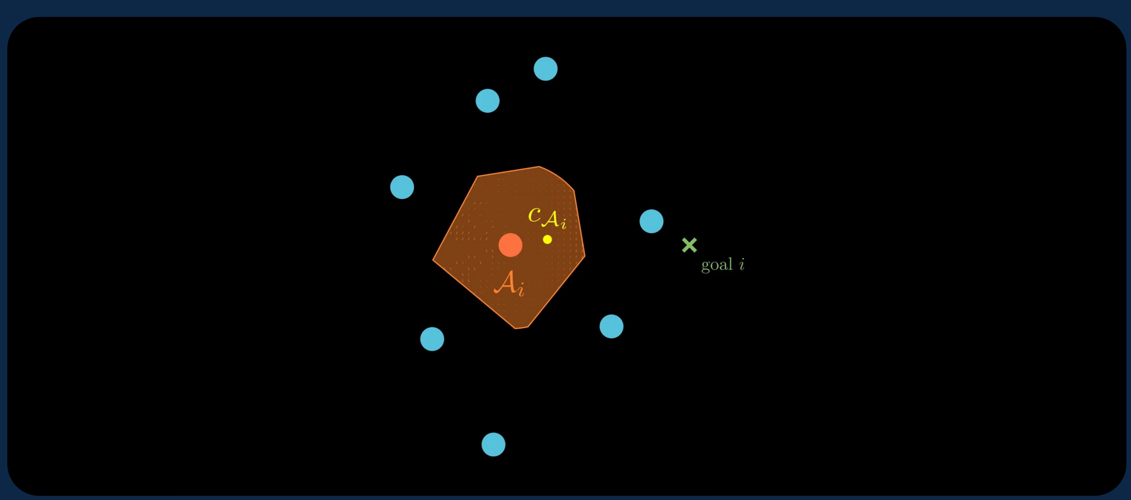
Problem

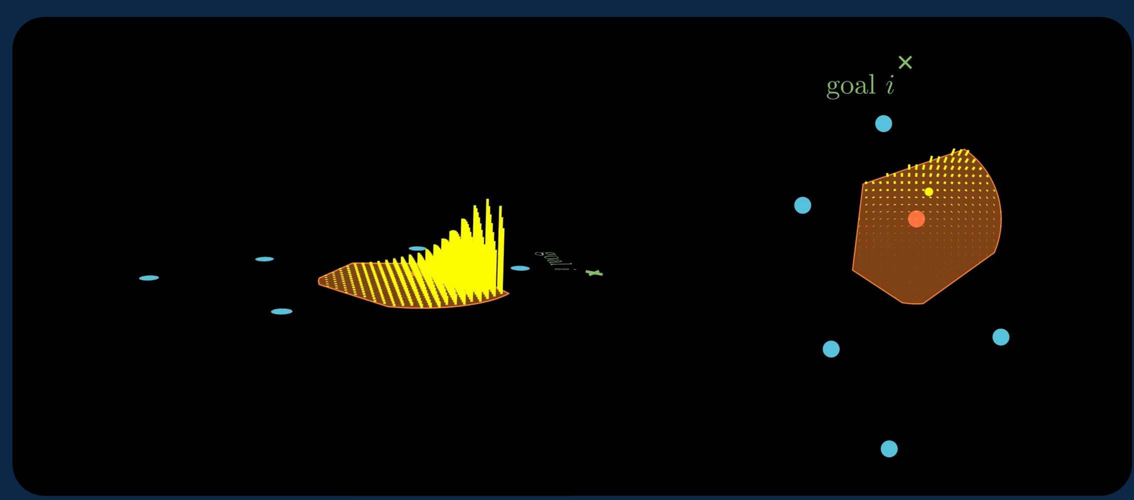
Steer N robots towards their goal locations — like a flock of birds or a school of fish: no leader, each robot decides from what it senses.

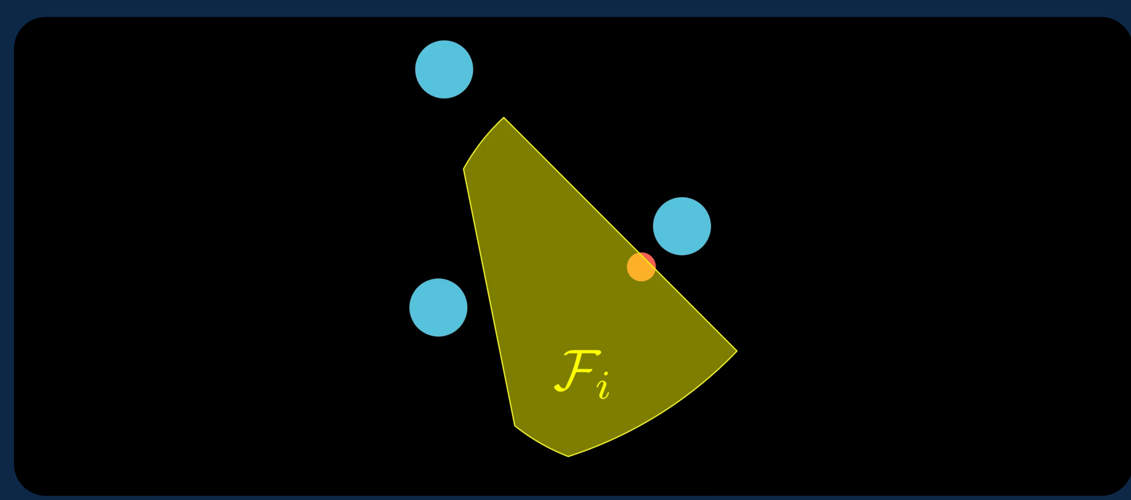
- ✓ Safety (collision & obstacle avoidance)
- ✓ Without explicit communication
- ✓ Distributed & asynchronous control
- ✓ Proximity maintenance
- ✓ Dealing with uncertainties
- ✓ On-board localization only

1 The basic idea

Each robot only needs relative positions of what it perceives.







The Lloyd-based algorithm

- Each robot computes its cell A_i from sensed neighbours & obstacles
- ...and moves towards the cell centroid

$$\dot{p}_i = -k_{p,i}\,(p_i - c_{\mathcal{F}_i})$$

Manipulating the density function

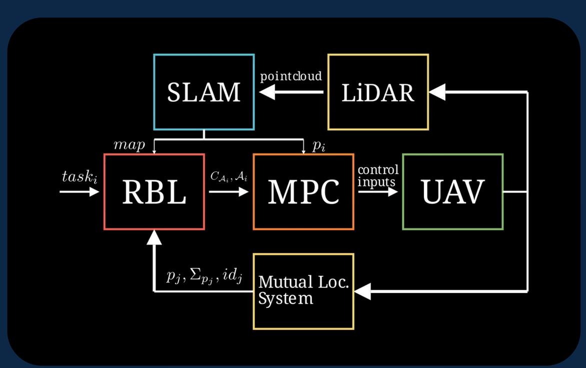
- Affects convergence and performance to the goal
- Accounts for tracking errors and uncertainties

$$\varphi_i(q) = \exp\left(-\|q - \bar{p}_i\| \,/\, \beta_i\right)$$

Reshaping the cell

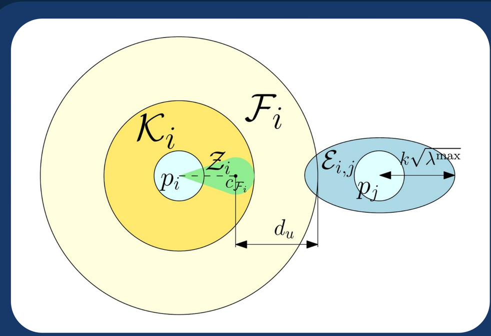
$\mathcal{A}_i = \tilde{\mathcal{V}}_i^p \cap \tilde{\mathcal{V}}_i^o \cap \mathcal{S}_i$	safe cell, collision-free by convexity
$\tilde{\mathcal{V}}_i^p$, $\tilde{\mathcal{V}}_i^o$	convex weighted Voronoi cells w.r.t. neighbours / obstacles (inflated by size)
$\mathcal{S}_i$	disc of radius half the sensing range
$\mathcal{M}_i$	proximity: $\|q - p_j\| \le \Gamma_{ij}$ (flocking)

$$\mathcal{F}_i = \tilde{\mathcal{V}}_i^p \cap \tilde{\mathcal{V}}_i^o \cap \mathcal{S}_i \cap \mathcal{M}_i$$



On-board perception and computation

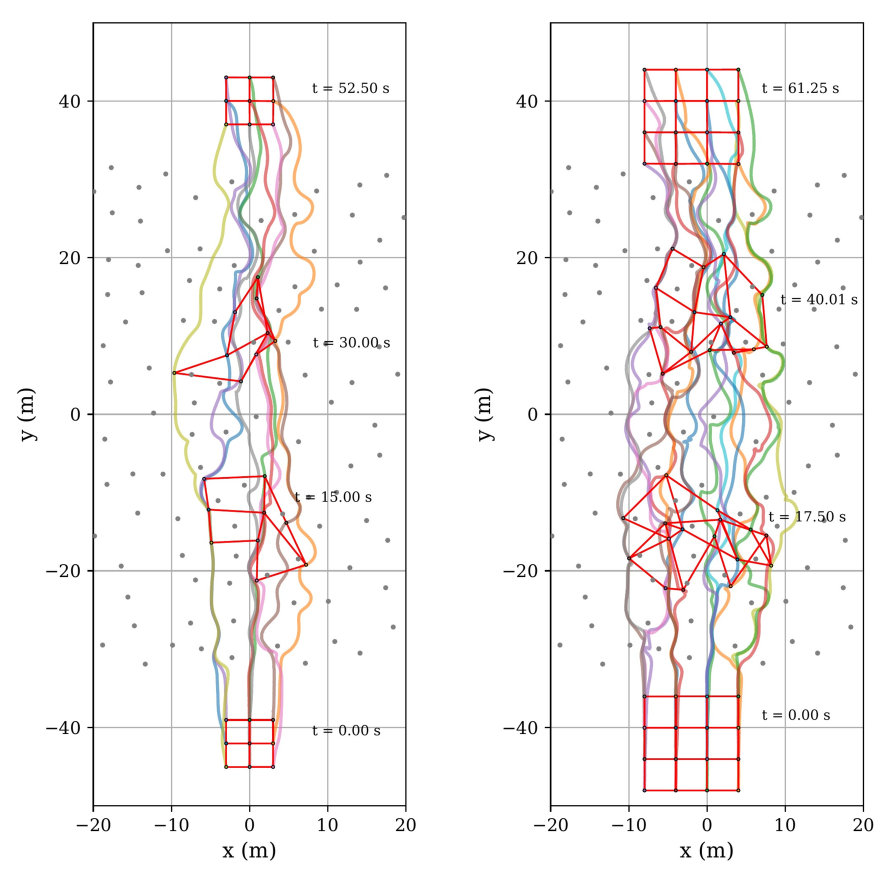
RBL outputs the cell and its centroid to an MPC. Obstacles come from 2-D LiDAR + SLAM; neighbours (p_j, Σ_j, id_j) from the UVDAR mutual localization system.



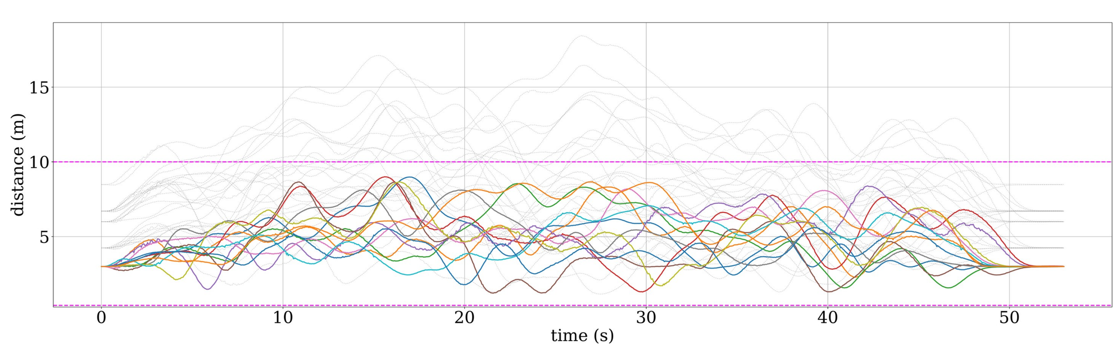
Dealing with uncertainties

Centroid kept ≥ d_u from the cell boundary, accounting for both the tracking error and the neighbours' measurement uncertainty.

2 Simulation

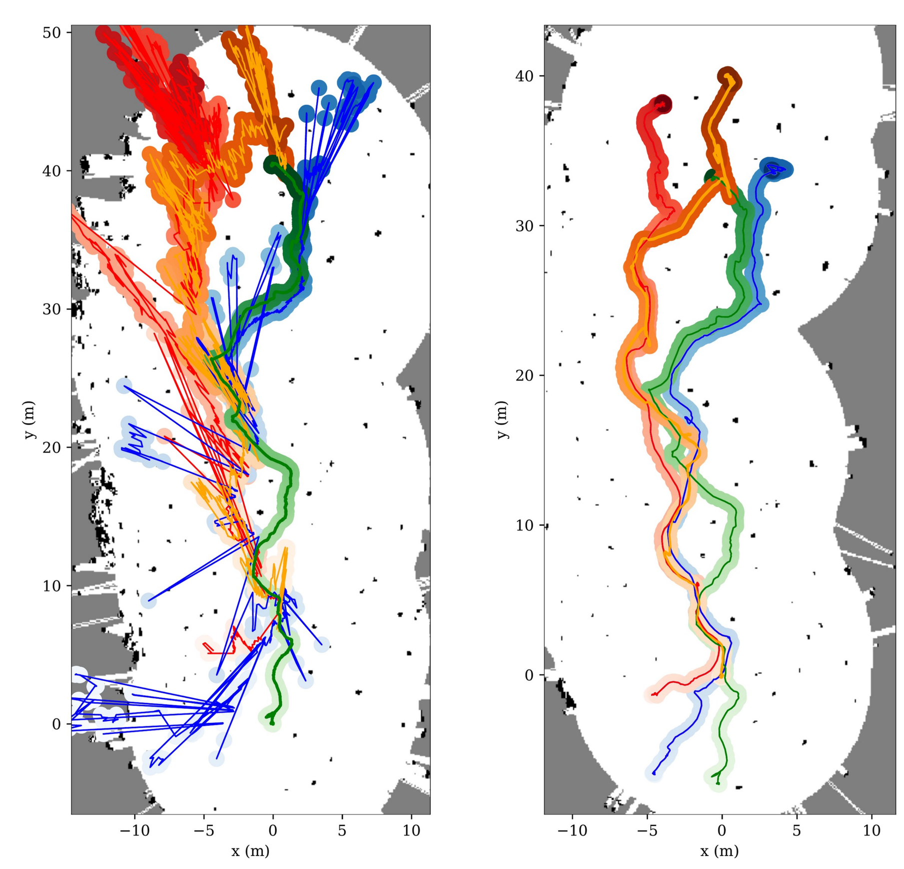


N = 9   N = 16

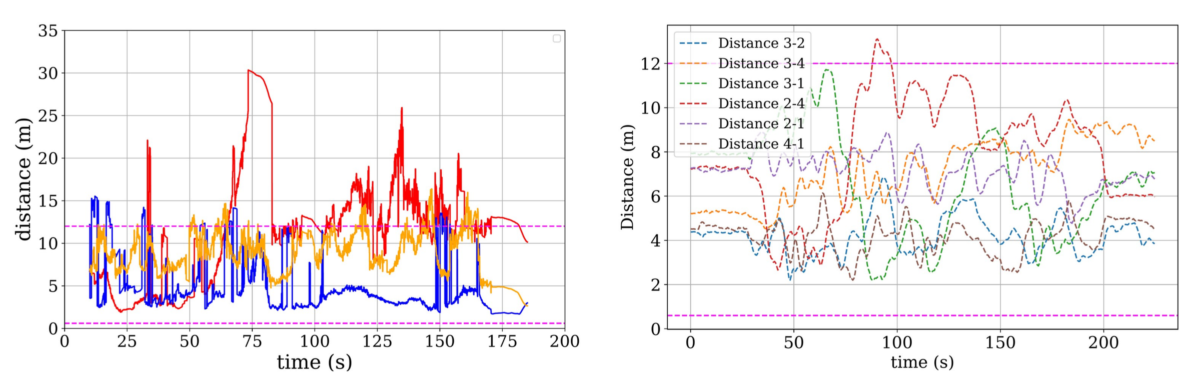


Inter-robot distances (N = 9) stay between the safety and flocking limits (magenta).

3 Forest experiments



UVDAR view   All tracks



Distances measured by UVDAR (UAV 2).   *True distances (aligned odometry).*

NEW ON ARXIV · FOLLOW-UP WORK

Perception-Aware Multi-UAV Implicit Coordination in the Wild

M. Boldrer, M. Kamler, A. Ahmad, M. Saska

Full 3-D coordination, no communication: one anisotropic LiDAR per UAV for SLAM, obstacles and neighbours, with a perception-aware planner for its limited field of view.

Paper · arXiv   Video   Code

Next steps Minimal communication for higher-level decisions. Human decision at the mission level

Video mrs.fel.cvut.cz/rbl

Code github.com/ctu-mrs/rbl

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