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Optimal Search Strategies for Pollutant Source Localization

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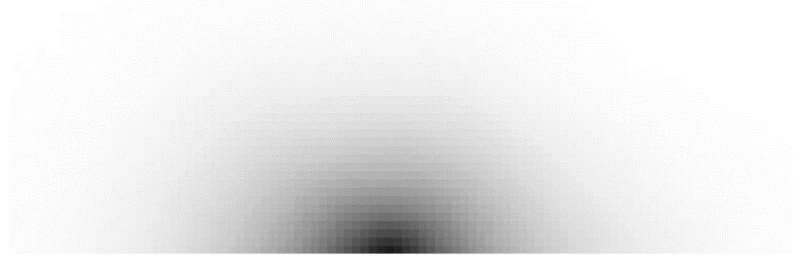
Abstract: This work is aimed at developing **optimal motion planning** of a single surface vehicle (robot/agent) equipped with an on-board pollutant sensor that will **maximize the sensor information** available for source seeking. The surface vehicle uses a nonlinear diffusion model of the pollutant source to estimate the intensity/level of the pollution at the current robot location. The rate of detection of particles depends on the relative distance between the surface robot and the source. First we use a probabilistic map of the source location built through the sensor information, for a source seeking dynamic motion planning based on an entropy reduction formulation where the Fisher information matrix (FIM) is used for **entropy reduction or information gain**. We derive the FIM for the set-up and investigate optimal trajectories. Next, we present an online nonlinear Monte Carlo algorithm that uses the obtained sensor information about the pollutant at different vehicle locations to update a **probabilistic uncertainty map of pollutant source location**. As the mission unfolds the agent motion is updated by considering a moving-horizon interval of decision, which will allow for the **inclusion of new information available for optimal motion planning**. The proposed motion planning approach is extended to take into account external disturbances, and it is able to minimize the uncertainty in the pollutant source.

Main Question:

"Given a temporal window and the initial location of the searcher, what are the best sequences of actions for the searcher to maximize the information about the source location?"



Expected rate of detected particles for a pollution source[1].

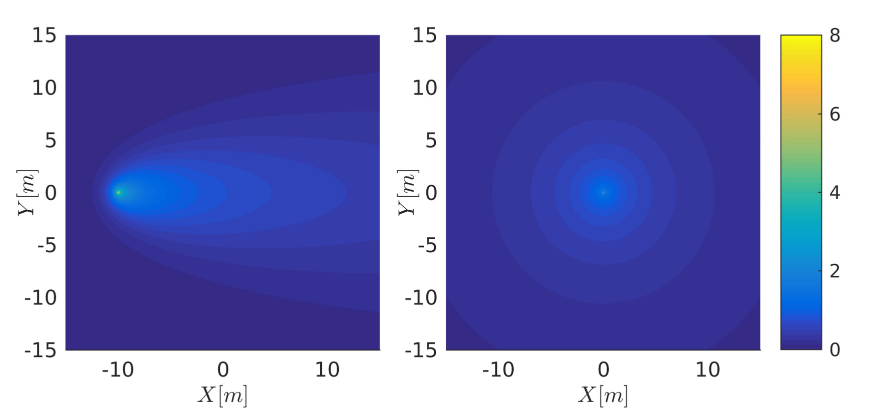
Single snapshot of detected particles for a pollution source[1].

Mathematical Model of the Pollution Diffusion Process

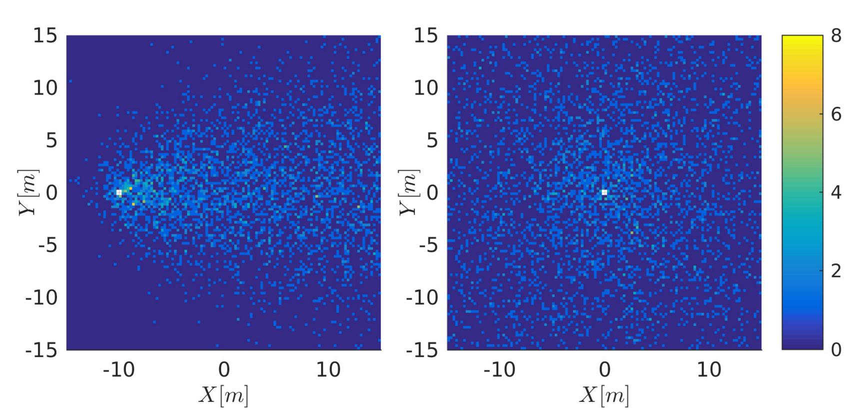
Rate of particle emission: $$R(\boldsymbol{r}|\boldsymbol{s}) = \frac{Q_0}{\ln(\lambda/a)} \exp\left[\frac{\boldsymbol{v}_c'(\boldsymbol{r}-\boldsymbol{s})}{2D}\right] K_0\left(\frac{\|\boldsymbol{r}-\boldsymbol{s}\|}{\lambda}\right)$$

$$\lambda := \sqrt{\left(1+\frac{\|\boldsymbol{v}_c\|^2\tau}{4D}\right)^{-1} D\tau}.$$

$\boldsymbol{v}_c$: Velocity of current
$\boldsymbol{r}$: Robot/Searcher location
$\boldsymbol{s}$: Source location
Q_0: Source emission rate
D: Diffusity parameter
τ: Lifetime of particles
a: Sensor size



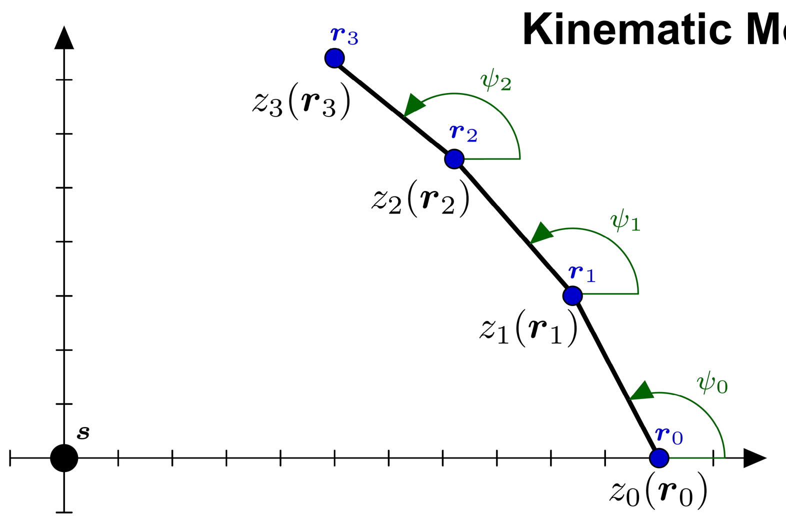
Expected rate of detected particles for a simulated pollution source: (left) with current $\boldsymbol{v}_c$=[1,0]', (right) without current.



Snapshot of detected particles for a simulated pollution source: (left) with current $\boldsymbol{v}_c$=[1,0]', (right) without current.

Stochastic Measurements are modelled with Poisson distribution.

Kinematic Model of the Searcher



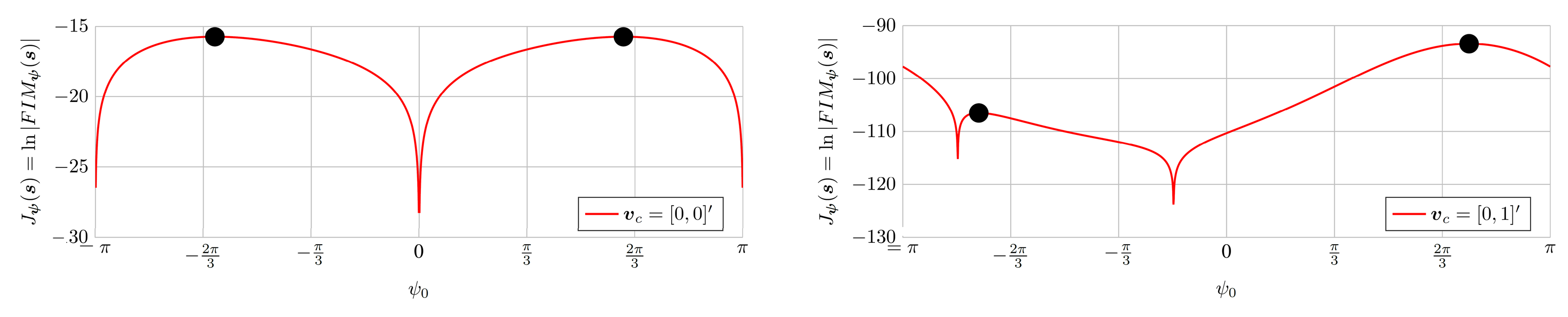
$$\boldsymbol{r}_{i+1} = \boldsymbol{r}_i + \left(v\begin{bmatrix}\cos\psi_i\\ \sin\psi_i\end{bmatrix} + \boldsymbol{v}_c\right)(t_{i+1}-t_i),$$
$$i \in \{0,1,..,m-2\}$$

Formulating the Best Action in a Constrained Optimization Problem

$$\boldsymbol{\psi}^* = \underset{\substack{\text{subject to:}\\ \text{searcher kinematics,}\\ \boldsymbol{r}_0=[x_0,y_0]'.}}{\arg\max} \ln|FIM_{\boldsymbol{\psi}}(\boldsymbol{s})|$$

FIM (Fisher Information Matrix) is directly related to minimum covariance achievable with any unbiased estimator.

Sample of Cost Function

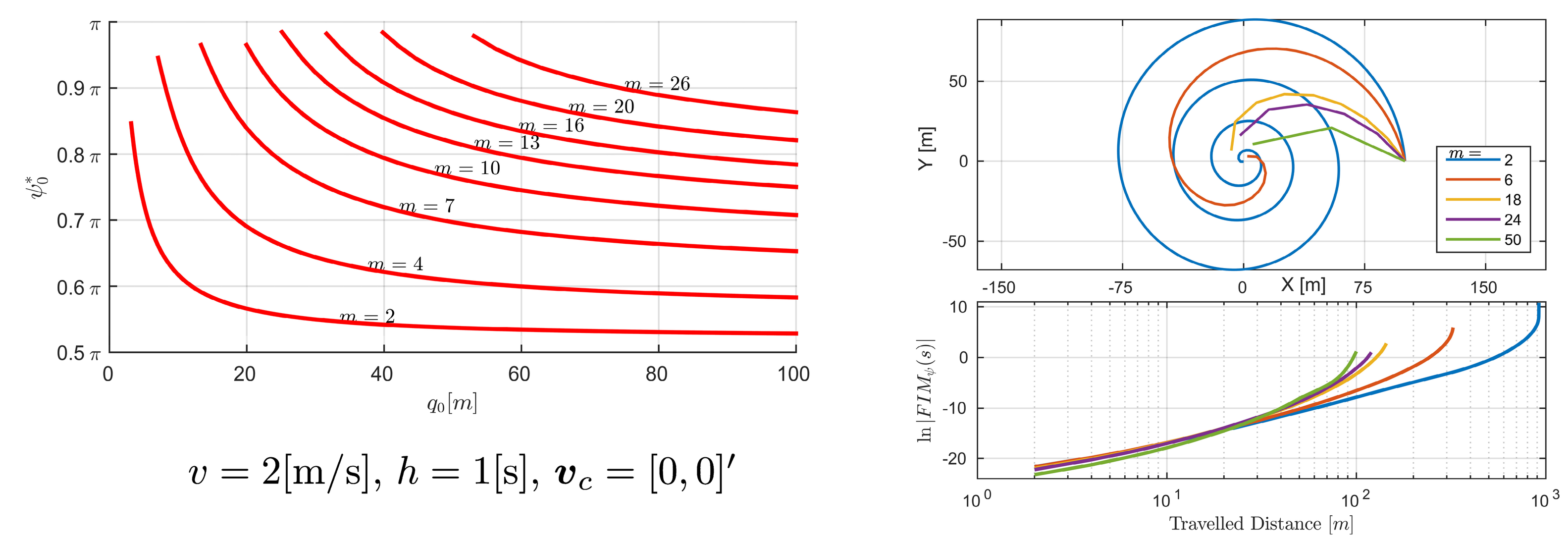


$v = 2[\text{m/s}], \quad h = 1[\text{s}], \quad (\boldsymbol{r}_0 - \boldsymbol{s}_0) = [100, 0]'[\text{m}], \quad m = 5$ samples

Numerical Results

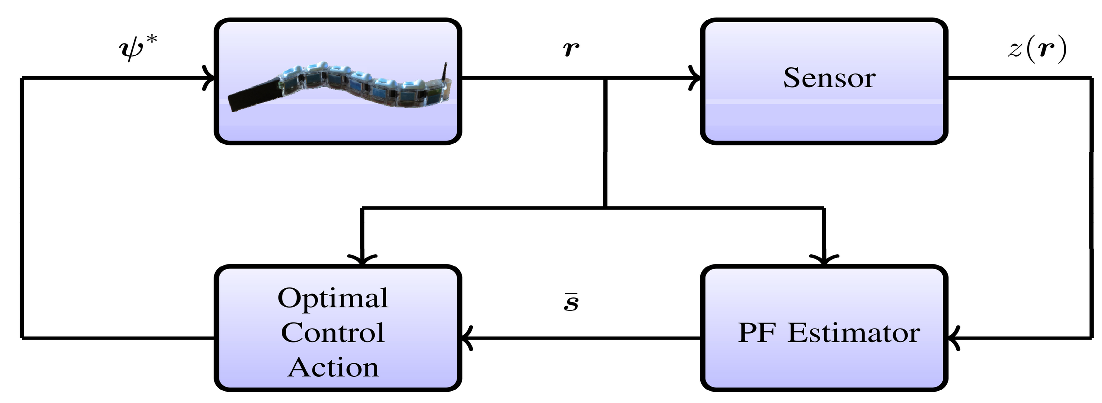
Solution without current

Sequential action update

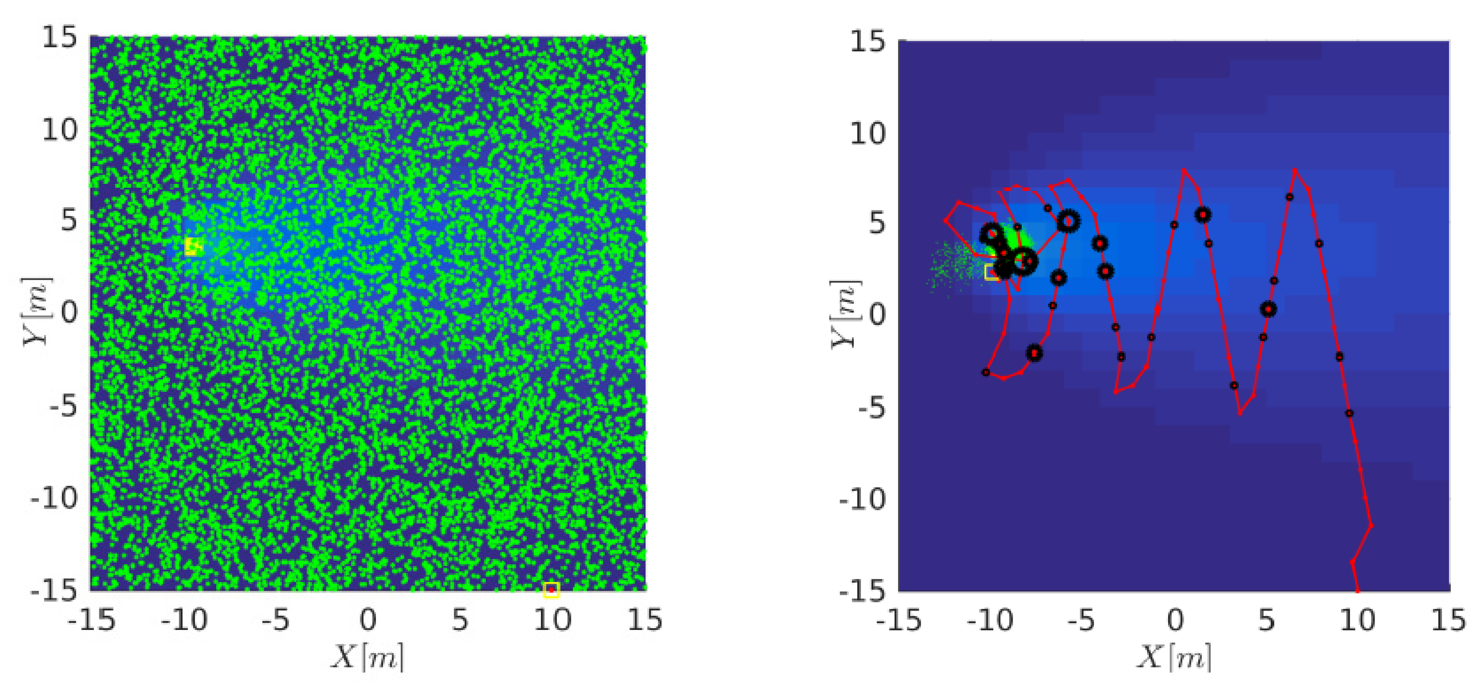


$v = 2[\text{m/s}],\ h = 1[\text{s}],\ \boldsymbol{v}_c = [0,0]'$

Overall Approach



Simulation Results



Simulation results of 1000 runs with random initial conditions of the proposed source seeking algorithm showed 97.6% success rate in localizing the source within a ball with radius of 5[m], with an average localization error of [0.47,0.5][m] and standard deviation of [1.05,1.12][m].

Conclusions

Motivated by environmental applications, in this work we proposed a optimal motion planning algorithm for an agent carrying a pollutant sensor for source seeking, where the emphasize is to maximize pollutant related measurement information available for the source localization. We used the Fisher information matrix along the trajectory of the searcher, computed on a moving-horizon interval of decision, which allows incorporating new information available for optimal motion planning. Future work includes the implementation of the proposed method on the Envirobot to conduct tests in real-world environment.

References:
[1] B. Ristic, A. Skvortsov, and A. Gunatilaka, "A study of cognitive strategies for an autonomous search," Information Fusion, vol. 28, pp. 1–9, March 2016.