Multi-agent coverage for heterogenous agents with anisotropic and spatially probabilistic coverage footprint

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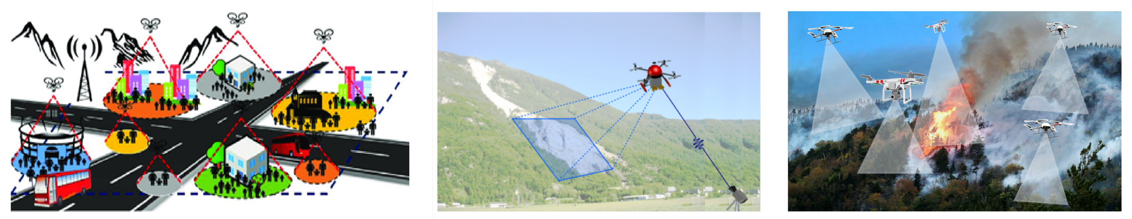
Objective statement

We consider a multi-sensor service matching deployment problem over a set of discrete target points that populate a finite flat surface.

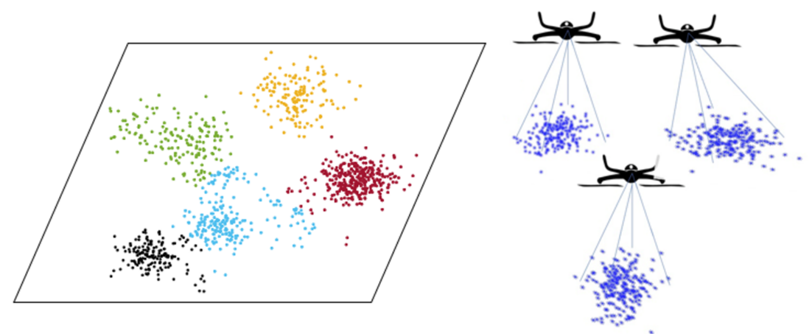


- The distribution of targets is not known a priori
- The agent's quality of service (QoS) can be spatially non-uniform and insotropic

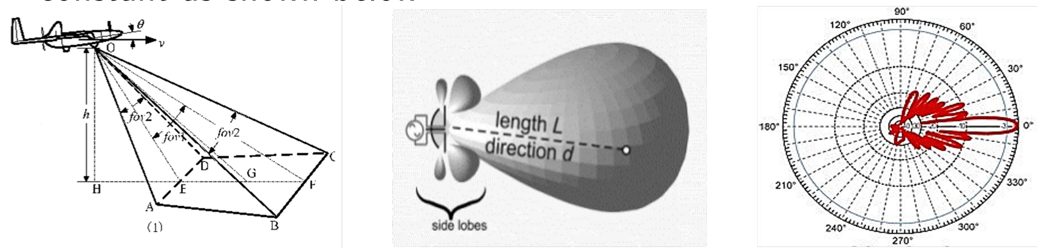
To provide the best service, the objective is to deploy the agents such that their collective QoS distribution is as close as possible to the density distribution of the targets. We determine the QoS based on the earth mover distance and in doing so we incorporate the freedom to transform the sensors in the earth move minimization problem formulation

Problem settings

- $p(\mathbf{x})$: the density distribution of targets is not known to the agents
- Agents only observe the targets



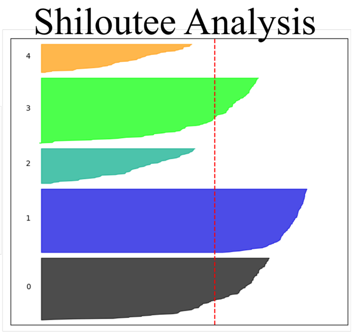
- Agents communicate over a connected graph
- $\mathbf{x}_{\mathrm{s}}^{i}$ is the location of the projection of UAV i onto the ground
- QoS provided by a service agent ($i \in V_{\mathrm{s}}$) is
  - $Q(\mathbf{x}|\mathbf{x}_{\mathrm{s}}^{i}) = \omega_{\mathrm{s}}^{i} q^{i}(\mathbf{x}|\mathbf{x}_{\mathrm{s}}^{i}, \theta_{\mathrm{s}}^{i})$, where $q^{i}(\mathbf{x}|\mathbf{x}_{\mathrm{s}}^{i}, \theta_{\mathrm{s}}^{i})$ can be a anisotropic or isotropic depending on the objective in hand, where $w^{i} \in$ is the scale constant as shown below

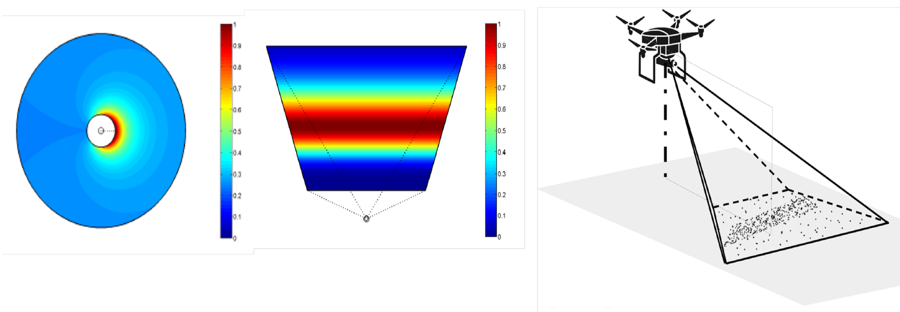


Solution approach

- Partition the environment as K means. Use shiloutee analysis to find the best K

$$MSE = \sum_{i=1}^{m} \|\mathbf{t}_i - \mu_K\|^2$$

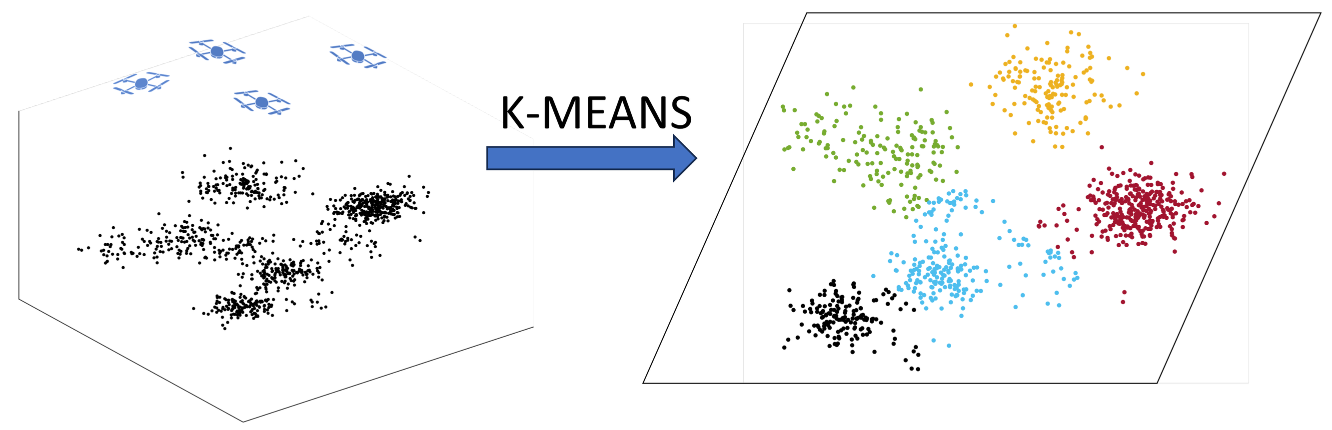




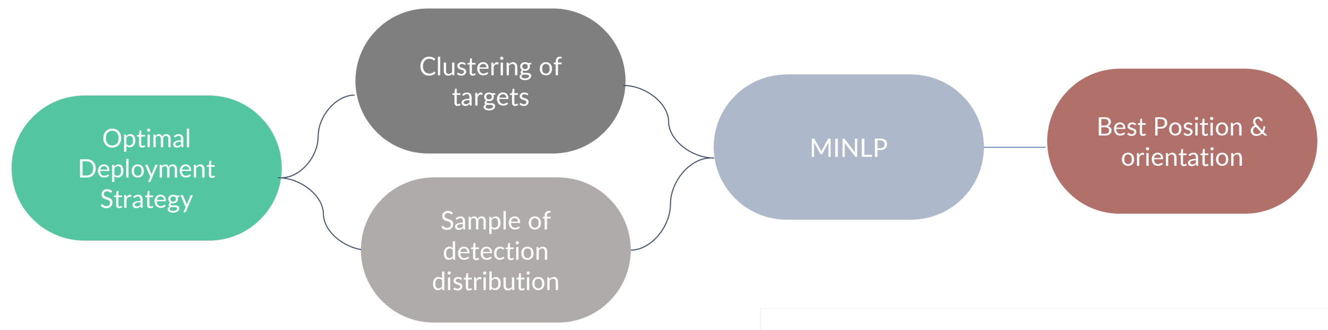
- Samples are drawn from the anisotropic sensor model
- Problem is formulated as a mixed integer non-linear program problem (MINLP), and the correspondence is calculated using the Iterative Closest Point (ICP) Algorithm.
- Solve an assignment problem between the cluster and the footprint of the sensor

The proposed framework

- The first stage involves partitioning the environment. This is done using the K-means clustering algorithm, which essentially divides our 2D plane into distinct clusters based on the proximity of our targets



- Proposed pipeline with underlying MINLP Formulation



$$C^{\star}_{i,j} = \min_{\mathbf{R}_{i,j},\mathbf{d}_{i,j},\mathbf{T}} \sum_{l=1}^{n_{i,j}} \sum_{k=1}^{n_{i,j}} T_{l,k} \|\mathbf{R}_{i,j}\mathbf{s}_l^i + \mathbf{d}_{i,j} - \mathbf{t}_k^j\|^2, \text{ s.t.} \quad (1a)$$

$$T_{l,k} \in \{0,1\}, \qquad 0 < l,k \leq n_{i,j}, \quad (1b)$$

$$\sum\nolimits_{l=1}^{n_i^{\mathrm{s}}} T_{l,k} = 1, \quad l = 1, \cdots, n_{i,j}, \quad (1c)$$

$$\sum\nolimits_{l=1}^{n_i^{\mathrm{s}}} T_{l,k} = 1, \quad k = 1, \cdots, n_{i,j}, \quad (1d)$$

$$\mathbf{R}_{i,j}^{\top}\mathbf{R}_{i,j} = \mathbf{R}_{i,j}\mathbf{R}_{i,j}^{\top} = \mathbf{I}_2. \quad (1e)$$

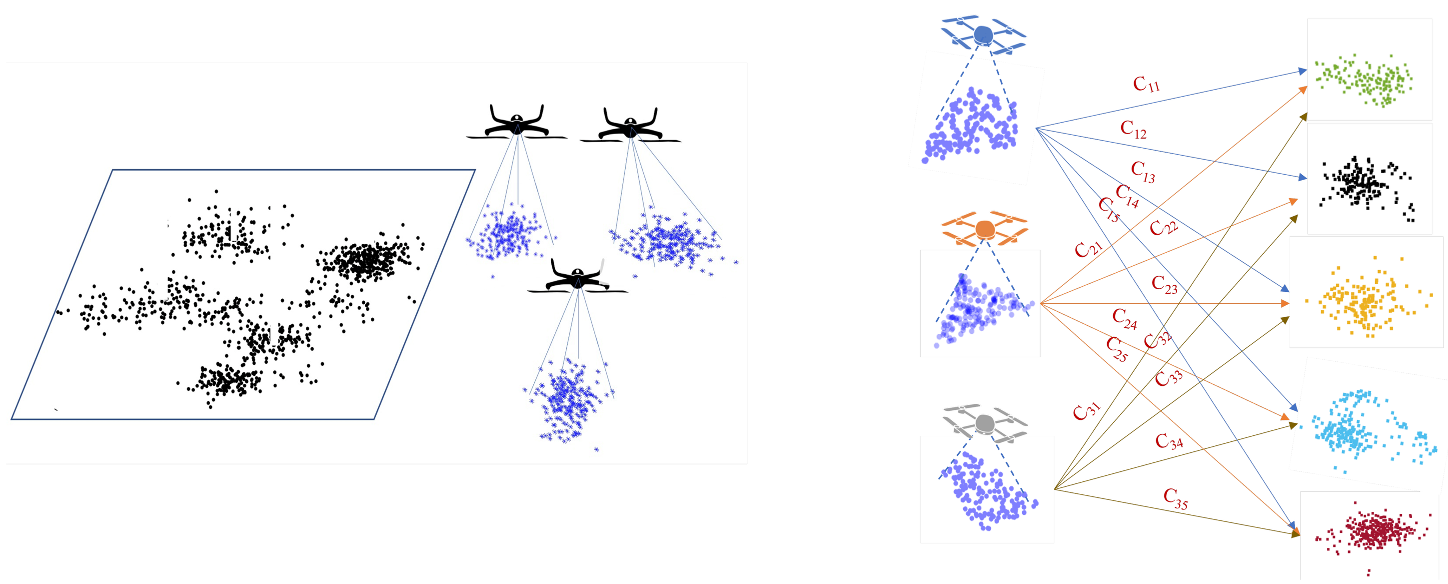
$$\mathbf{Z}^{\star} = \arg\min \sum\nolimits_{i\in\mathcal{V}_{\mathrm{s}}} \sum\nolimits_{j\in\mathcal{K}} Z_{i,j} C^{\star}_{i,j}, \quad (2a)$$

$$Z_{i,j} \in \{0,1\}, \quad i \in \mathcal{V}_{\mathrm{s}},\ j \in \mathcal{K}, \quad (2b)$$

$$\sum\nolimits_{j\in\mathcal{K}} Z_{i,j} = 1, \ \forall i \in \mathcal{V}_{\mathrm{s}}, \quad (2c)$$

$$\sum\nolimits_{i\in\mathcal{V}_{\mathrm{s}}} Z_{i,j} \leq 1, \ \forall j \in \mathcal{K}, \quad (2d)$$

- Assignment Problem:The second stage is about assigning the sensors, or our UAVs, to these clusters. This is a critical decision that is influenced by capabilities of our different sensors onboard the UAVs.



Methodology

- For the above mixed MINLP finding correspondence $T_{l,k}$ is not a trivial task as the problem is coupled.

$$C^{\star}_{i,j} = \min_{\mathbf{R}_{i,j},\mathbf{d}_{i,j},\mathbf{T}} \boxed{\sum_{l=1}^{n_{i,j}} \sum_{k=1}^{n_{i,j}} T_{l,k} \|\mathbf{R}_{i,j}\mathbf{s}_l^i + \mathbf{d}_{i,j} - \mathbf{t}_k^j\|^2}, \text{ s.t.}$$

We need to decompose it into two problems

Registration Error

$$E(\mathbf{R},\mathbf{d}) = \|\mathbf{R}_{i,j}\mathbf{s}_l^i + \mathbf{d}_{i,j} - \mathbf{t}_k^j\|^2 \quad (3)$$

Optimal Correspondence

$$k^{*} = \min_{k\in\{1,\cdots,M\}} \|\mathbf{R}_{i,j}\mathbf{s}_l^i + \mathbf{d}_{i,j} - \mathbf{t}_k^j\|^2 \quad (4)$$

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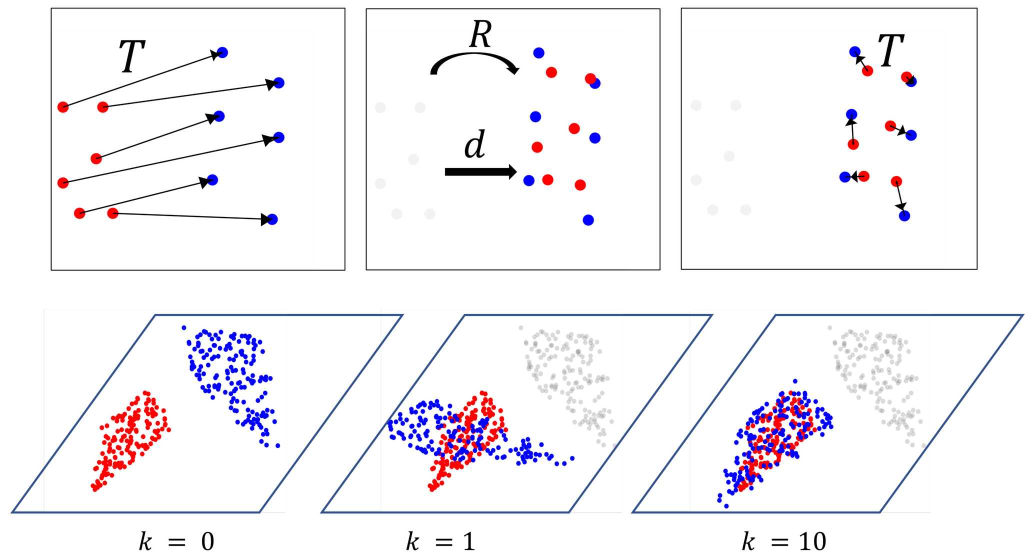
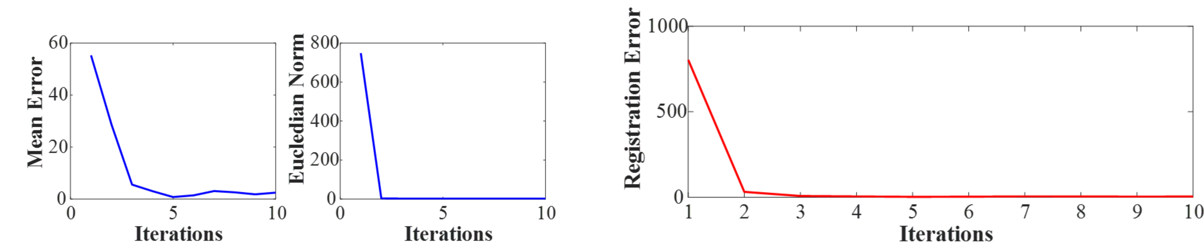
Methodology contd.

- ICP Formulation: To solve the coupled problem we are inspired by the ICP Algorithm, a commonly used method in computer vision

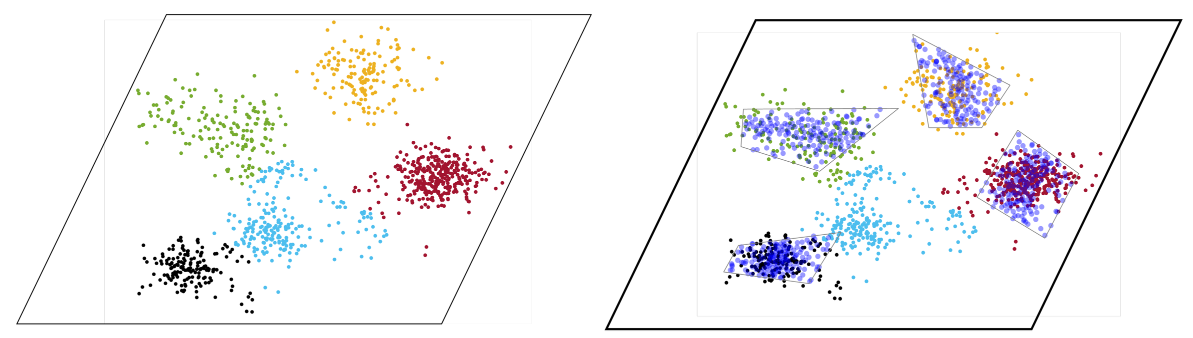


- Convergence of ICP:

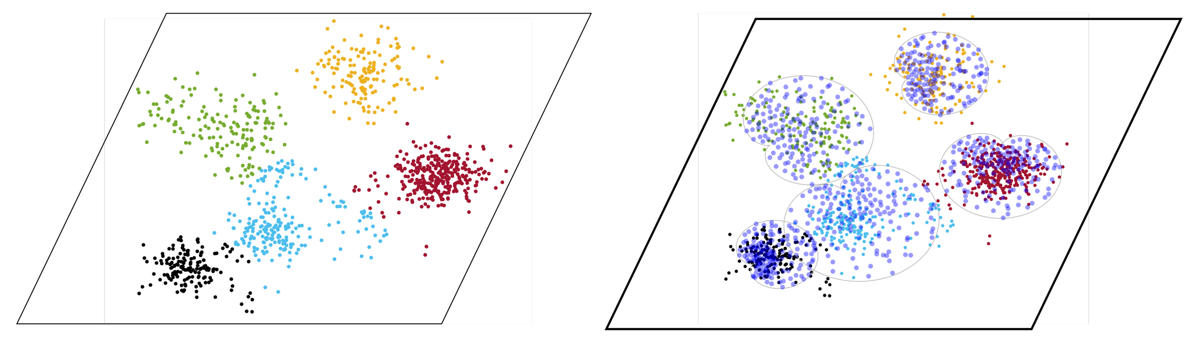


Numerical examples

- We consider two examples, where the environment $\mathcal{W}$ is a rectangle of $[-350, 350] \times [-300, 300]$ meters, and number of targets, $N = 1000$. The sensors we will be using for this example are camera and acoustic sensors, which are both anisotropic.
- Camera sensor



- Acoustic sensor



Vision

- Praised for their low cost, easy use, and capture of on-demand visuals, UAVs are a game-changing technology for many applications such as
  - area monitoring
  - on demand wireless access
  - disaster relief
- In the future, UAVs using advanced perception, planning, and control algorithms will be able to self-deploy and coordinate among themselves to provide optimal, reliable and resource-aware service-matching coverage.

Sponsors

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