Filtering and estimation for localization of underwater plumes using AUVs

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FeedNetback
co-design for networked control systems

Motivation

WP8 “Application to underwater exploration by multi-agent systems”

Aim: localize and visit origin of underwater source flow with AUVs

AUV: **A**utonomous **U**nderwater **V**ehicles

source flow: named here as plume

Why should we do this?

- Exploration/monitoring of ocean environment
- Underwater plumes hard to locate
- Moorings/single ships $\rightarrow$ too static and expensive
- A fleet of AUVs $\rightarrow$ autonomous and faster
- Visiting $\rightarrow$ refining measurements while moving, more robust

Problem Statement

Source seeking or *Gradient search* problem

- Plume a scalar field with concentration gradient
- Very complex/unknown shapes (e.g. multi sources, topography etc.)
- Gradient knowledge based on local measuremtents
- Need for communication betweem AUVs
- Strong constraints (limited com. range, water currents, etc.)
- Dual control problem (movements vs. measurments)

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No knowledge of plume → non-optimal movements

Outline

1. Modelling
   - General plume modelling
   - Actual model
2. Estimation Algorithms
   - Recursive Estimation
   - Batch Estimation
3. Current and Future Work

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General Plume Modelling

Modelling a realistic underwater plume

Computational fluid dynamics solving Navier-Stokes equations:

- Traditional grid based methods like FVM and FEM
- Spectral methods
- Smoothed-particel hydrodynamics (SPH)
- Boundeary Elements (BEM)

Problems that arise with these methods:

- Computational very expensive
- Knowledge about boundary or initial conditions required.
- Number of states, strong identifiability problems.
- Disturbance by sea almost impossible to include.

General Plume Modelling

What kind of model is needed?

- Less parameters as possible
- Parameters must be identifiable
- Determine accuratly unique maximum
- Minimize number of required measurments/sensors

Some assumption are made to simplify things:

- Consider only main physical laws, convection and diffusion
- Plume in steady state, mission time shorter than diffusion time
- Single punctual source to ensure unique maximum

Actual Model

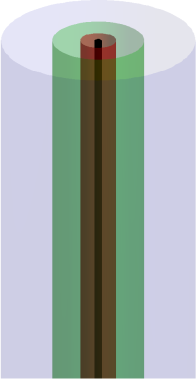
Simplified model from connect project used for FeedNetback WP8

equation of concentration field:

$$c_{gf}(x, y, z) = e^{-((x-xs)^2+(y-ys)^2))}$$

Take into consideration:

- Concentric diffusion in 2D plane
  (x_s, y_s): source location



Actual Model

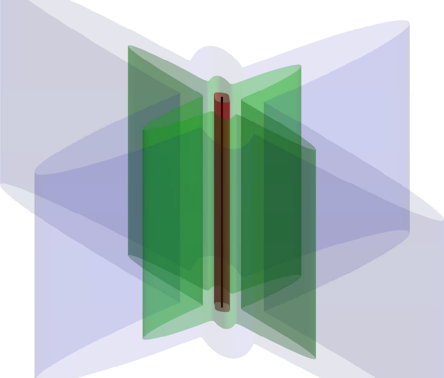
Simplified model from connect project used for FeedNetback WP8

equation of concentration field:

$$c_{gf}(x, y, z) = \sum_i e^{-(a_i(x-x_s)^2 + b_i(x-x_s)(y-y_s) + c_i(y-y_s)^2)}$$

Take into consideration:

- Concentric diffusion in 2D plane
  (x_s, y_s): source location
- Distortion by currents
  a, b, c: ellipse parameters



Actual Model

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equation of concentration field:

$$c_{gf}(x,y,z) = \sum_i d_{c,i}(z) \cdot e^{-(a_i(x-x_s)^2 + b_i(x-x_s)(y-y_s) + c_i(y-y_s)^2)}$$

Take into consideration:

- Concentric diffusion in 2D plane
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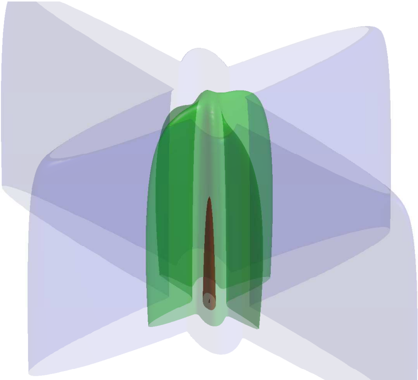
- Diffusion with depth



Actual Model

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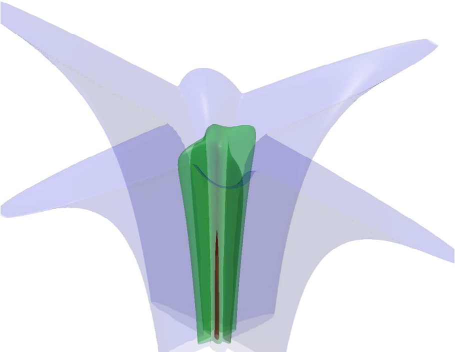
equation of concentration field:

$$c_{gf}(x,y,z) = \sum_i d_{c,i}(z) \cdot e^{-m(z)(a_i(x-x_s)^2 + b_i(x-x_s)(y-y_s) + c_i(y-y_s)^2)}$$

Take into consideration:

- Concentric diffusion in 2D plane
  (x_s, y_s): source location
- Distortion by currents
  a, b, c: ellipse parameters
- Diffusion with depth
- Convection effects



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Recursive Estimation

Demonstration toy example

Field of a single elliptic diffusion in 2D plane:

$$c_{gf}(\mathbf{x}) = e^{-((\mathbf{x}-\mathbf{x_s})^T M(\mathbf{x}-\mathbf{x_s}))}, \quad \text{where} \quad M = \begin{bmatrix} a & \frac{b}{2} \\ \frac{b}{2} & c \end{bmatrix} \tag{1}$$

Note: The parameter to be estimated are $\mathbf{p} = \begin{pmatrix} a & b & c & x_s & y_s \end{pmatrix}^T$
Any weigth multiplying the paramters a, b, c is neglected

Non-linear Recursive Least Squares

$$\hat{p}(k) = \hat{p}(k-1) + K(k)\left[z(k) - h(\hat{p}_{k-1})\right]$$

Note: The measurement noise is assumed Gaussian with sdev of 1%.

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Recursive Estimation

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Video

Recursive Estimation

Problems which occur:

- identifiability of parameters (e.g. weights, which multiply with parameters)
- estimated paramters not restricted to realistic parameters
  $\rightarrow$ here pos. def. of matrix M
  $\rightarrow ac - \frac{b}{2}^2 > 0$
- no guarantee so far to ensure convergence
  $\rightarrow$ depending on obtained information (initial position, fleet path, etc.)

Batch Estimation

Rewriting the elliptic equation as linear regressor form

By rewriting the exponent of (1) we obtain:

$$-\begin{bmatrix} x - x_s \\ y - y_s \end{bmatrix}^T \begin{bmatrix} m_1 & m_2 \\ m_2 & m_3 \end{bmatrix} \begin{bmatrix} x - x_s \\ y - y_s \end{bmatrix}) = -\begin{bmatrix} x \\ y \\ xy \\ x^2 \\ y^2 \\ 1 \end{bmatrix}^T \begin{bmatrix} -2(m_1 x_s + m_2 y_s) \\ -2(m_2 x_s + m_3 y_s) \\ 2m_2 \\ m_1 \\ m_3 \\ m_1 x_s^2 + 2m_2 x_s y_s + m_3 y_s^2 \end{bmatrix}$$

and finally:

$$c_{gf}(\mathbf{x}) = e^{-\Phi^T \Theta}$$

Batch estimation

- Assume perfect knowledge of AUV position, i.e. of Φ
- Minimize $|| \log y - (-\Phi^T \Theta)||$ $\rightarrow$ obtain the estimates for $\hat{\Theta}$.

Obtaining the source loaction

What follows is a matrix inversion of

$$\begin{bmatrix} \hat{\Theta}_1 \\ \hat{\Theta}_2 \end{bmatrix}^T = -2 \begin{bmatrix} m_1 x_s + m_2 y_s \\ m_2 x_s + m_3 y_s \end{bmatrix} = -2M \begin{bmatrix} x_s \\ y_s \end{bmatrix}$$

requiring again posing pos. def. for the Matrix M.

Note: the structure here is nice to obtain values for m_1, m_2, m_3

Batch Estimation

Some issues:

- Requires a lot of memory, computational power
- Collecting a lot of measurments vs. source seeking

Collecting only a certain number of measurements:

- Certificate for convergence
- Determine best exitation

Outline

Current and Future Work

- Sophisticated modelling
  - Model order reduction,
  - Principal Component Analysis
  - Only care about source location
- Recursive Online Methods
  - Constrained N-RLS
  - Guarentee certificate for convergence
- Different estimation algorithms
- Optimizing fleet trajectories/ information exitation
- Distribute estimation to AUVs

Thank You