Information-driven Sensor Path Planning for Mobile Monitoring of Source Emissions

IGERT: Wireless Intelligent Sensor Networks (WISeNet)

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Introduction

Modern Sensor Systems – multiple sensors installed on mobile platforms

-- Environmental monitoring and prediction
-- Landmine detection and identification
-- Monitoring of urban environments (disaster relief, security, ..)

Traditional paradigm: sensor information is used as feedback to the vehicle in order to support the vehicle navigation

New paradigm: the sensor motion is planned in view of the expected measurement process, in order to support the sensing objectives

IGERT WISeNet Research Area: Geometric Sensor Path Planning

-- Address couplings between sensor measurements and sensor dynamics
-- Plan sensor motion to optimize sensing objectives (e.g., sensor coverage, detection, classification, tracking..)
Sensor Model

• The sensor is characterized by a field-of-view (FOV), represented by a discrete geometric object, and by a joint probability density or mass function (PDF or PMF):

\[ p(z_k, \hat{z}_k, \lambda_k) = p(z_k | \hat{z}_k, \lambda_k) p(\hat{z}_k | \lambda_k) p(\lambda_k) \]

Probabilistic measurement model

• The vehicle is characterized by a discrete geometric object and a dynamic equation.

\[ \dot{x}(t) = f(x(t), u(t), w(t), t) \]

Vehicle equation of motion

Examples:

Duality of Sensor and Robot Path Planning

• In classical robot path or motion planning, a discrete geometric object \( A \) (the robot) must avoid intersections (collisions) with multiple objects (obstacles) \( B_1, B_2, \ldots \)

• In sensor path planning, a discrete geometric object \( S \) (the sensor’s FOV) must intersect (measure) multiple objects (targets) \( T_1, T_2, \ldots \)

Robot path planning:

\[ A \cap B = \emptyset \]

Sensor path planning:

\[ S \cap T \neq \emptyset \]

Measurements

Kinodynamic model:

\[ \dot{x}(t) = f(x(t), u(t), w(t), t) \]
Sensing Performance Function

The sensor classification performance, typically, is not available in closed-form.

**Target Information Value or Information Gain:**

**Expected Entropy Reduction (EER) [Cai, Ferrari 2007]**

\[
\Delta H(\xi; z \mid \lambda) = H(\xi \mid \lambda) - \sum_{z \in Z} [H(\xi \mid \lambda, z) p(z \mid \lambda)]
\]

Advantage: additive, symmetric, non-myopic, ...

\[\mathcal{S} \cap \mathcal{T} \neq 0 \implies \text{Measurements, } z\]

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Information-driven Sensor Path Planning

**Ground mobile sensors for fixed target classification**
- Cell decomposition
- Information potential function
- Probabilistic information roadmap method

**Ground mobile sensors for target tracking and surveillance**
- Particle filter-based method
- Disjunctive programming

**Underwater mobile sensors for cooperative target tracking**
- Optimal control

**Air mobile sensor deployed for fixed target detection and classification**
- Approximate dynamic programming (ADP)

**Air and ground sensors for target detection, tracking, localization, and pursuit**
- Cell decomposition, probabilistic roadmap method, and particle filter-based method

**Computer games (CLUE, Ms. Pacman, and Marco Polo)**
- Cell decomposition
- Influence diagrams
- Reinforcement learning, and ADP
Application Example

**Indoor Monitoring and Surveillance**

- **Single agent**
  - Mobile, autonomous
  - Wireless communication
  - Sensors

- **Multiple agents**

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**Treasure Hunt Problem**

For a given layout $\mathcal{W} \subset \mathbb{R}^3$ with $r$ targets and $n$ obstacles and a given joint probability mass function $p(z, \xi, \lambda)$, find the obstacle-free path that minimizes the distance traveled by a robot $\mathcal{A}$ between two configurations $q_0$ and $q_f$, and maximizes the total information value, for a sensor with field-of-view $S$, installed on $\mathcal{A}$.

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Sensors must also avoid collisions with other moving sensors, based on knowledge of their instantaneous configuration.

GMAP Remote Emissions Measurement

**GMAP-REM Concept:**
Detect and quantify emissions of a specific species from a large area or distributed source via mobile sampling and plume dispersion diagnostics.

**Example projects:**
1. Detection of methane emissions from distributed oil and gas production wells using a Direct Assessment (DA) approach
2. Quantification of methane emissions from landfills using an acetylene tracer via the Tracer Correlation (TC) approach
Large area source measurements

GMAP REM TC

- Release tracer gas from strategic locations within the facility
- Use mobile sampling platform to map target source and tracer plumes
- Calculate dilution ratio based on known tracer rate
- EPA method development research
  Waste Management CRADA #372-A-08, EP-C-07-15 WA 2-10


Oil and gas production: distributed sources

> 25,000 active wells

Denver CO

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WISeNet Trainees contribute to the development of intelligent sensor systems that process, store, and learn from data so as to improve their ability to gather information over time. By participating in WISeNet laboratory and field experiments, trainees also contribute first hand to unprecedented observations of environmental and ecological processes, and more effective and reliable use of sensors for defense and national security.

WISeNet is currently accepting applications
Trainees must be enrolled in a Ph.D. program in one of the participating departments at Duke University. Duke students who are interested in applying should request application material from the WISeNet Program Director, Prof. Silvia Ferrari (Email: webmaster@lisc.pratt.duke.edu). Non-Duke students interested in WISeNet are strongly encouraged to apply to the graduate program of interest through Duke Graduate School (http://gradschool.duke.edu/admissions/).

For more information visit: http://wisenet.pratt.duke.edu/
References


References


PDFs AVAILABLE UPON REQUEST: sferrari@duke.edu