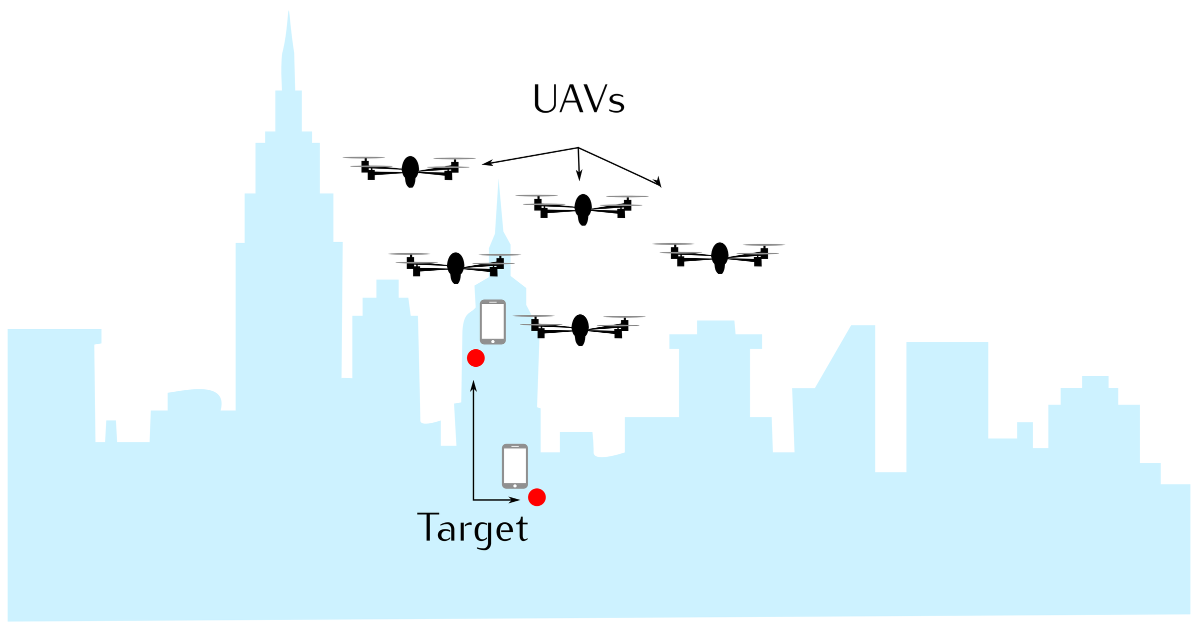
Collaborative Target-Localization and Information-based Control in Networks of UAVs

Anna Guerra* Nicola Sparnacci* Davide Dardari* Petar M. Djurić**

*DEI, University of Bologna, **ECE, Stony Brook University

E-mail contact: anna.guerra3@unibo.it

Research context



- We envision an emergency situation (e.g., a fire) in which a team of N UAVs acts as a **distributed wireless sensor network** to track targets (e.g., firemen) inside buildings. The UAV positions are considered a-priori known.
- Each UAV accomplishes the following tasks:
  - Exchange the gathered information only with its closest neighbors (multi-hops);
  - Fuse the collected data to infer the target position and optimize the trajectory;
- In this paper, we focus on the **decentralized control** of UAVs and the assessment of a trade-off between **localization accuracy** and **convergence speed**.

Information-seeking control

Goal: Each UAV estimates its own control signals in order to minimize the error in localizing the target and avoiding collisions between UAVs and obstacles.

Problem statement:

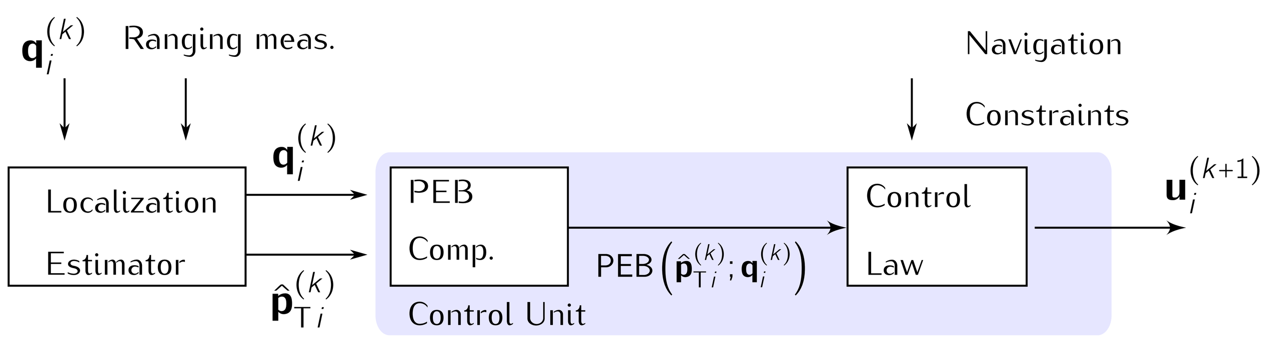
$$\left(\mathbf{q}_i^{(k+1)}\right)^* = \underset{\mathbf{q}_i^{(k+1)}\in\mathbb{R}^2}{\arg\min}\ \mathrm{PEB}\left(\hat{\mathbf{p}}_{\mathrm{T}\,i}^{(k)};\mathbf{q}_i^{(k+1)}\right)$$

UAV desired formation Position Error Bound Target pos. estimate

Search, among the future UAV formations, the one that minimizes the localization error

- $\mathbf{q}_i^{(k)} = \left[\ldots,\mathbf{p}_j^{(k-h+1)},\ldots\right]^{\mathrm{T}}$: locations of all the UAVs as known by the ith UAV at time slot k. h is the number of hops between the ith and jth UAV;
- $\hat{\mathbf{p}}_{\mathrm{T}\,i}^{(k)} = \left[\hat{x}_{\mathrm{T}\,i}^{(k)},\hat{y}_{\mathrm{T}\,i}^{(k)}\right]^{\mathrm{T}}$: estimated target position by the ith UAV at time slot k.

UAV control signal: $\mathbf{u}_i^{(k+1)} = \left[\left(\mathbf{q}_i^{(k+1)}\right)^*\right]_i - \mathbf{p}_i^{(k)}$



Position Error Bound

Fisher Information Matrix:

$$\mathrm{PEB}\left(\mathbf{p}_{\mathrm{T}};\mathbf{q}_i^{(k)}\right) = \sqrt{\mathrm{tr}\left(\mathbf{J}^{-1}\left(\mathbf{p}_{\mathrm{T}};\mathbf{q}_i^{(k)}\right)\right)} \qquad \mathbf{J}\left(\mathbf{p}_{\mathrm{T}};\mathbf{q}_i^{(k)}\right) = -\mathbb{E}_{\mathbf{z}_i^{(k)}}\left\{\nabla_{\mathbf{p}_{\mathrm{T}}}\left[\nabla_{\mathbf{p}_{\mathrm{T}}}\Lambda\left(\mathbf{z}_i^{(k)}|\mathbf{p}_{\mathrm{T}}\right)\right]^{\mathrm{T}}\right\}$$

Log-likelihood function: $\Lambda\left(\mathbf{z}_i^{(k)}|\mathbf{p}_{\mathrm{T}}\right) = \sum_{j=1}^{N}\ln f\left(z_j^{(k-h+1)}|\mathbf{p}_{\mathrm{T}}\right)$

Measurement model: $\mathbf{z}_i^{(k)} = \left[\ldots,z_j^{(k-h+1)},\ldots\right]^{\mathrm{T}} \longrightarrow z_i^{(k)} = d_i^{(k)} + v_i^{(k)}$

UAV-Target range $\mathcal{N}\left(v_i^{(k)};0,\left(\sigma_i^{(k)}\right)^2\right)$

Ranging model: $\left(\sigma_i^{(k)}\right)^2 = \sigma_0^2\left(d_i^{(k)}/d_0\right)^{\alpha} + \eta_i^{(k)}\,\sigma_b^2$

Ranging error @ d_0 Path-loss exp. NLOS bias error

Constrained navigation

Gradient-based solution: $\mathbf{u}_i^{(k+1)} = -\gamma\,\mathbf{P}\,\nabla_{\mathbf{p}_i^{(k)}}\mathrm{PEB}\left(\hat{\mathbf{p}}_{\mathrm{T}\,i}^{(k)};\mathbf{q}_i^{(k)}\right) - \mathbf{N}\left(\mathbf{N}^{\mathrm{T}}\mathbf{N}\right)^{-1}\mathbf{g}$

Projection matrix: $\mathbf{P} = \mathbf{I} - \mathbf{N}\left(\mathbf{N}^{\mathrm{T}}\mathbf{N}\right)^{-1}\mathbf{N}^{\mathrm{T}}$ with $\mathbf{N} = \nabla_{\mathbf{p}_i^{(k)}}(\mathbf{g})$

Activated constraint: $\mathbf{g} = \tilde{\mathbf{d}}_i^{(k)} - d^*$, $\tilde{\mathbf{d}}_i^{(k)} = \left\{\tilde{d}_i^{(k)} : \tilde{d}_i^{(k)} < d^*\right\}$

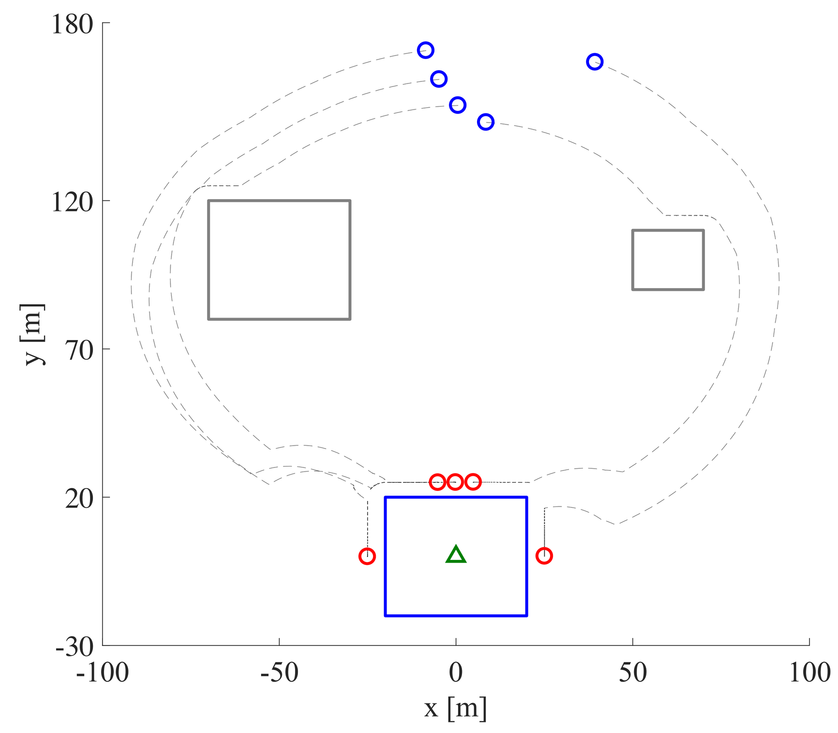
$\tilde{d}_i^{(k)}$: UAV distance from other UAVs/target/obstacles

d^*: safety distance

Results and conclusions

2D indoor/outdoor scenario:

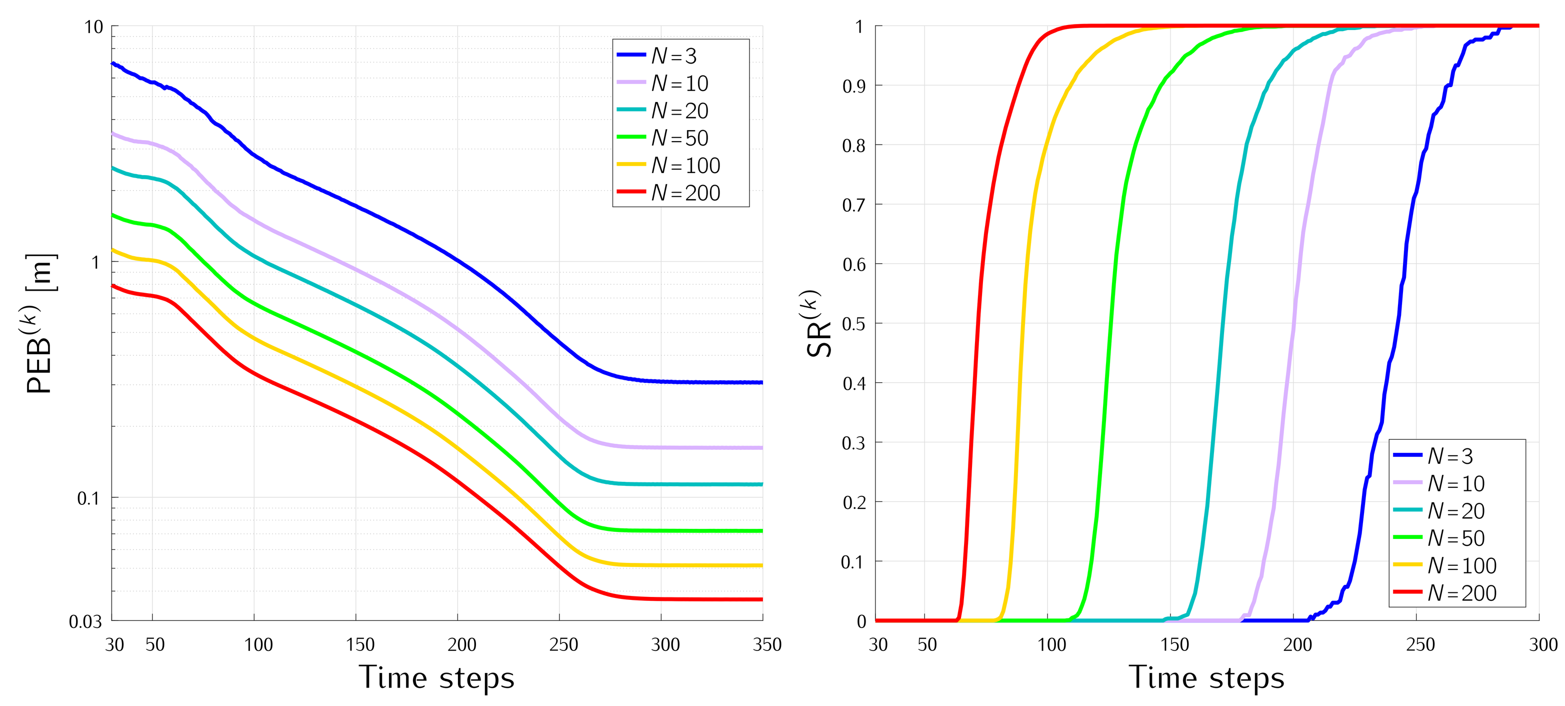
- Blue dots: UAV initial positions;
- Green triangle: Target position;
- Gray rectangles: obstacles;
- Black line: UAV trajectory.



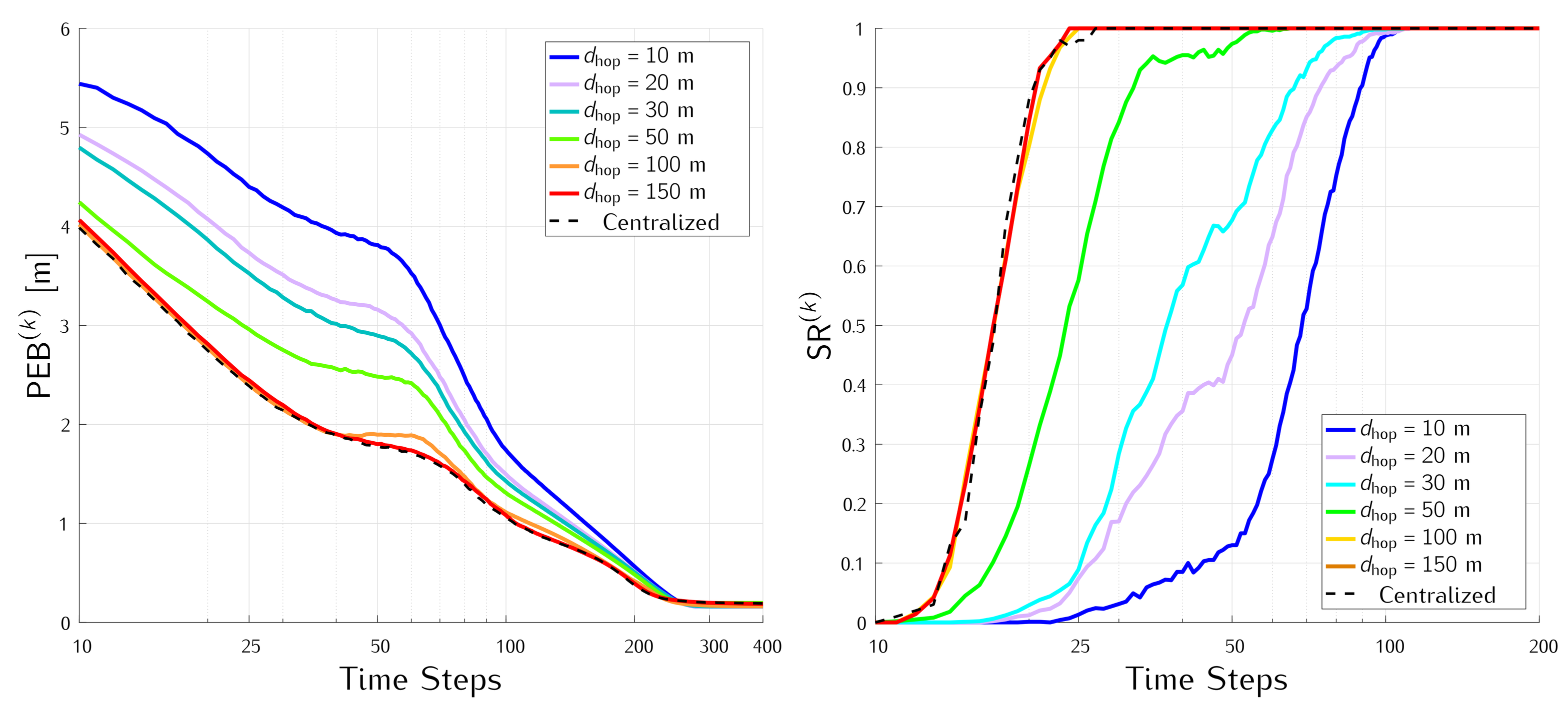
Success rate:

$$\mathrm{SR}^{(k)} = \frac{\sum_{m,i}\mathbf{1}\left(\mathrm{PEB}\left(\hat{\mathbf{p}}_{\mathrm{T}\,im}^{(k)};\mathbf{q}_{im}^{(k)}\right)\le\xi^*\right)}{N\,N_{\mathrm{MC}}}$$

- ξ^*: desired PEB value; $\mathbf{1}(\cdot)$: indicator function; N_{MC}: Monte Carlo iterations; d_{hop} commun. range; $h_{\max}$ maximum number of hops.



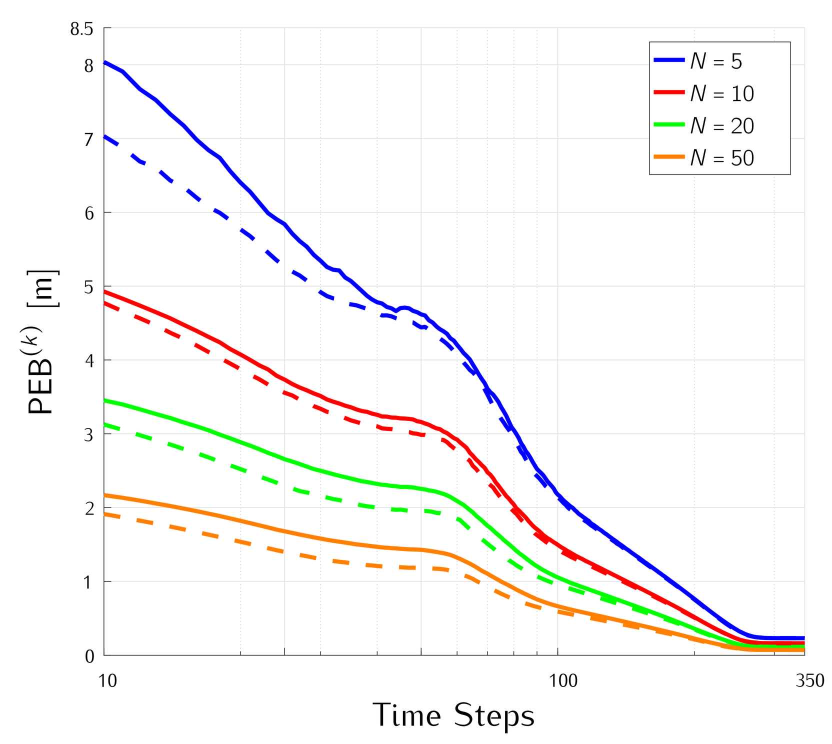
Left: Averaged PEB as a function of N with $d_{\mathrm{hop}}=20$ m and $h_{\max}=1$; Right: Success rate vs. N with $d_{\mathrm{hop}}=20$ m, $h_{\max}=1$ and $\xi^*=0.5$ m



Left: Averaged PEB vs. d_{hop} with $N=10$ and $h_{\max}=1$; Right: Success rate vs. d_{hop} with $N=10$, $h_{\max}=1$ and $\xi^*=3$ m

Conclusions:

- An increased number of UAVs translates in a better localization accuracy and improved convergence speed;
- An increased d_{hop} allows for the collection of more up-to-date measurements, and, hence, improved performance;
- Passing from $h_{\max}=1$ to $h_{\max}=3$ (i.e., collecting more not-updated measurements from UAVs that are further away) does not improve the results.



Averaged PEB vs. $h_{\max}$ with $d_{\mathrm{hop}}=20$. Dashed lines refer to the case $h_{\max}=3$ while continuous lines to $h_{\max}=1$