Stein Coverage: A Variational Inference Approach to Distribution-Matching Multisensor Deployment

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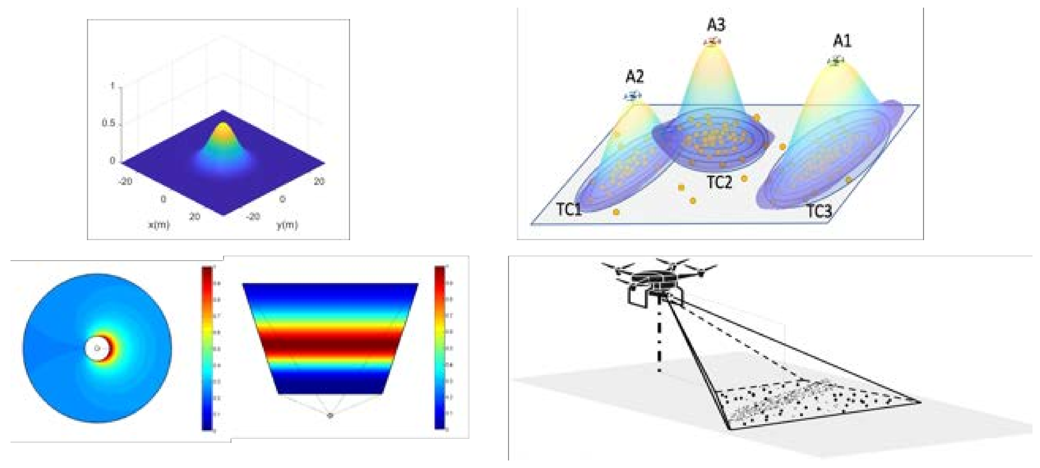
Problem setting

We consider a multi-sensor service matching deployment problem in a known convex environments where the sensors are heterogeneous and anisotropic.

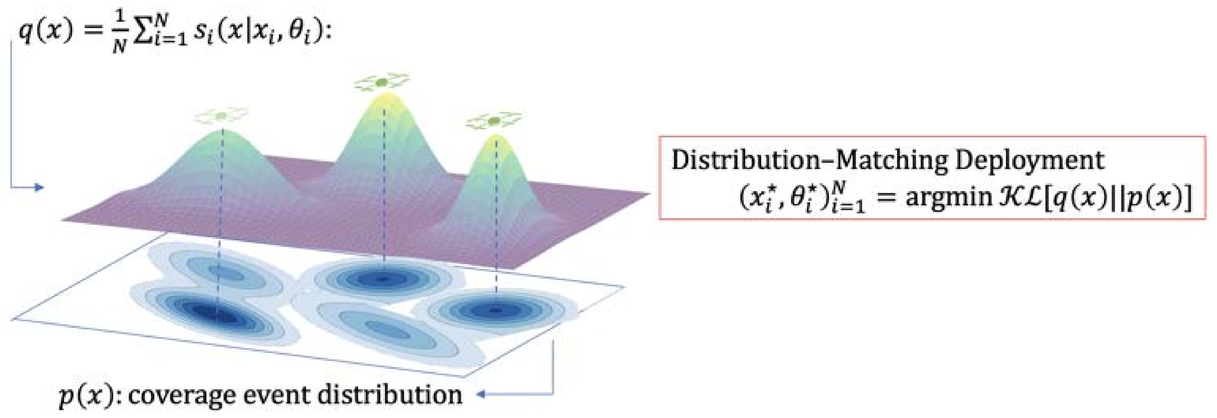
- Consider a density function $p(x): \mathbb{R}^2 \to \mathbb{R}_{\geq 0}$ that describes the spatial probability distribution of events of interest occurring within the domain $\mathcal{W}$.
- These events may include individuals or animals, sources of information, pollution incidents, forest fires, or specific locations indicative of areas at risk that require close monitoring.
- The QoS of each sensor is described by a spatial coverage distribution $s_i(x|x_i, \theta_i)$, where $(x_i, \theta_i) \in \mathcal{W} \times [0, 2\pi]$ is the pose (position and orientation) of sensor $i \in \mathcal{A} = \{1, \cdots, N\}$.



Objective statement

We seek a distribution-matching multisensor deployment methods:

- Achieve a final sensor configuration with a spatial service distribution similar to the spatial distribution of events induced by ground targets.
- In the statistical sense, the ultimate goal for optimal coverage is finding (x_i, θ_i) configuration for each sensor $i \in \mathcal{A}$ such that the collective distribution of $\frac{1}{N}\Sigma_{i\in\mathcal{A}} s_i(x|x_i, \theta_i)$ of the team is as similar as possible to the distribution of $p(x)$



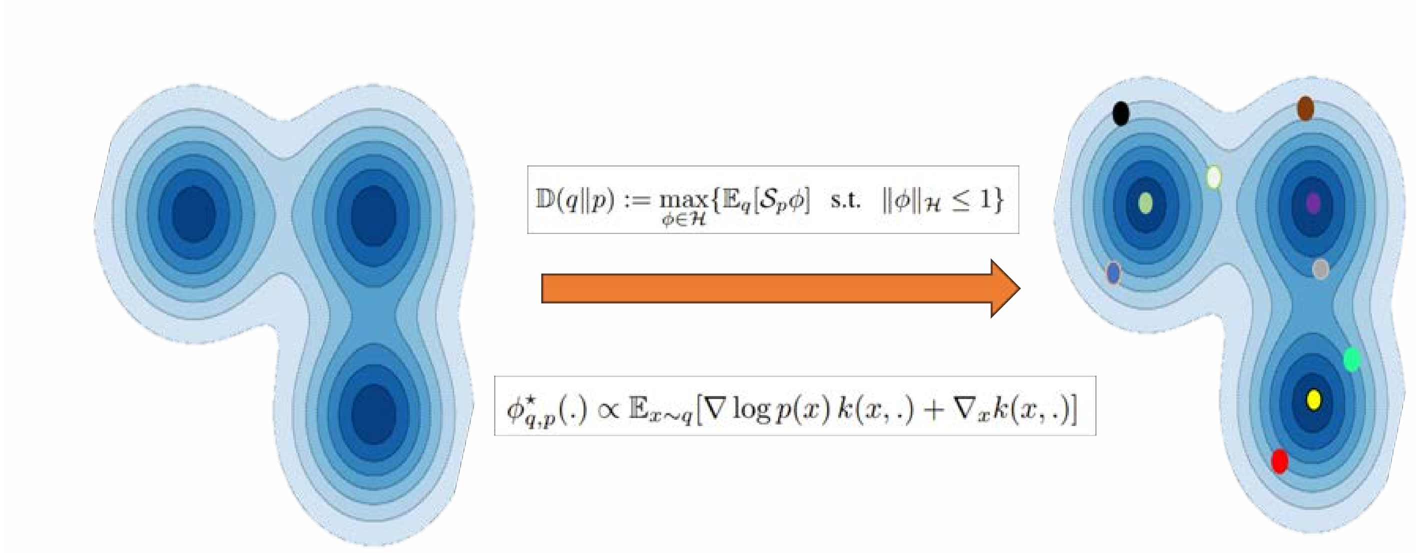
Solution approach

- The distribution-matching optimization problem is nonlinear and is not solvable easily.
- The literature resorts to solving the problem under various assumptions, such as an isotropic or uniform coverage distribution for sensors or seeking suboptimal solutions.
- This study aims to present a suboptimal solution that departs from these assumptions, enabling the inclusion of diverse sensors with varying spatial QoS distributions.
- We propose a two-step procedure,
  - First find 'appropriate' points of interest (PoIs) on $\mathcal{W}$; we use a novel approach based on variational inference, called Stein Variational Gradient Descent(SVGD), to determine suitable sensor deployment locations.
  - Cast the sensor deployment problem as a bipartite optimal linear assignment problem, where the assignment cost of each sensor to each PoI is the similarity measure between the service and target distribution.

The proposed framework

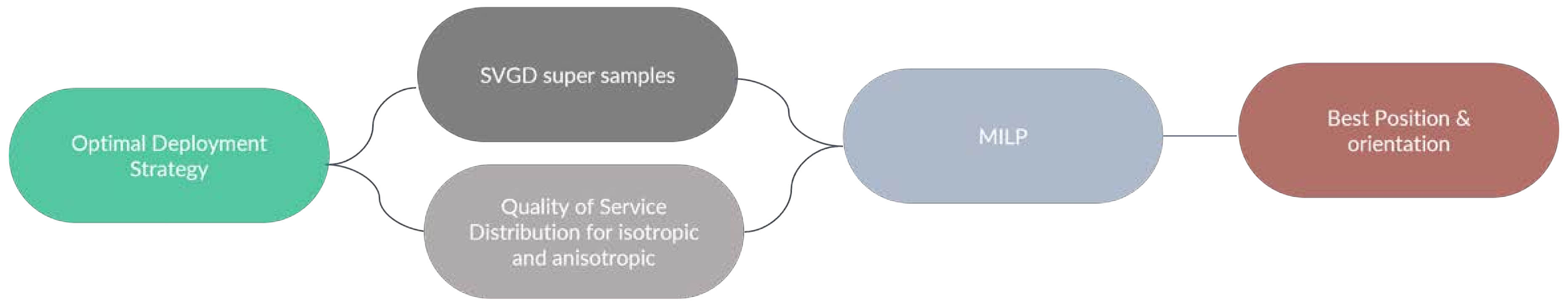
To deploy the robot team $\mathcal{A}$, we propose a two-step procedure described below, which allows the consideration of heterogeneous sensors with any spatial QoS distribution.

- The first step, we identify representative samples called points of interest (PoIs), from $\mathcal{W}$ based on the spatial distribution of the coverage event $p(x)$.

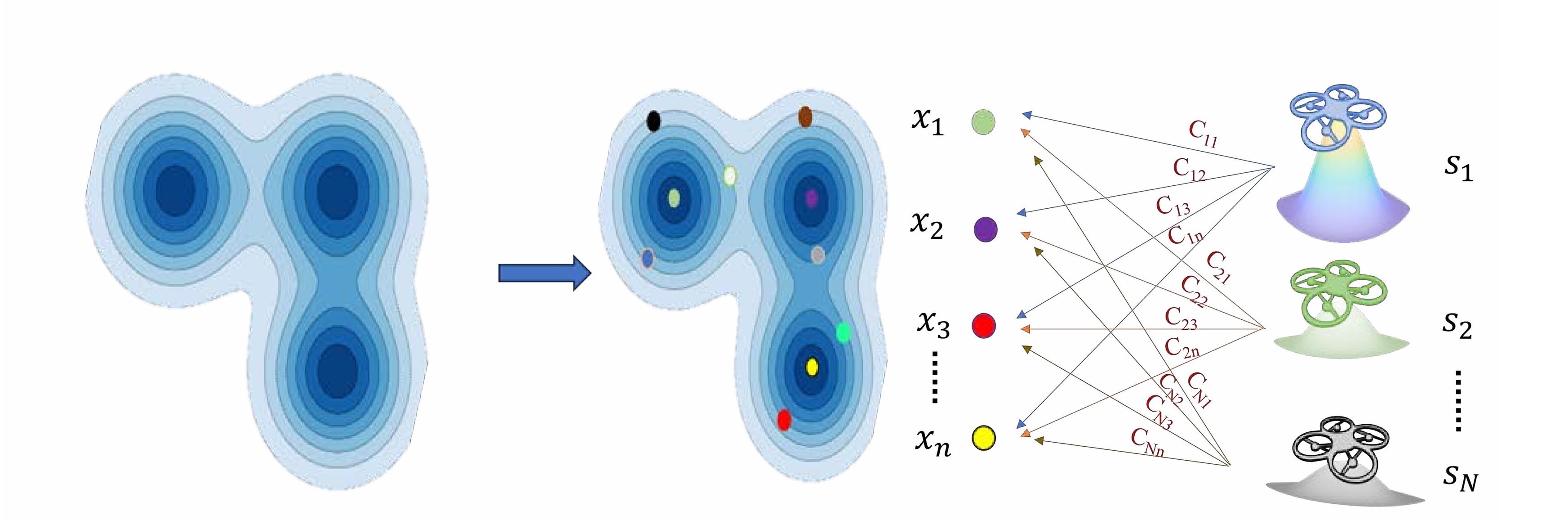


$$\mathbb{D}(q||p) := \max_{\phi\in\mathcal{H}}\{\mathbb{E}_q[\mathcal{S}_p\phi] \text{ s.t. } \|\phi\|_{\mathcal{H}} \leq 1\}$$

- Proposed pipeline with underlying MILP formulation

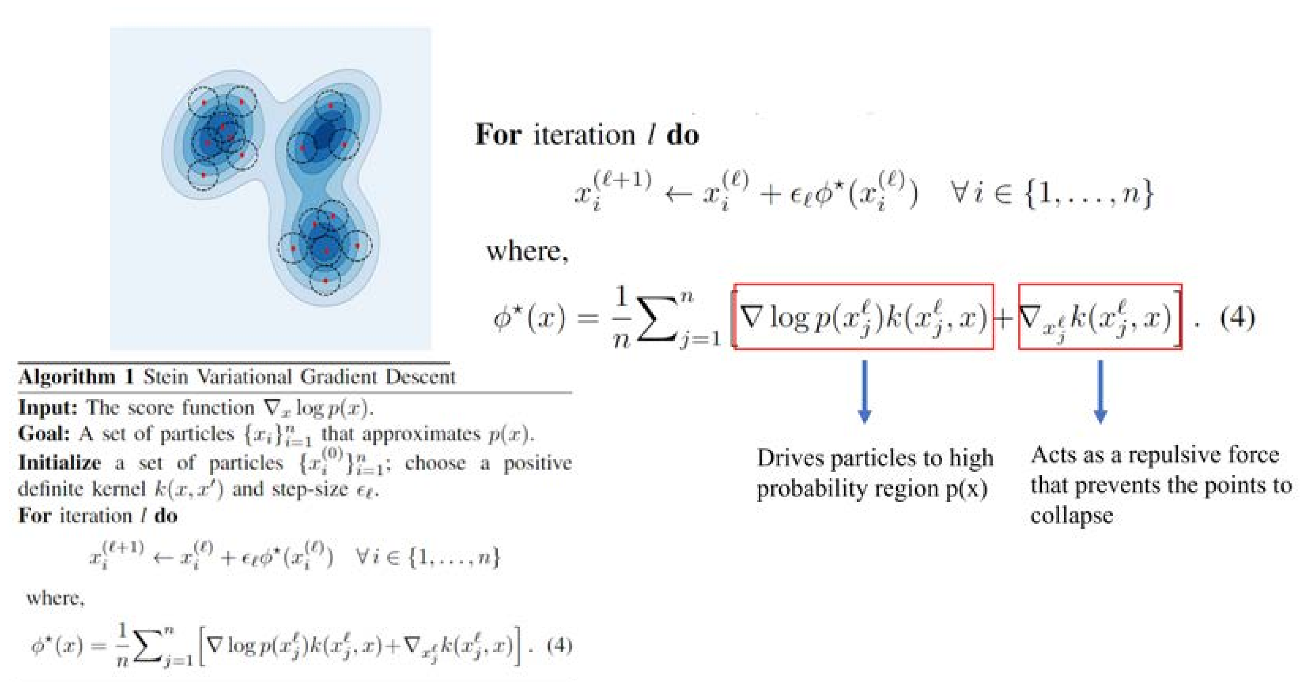


- Assignment Problem:The second stage is about assigning the sensors, or our UAVs, to these clusters. This is a critical decision that is influenced by capabilities of our different sensors onboard the UAVs.



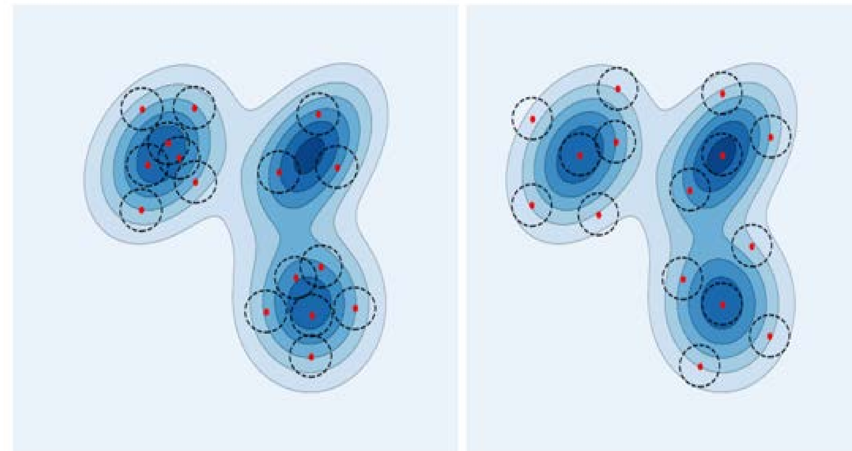
$$C^\star_{i,j} = \min_{\theta_i\in\Theta}\{\mathcal{KL}(s(x|x_j, \theta_i)||p(x)) \text{ for } x \in \mathcal{C}_i(x|x_j, \theta_i)\}$$

Methodology



Methodology contd.

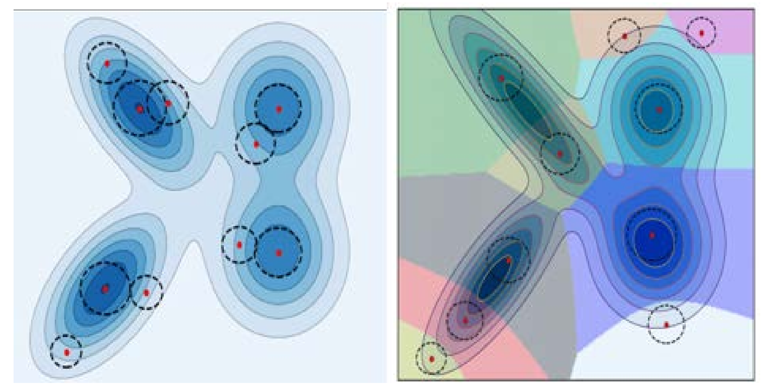
- We use SVGD to find the Points of Interest (PoIs), but it's not the immediate application of SVGD.
- The sampling method is oblivious to the coverage footprint of the sensor and can result in significant overlap in coverage provided by the sensor, as shown in the left figure.



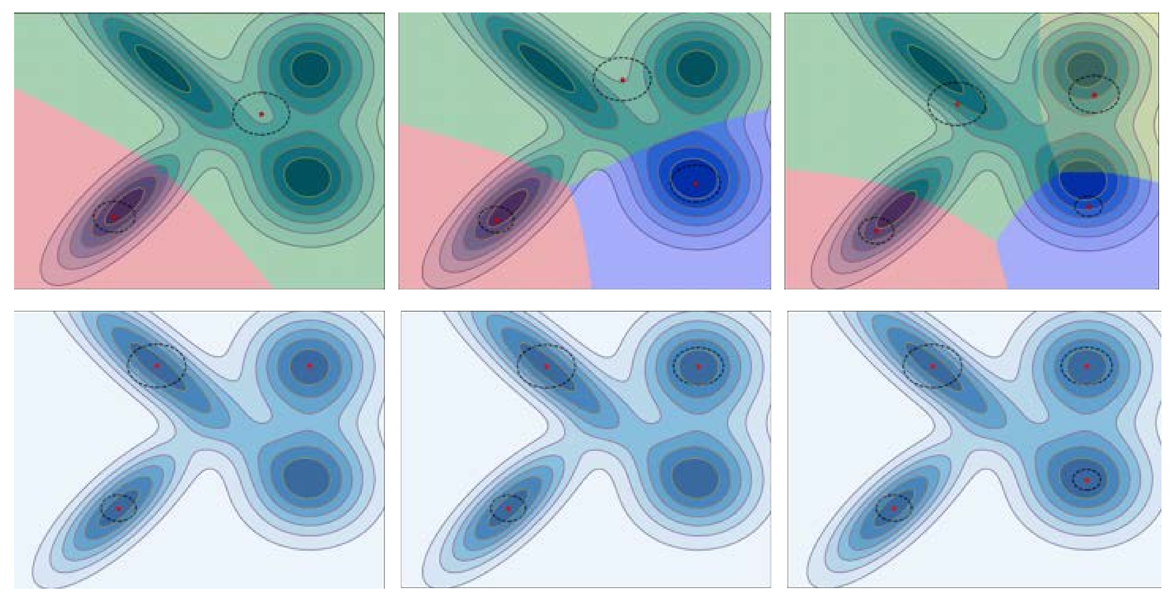
- We include a repulsive force using a kernel to spread the samples to avoid overlap for the deployed sensors.

Numerical examples

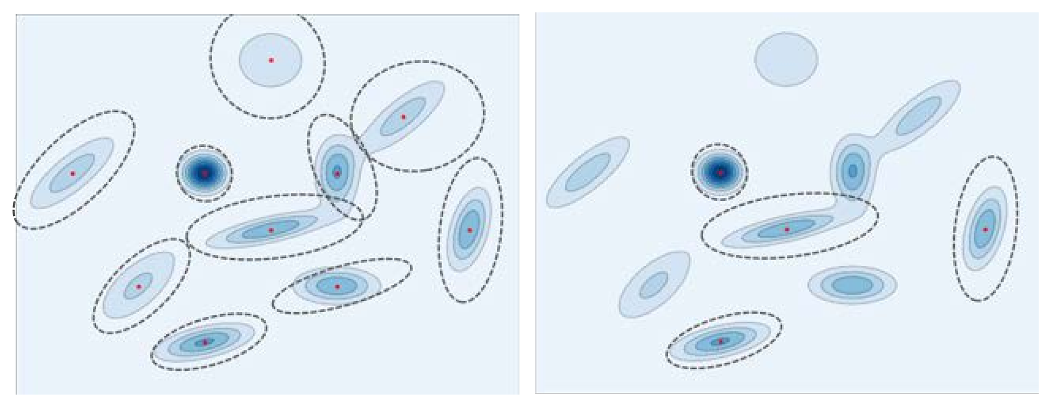
- To illustrate the collective behavior, we first consider a 50×50 square environment. The event distribution function $p: [0, 50]^2 \to \mathbb{R}_{>0}$ is given by a GMM
- We compare the Stein Coverage with Voronoi Sensor for Heterogeneous sensor



- We compare the Stein Coverage with Voronoi Sensor when number of sensors is very limited.



- Finally, we have Sensor deployment for anisotropic heterogeneous sensors.



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