Set theoretic approach for target localization and tracking using a fleet of drones

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Outline

Context

Considered problem:

- Searching, detecting, and tracking mobile targets
- Potentially large region of interest
- Cooperative agents (*e.g.* UAVs)

Search process usually based on probabilistic information [Bertuccelli and How, 2005, Khodayi-mehr et al., 2019, Li and Duan, 2017, Moon, 2008, Sun et al., 2014, Yao et al., 2016, Yang et al., 2007, Zhang et al., 2017]

- Efficiency depends on
  - availability,
  - quality,
  - and reliability of the information.

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Problem statement

Performance sensitive to *a priori* assumptions on Probability Density Function of process [Gu et al., 2015].

Alternative assumption:

- Noises and uncertainties bounded

Approach:

- Set-membership state estimation [Reynaud et al., 2018, Reboul et al., 2019]
- Set-membership compliant Model Predictive Control (MPC)

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Objectives

Targets search considering the following issues:

- Limited field of view and communication range
- Unknown displacement of targets
- Presence of decoys/false targets
- Confusion between target tracks
- Non-detection occurrences
- Uncertainties of the position of each drone

Main objective:

- Developing set-membership estimator
- Designing cooperative guidance scheme

Outline

1. Introduction

2. Accounting for decoys

3. Detailed Framework

4. Conclusion

Limited FoV and presence of decoys

Considering localization within search area:

- of *a priori* unknown number of targets
- in presence of static decoys
- search area uncluttered
- non-detection not considered

Robust state estimator processes sets guaranteed to contain state of true targets already detected.[1]

[1] J. Ibenthal, L. Meyer, M. Kieffer, H. Piet-Lahanier, Bounded-error target localization and tracking in presence of decoys using a fleet of UAVs, presented at 21st IFAC World Congress in Berlin, Germany, 2020

Limited communication, obstacles and moving decoys

Considering localization within search area:

- of *a priori* unknown number of indistinguishable targets
- in presence of moving decoys
- search area with known obstacles
- limited communication
- non-detection not considered herein[2]

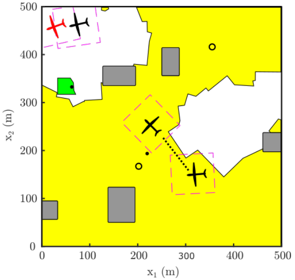

Figure: Simulations

[2] J. Ibenthal, L. Meyer, H. Piet-Lahanier, M. Kieffer, Target search and tracking using a fleet of UAVs in presence of decoys and obstacles, presented at IEEE CDC, Jeju Island, 2020.

Generalization of the prior approaches

Considering localization within search area:

- of *a priori* unknown number of targets
- in presence of moving decoys
- with limited and delayed communication
- non-detection still not considered[3]

- Identification condition modeled by unknown geometric conditions
- Extensive study of the parameters in simulations

[3] J. Ibenthal, M. Kieffer, L. Meyer, H. Piet-Lahanier, Bounded-error target localization and tracking using a fleet of UAVs, Automatica, accepted 2021.

Outline

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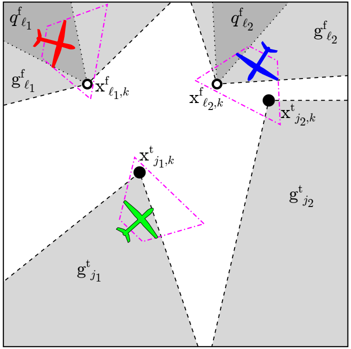
Problem formulation

Consider

- fleet of UAVs equipped with optical seekers
- moving true targets
- moving false targets
- detection and identification under specific conditions



UAVs and targets

Region of interest and possible target locations $\mathbb{X}_0$
Time is discretized: at time instant $t = kT$

- state vector $\mathbf{x}^{\mathrm{u}}_{i,k}$ of UAV $i = 1, \ldots, N_{\mathrm{u}}$ evolves as

$$\mathbf{x}^{\mathrm{u}}_{i,k+1} = \mathbf{f}^{\mathrm{u}}_{k}\left(\mathbf{x}^{\mathrm{u}}_{i,k}, \mathbf{u}_{i,k}\right),$$

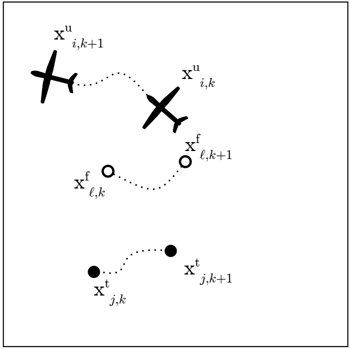
  with control input $\mathbf{u}_{i,k} \in \mathbb{U}$

- state vector $\mathbf{x}^{\mathrm{t}}_{j,k}$ of target j evolves as

$$\mathbf{x}^{\mathrm{t}}_{j,k+1} = \mathbf{f}^{\mathrm{t}}_{k}\left(\mathbf{x}^{\mathrm{t}}_{j,k}, \mathbf{v}_{j,k}\right),$$

  with state perturbation $\mathbf{v}_{j,k} \in [\mathbf{v}_k]$

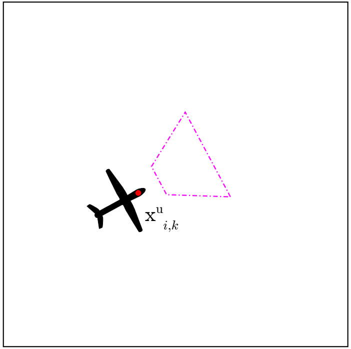
- false targets may be static or moving



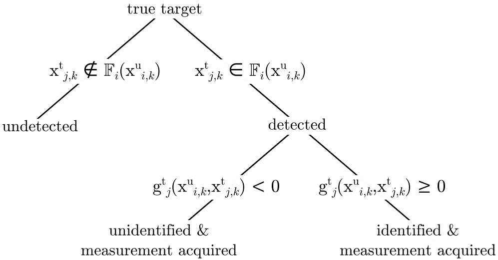
Measurements

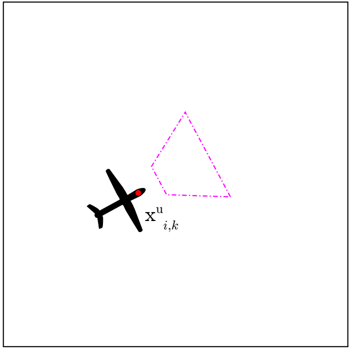
UAVs equipped with optical seekers:

- Field of view $\mathbb{F}_i\left(\mathbf{x}_i^{\mathrm{u}}\right)$



Measurements for true targets





Measurements for true targets

- true target
  - $x^t_{j,k} \notin \mathbb{F}_i(x^u_{i,k})$
    - undetected
  - $x^t_{j,k} \in \mathbb{F}_i(x^u_{i,k})$
    - detected
      - $g^t_j(x^u_{i,k}, x^t_{j,k}) < 0$
        - unidentified & measurement acquired
      - $g^t_j(x^u_{i,k}, x^t_{j,k}) \geq 0$
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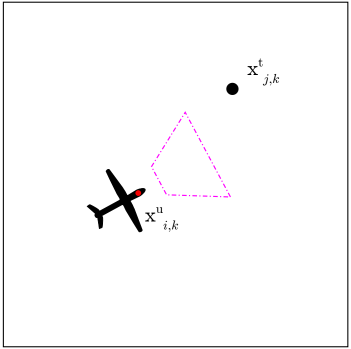

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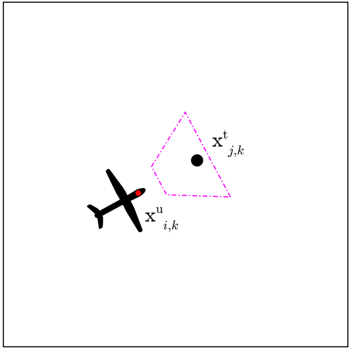

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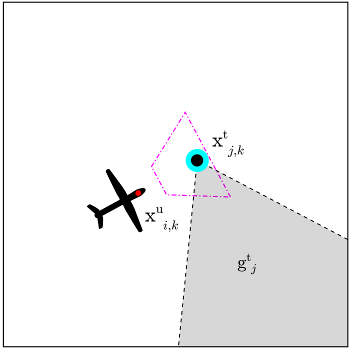

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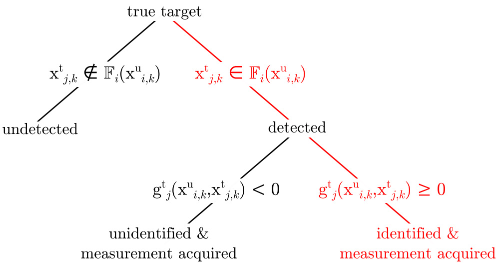

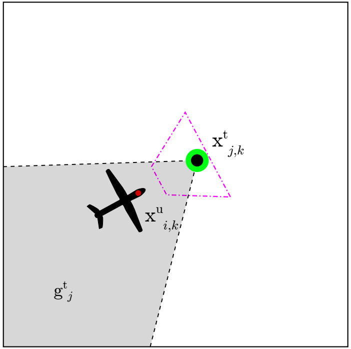

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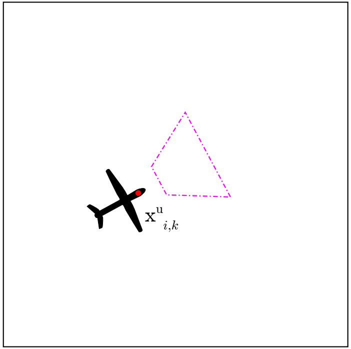

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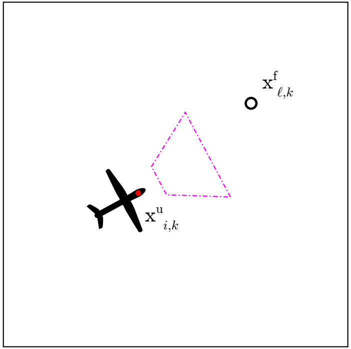

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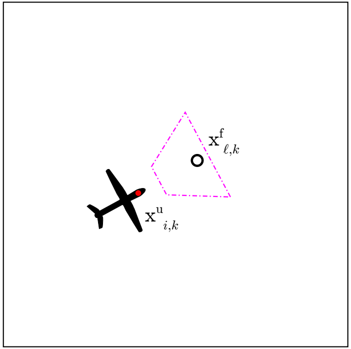

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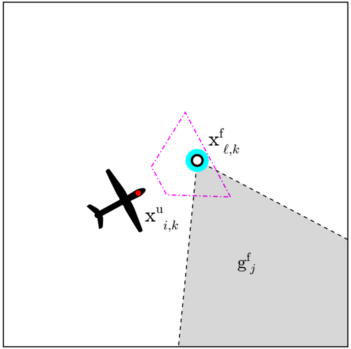

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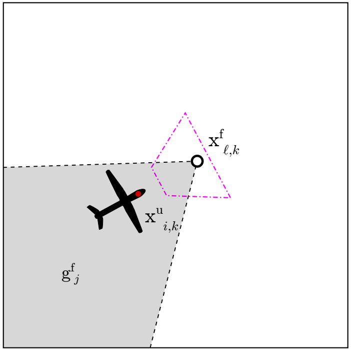

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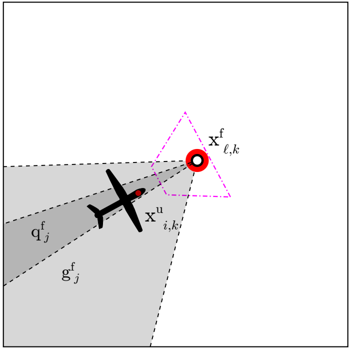

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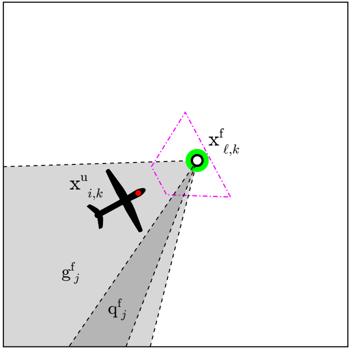


Observation

Noisy observation of target state

$$\mathbf{y}_{i,j,k} = \mathbf{h}_i \left(\mathbf{x}^{\mathrm{u}}_{i,k}, \mathbf{x}^{\mathrm{t}}_{j,k} \right) + \mathbf{w}_{i,j,k}$$

$\mathbf{w}_{i,j,k}$ represents the measurement noise, bounded in some known box $[\mathbf{w}]$

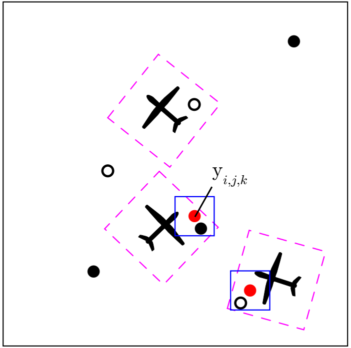


Figure: Collecting observations

Communication

Two UAVs in the vicinity are able to communicate.

Exchanged Information:

- UAV state value
- Control inputs
- Set estimates

Assumption:

- communication without error

Outline

Estimates

Unexplored set $\overline{\mathbb{X}}_{i,k}$

- Possible states of not yet detected targets

Target state estimate $\mathcal{X}_{i,k} = \{\mathbb{X}_{i,j,k}\}_{j \in \mathcal{L}_{i,k}}$ for identified targets

- may not contain a target due to presence of decoys
- $\mathcal{L}_{i,k}$: *list* of indices of targets already detected

Target state estimate $\mathbb{X}_k^{\mathrm{U}}$ for unidentified targets

- may contain targets and decoys

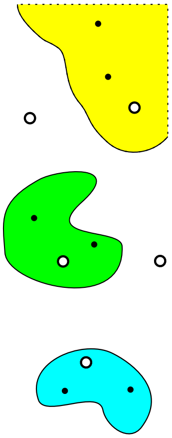


Figure: Estimates

Nonlinear recursive set-membership state estimator

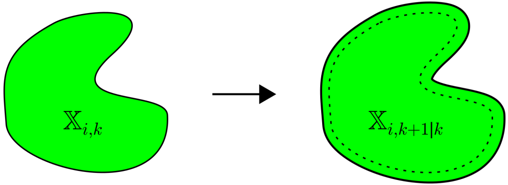
Initialization at $k = 0$:

- $\mathcal{L}_{i,0} = \emptyset$,
- $\mathcal{X}_{i,0} = \emptyset$,
- $\mathbb{X}^{\mathrm{U}}_{i,0} = \emptyset$
- and $\overline{\mathbb{X}}_{i,0} = \mathbb{X}_0$ for $i = 1, \ldots, N_{\mathrm{u}}$

Prediction

$$k \rightarrow k+1|k \rightarrow k+1|k+1 \rightarrow k+1$$

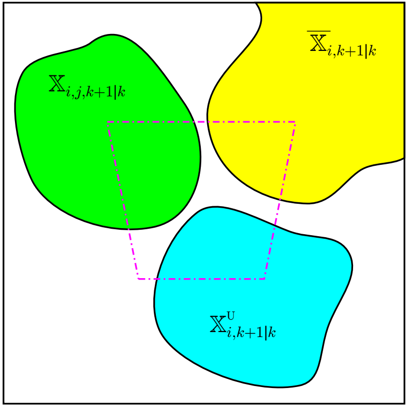
$$\mathbb{X}_{i,j,k+1|k} = \mathbf{f}_k^{t}\left(\mathbb{X}_{i,j,k}, [\mathbf{v}_k]\right) \cap \mathbb{X}_0$$



Correction from measurements

$$k \;\rightarrow\; k+1|k \;\rightarrow\; k+1|k+1 \;\rightarrow\; k+1$$

Set estimate update from measurements



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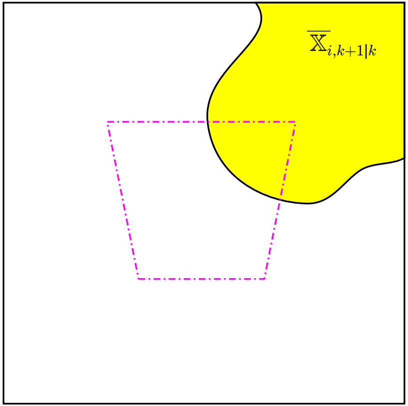
Updating unexplored set $\overline{\mathbb{X}}_{i,k+1|k}$

When no target is detected



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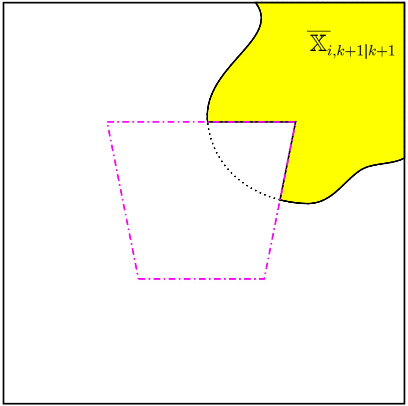
When no target is detected

$$\overline{\mathbb{X}}_{i,k+1|k+1} = \overline{\mathbb{X}}_{i,k+1|k} \setminus \mathbb{F}_i \left(\mathbf{x}^{\mathrm{u}}_{i,k+1} \right)$$



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Updating target set estimate

$\mathbb{X}_{i,j,k+1|k}$

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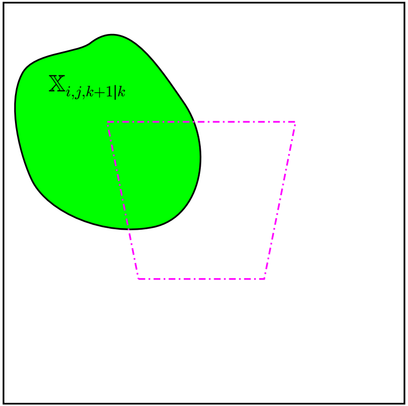

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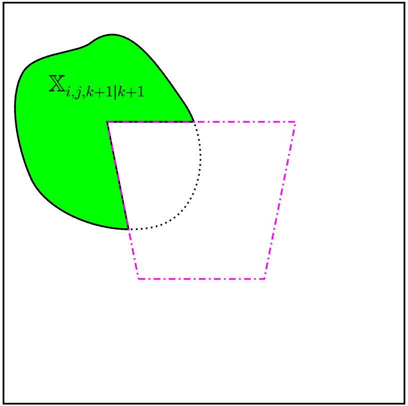

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Updating unidentified target set estimate $\mathbb{X}^{\mathrm{U}}_{i,k+1|k}$

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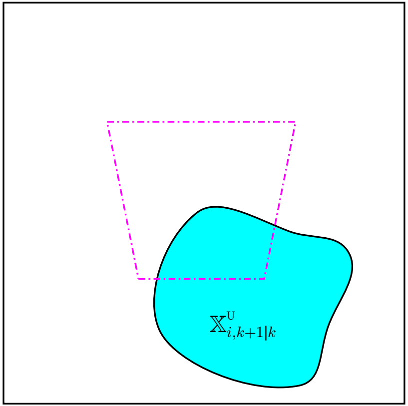

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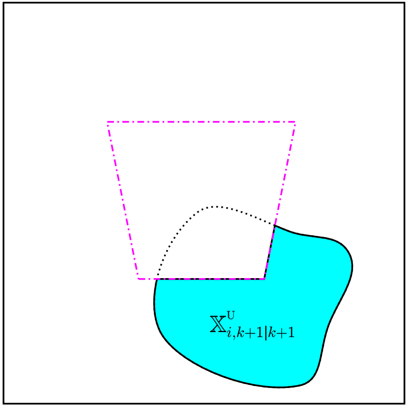

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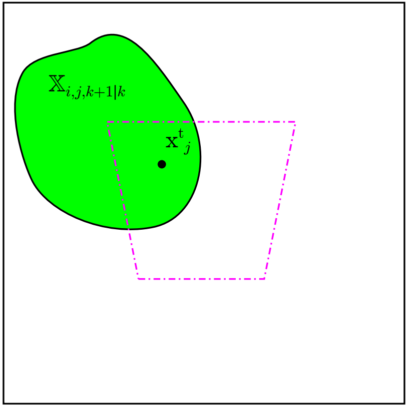
Updating target set estimate

$\mathbb{X}_{i,j,k+1|k}$

When a target is

- detected again
- and identified



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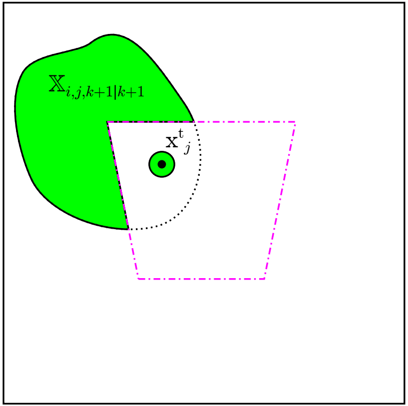
- detected again
- and identified

$$\mathbb{S}_1 = \Big\{ \mathbf{x} \in \mathbb{X}_{i,j,k+1|k} \mid \mathbf{h}_i\left(\mathbf{x}^{\mathrm{u}}_{i,k+1}, \mathbf{x}\right) \in \mathbf{y}^{\mathrm{l}}_{i,j,k+1} - [\mathbf{w}_{i,k}] \Big\}$$

$$\mathbb{X}_{i,j,k+1|k+1} = \left(\mathbb{X}_{i,j,k+1|k} \setminus \mathbb{F}_i\left(\mathbf{x}^{\mathrm{u}}_{i,k+1}\right)\right) \bigcup \mathbb{S}_1$$



Correction from measurements

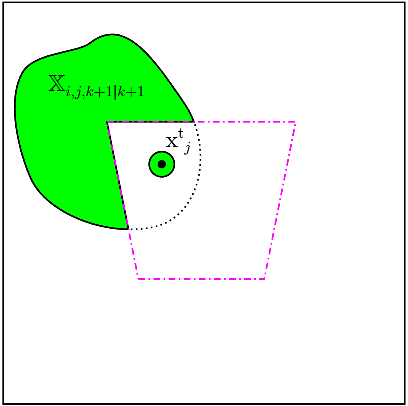
$$k \rightarrow k+1|k \rightarrow k+1|k+1 \rightarrow k+1$$

Updating target set estimate

$\mathbb{X}_{i,j,k+1|k}$

When a target is

- detected again
- and not identified



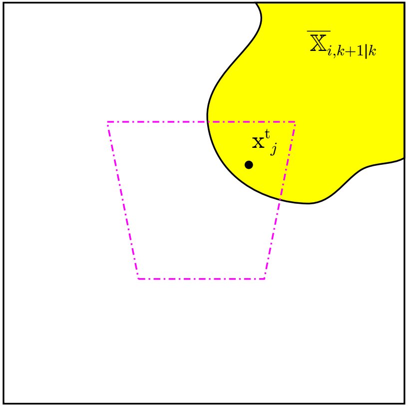
Correction from measurements

$$k \rightarrow k+1|k \rightarrow k+1|k+1 \rightarrow k+1$$

Updating target set estimate

$\mathbb{X}_{i,j,k+1|k}$

When a new target is identified



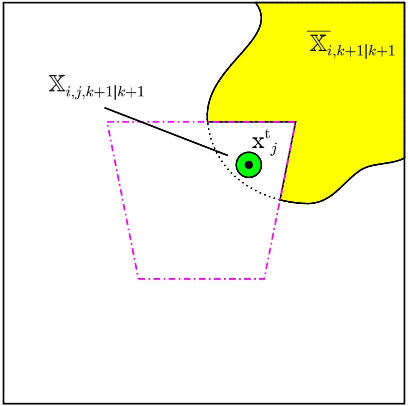
Correction from measurements

$$k \;\rightarrow\; k+1|k \;\rightarrow\; k+1|k+1 \;\rightarrow\; k+1$$

Updating target set estimate

$\mathbb{X}_{i,j,k+1|k}$

When a new target is identified

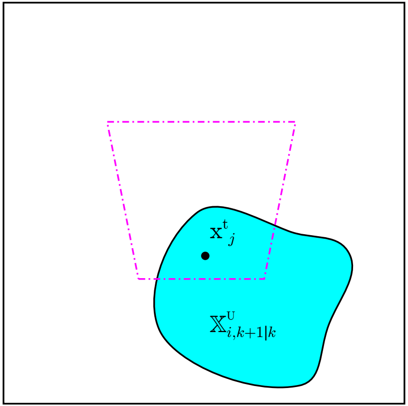


Correction from measurements

$$k \rightarrow k+1|k \rightarrow k+1|k+1 \rightarrow k+1$$

Updating target set estimate $\mathbb{X}_{i,j,k+1|k}$

When a unidentified target is identified

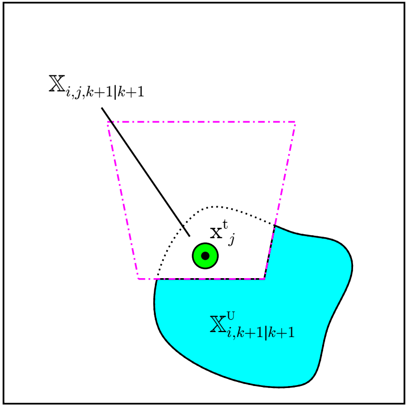


Correction from measurements

$$k \rightarrow k+1|k \rightarrow k+1|k+1 \rightarrow k+1$$

Updating target set estimate $\mathbb{X}_{i,j,k+1|k}$

When a unidentified target is identified



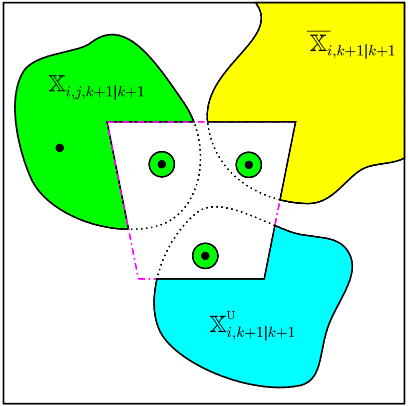
Correction from measurements

$$k \rightarrow k+1|k \rightarrow k+1|k+1 \rightarrow k+1$$

Updating target set estimate

$\mathbb{X}_{i,j,k+1|k}$

Accounting for all cases



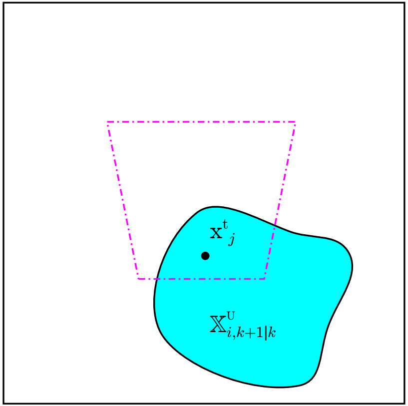
Correction from measurements

$$k \;\rightarrow\; k+1|k \;\rightarrow\; k+1|k+1 \;\rightarrow\; k+1$$

Updating unidentified target set estimate $\mathbb{X}^{\mathrm{U}}_{i,k+1|k}$

When a target is

- detected again
- and not identified



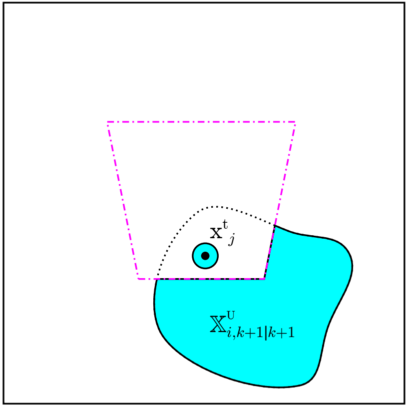
Correction from measurements

$$k \rightarrow k+1|k \rightarrow k+1|k+1 \rightarrow k+1$$

Updating unidentified target set estimate $\mathbb{X}^{\mathrm{U}}_{i,k+1|k}$

When a target is

- detected again
- and not identified

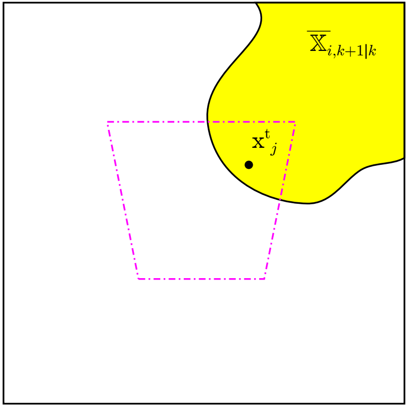


Correction from measurements

$$k \;\rightarrow\; k+1|k \;\rightarrow\; k+1|k+1 \;\rightarrow\; k+1$$

Updating unidentified target set estimate $\mathbb{X}^{\mathsf{U}}_{i,k+1|k}$

When new target is not identified

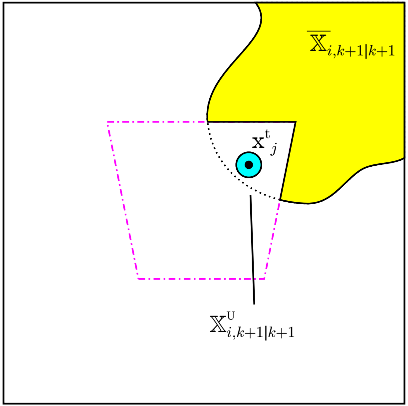


Correction from measurements

$$k \;\rightarrow\; k+1|k \;\rightarrow\; k+1|k+1 \;\rightarrow\; k+1$$

Updating unidentified target set estimate $\mathbb{X}^{\mathrm{U}}_{i,k+1|k}$

When new target is not identified

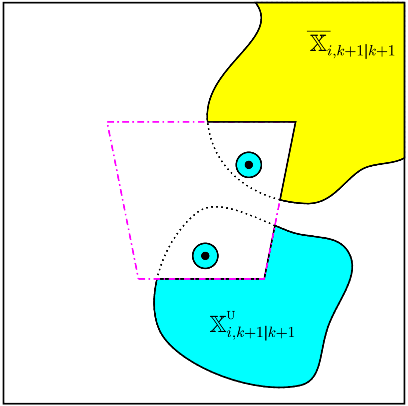


Correction from measurements

$$k \;\rightarrow\; k+1|k \;\rightarrow\; k+1|k+1 \;\rightarrow\; k+1$$

Updating unidentified target set estimate $\mathbb{X}^{\mathrm{U}}_{i,k+1|k}$

Accounting for all cases



Correction from communication

$$k \;\rightarrow\; k+1|k \;\rightarrow\; k+1|k+1 \;\rightarrow\; k+1$$

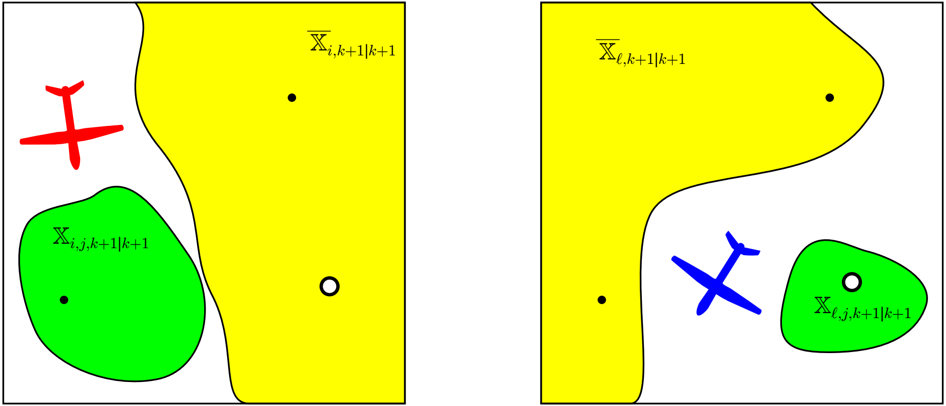
At the end of each time step k UAV i communicates with its neighbors

Exchanged information:

- Target set estimate
- Unexplored set
- Receiving the corresponding sets from its neighbors.

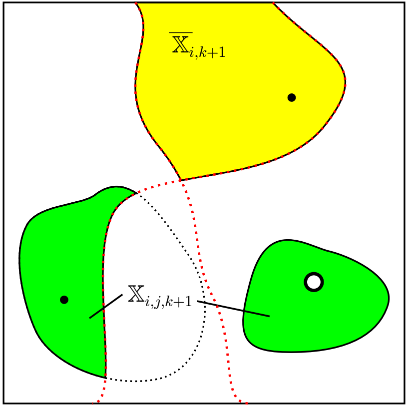
Correction from communication

$$k \;\rightarrow\; k+1|k \;\rightarrow\; k+1|k+1 \;\rightarrow\; k+1$$



Correction from communication

$$k \;\rightarrow\; k+1|k \;\rightarrow\; k+1|k+1 \;\rightarrow\; k+1$$



Outline

Cooperative distributed control design

Target state estimation uncertainty at time k for UAV i

$$\Phi\left(\mathcal{X}_{i,k}, \mathbb{X}^{\mathbf{U}}_{i,k}, \overline{\mathbb{X}}_{i,k}\right) = \phi\left(\left(\bigcup_{\mathbb{X}_{i,j,k} \in \mathcal{X}_{i,k}} \mathbb{X}_{i,j,k}\right) \cup \mathbb{X}^{\mathbf{U}}_{i,k} \cup \overline{\mathbb{X}}_{i,k}\right)$$

Each UAV

- has access to $\mathbb{X}_{i,j,k}$, $\mathbb{X}^{\mathbf{U}}_{i,k}$, and $\overline{\mathbb{X}}_{i,k}$
- determines sequence of control inputs minimizing estimation uncertainty

We rely on a model predictive control approach

Outline

Simulation conditions

The performance of the proposed approach is evaluated via simulations:

- Targets move on the ground with a constant speed module V^{t}
- UAVs fly at constant altitude and with constant speed
- UAVs are equipped with identical optical sensors
- The control input applied to yaw rate derivative
- Area of interest $\mathbb{X}_0$: cube of $[0, 400] \times [0, 400] \times [0, 100]$ m^3

Results - Impact of the fleet size

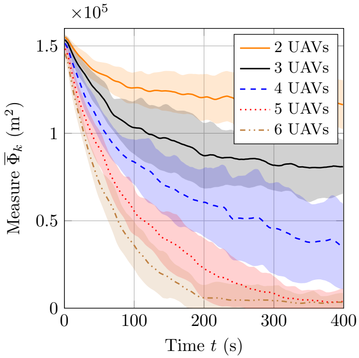


Figure: Mean values (line) and standard deviation (shaded area) of $\overline{\Phi}_k$ evaluated for 30 simulations with 3 true targets, 3 false targets, and 2 to 6 UAVs.

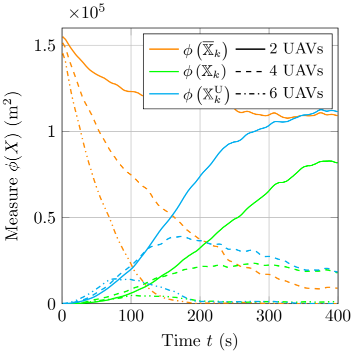


Figure: Mean values of $\phi(\overline{\mathbb{X}}_k)$,$\phi(\mathbb{X}_k^{\mathrm{U}})$, and $\phi(\mathbb{X}_k)$ evaluated with 3 true and 3 false targets, considering 2, 4 and 6 UAVs.

Outline

Conclusion

Development of several approaches solving the following issues:

- Cooperative target localization and tracking
- Static and dynamic targets
- Identification or detection of a target depends deterministically on the point of view
- Presence of static and dynamic decoys
- Presence of obstacles
- Distributed UAV control scheme

Conclusion

Other developments include

- Study of non-detection with moving targets
- Improve displacement strategies of UAVs accounting for their points of view
- Compare proposed approaches with probabilistic target search
- Implement on test platform (quadrotors)

Perspectives:

- Investigate game theory for cooperative guidance

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