Experiment Design for Identification of Marine Vessels

Fredrik Ljungberg and Martin Enqvist

Introduction

As marine vessels are becoming increasingly automated, having access to accurate simulation models is turning into a necessity. This holds both for facilitation of development and for achieving satisfactory model-based control. If the models are obtained through system identification, the choice of input signal during the data acquisition is a significant factor for their accuracy. Additionally, performing experiments for ships is expensive and it is important that the data is collected as efficiently as possible.

Problem formulation

- Most ships are unique (new model needed for each).
- Short commission times (few hours).
- Current solution: standard ship maneuvers.

Goal: Find $\boldsymbol{u}(k)$ which maximizes a scalar criterion of

$$\boldsymbol{G}(N) \triangleq \frac{1}{2}\frac{\partial^2}{\partial\boldsymbol{\theta}^2}\boldsymbol{V}_N^{IV}(\boldsymbol{\theta}) = \left[\frac{1}{N}\sum_{k=1}^{N}\boldsymbol{\Phi}(k)\mathbf{Z}^T(k)\right]\left[\frac{1}{N}\sum_{k=1}^{N}\boldsymbol{\Phi}(k)\mathbf{Z}^T(k)\right]^T.$$

Challenge: Non-convex problem (requires a good initial guess).

Suggested approach

Part 1

1. Choose candidate signals $\boldsymbol{u}_1(k), \dots, \boldsymbol{u}_Q(k)$ (standard maneuvers).
2. Estimate $\bar{\boldsymbol{G}}_1, \dots, \bar{\boldsymbol{G}}_Q$ (information matrices) based on simulation experiments with a nominal model.
3. Assume that $\boldsymbol{u}_1(k), \dots, \boldsymbol{u}_Q(k)$ are to be applied in sequence and solve an optimization problem to find the information-optimal mix, *i.e.*, for how long they should be applied w.r.t. each other.

Part 2

Solve a lattice-based motion-planning problem

$$\begin{aligned}
\underset{\{m_k\}_{k=0}^{M-1}, M}{\text{minimize}} \quad & \sum_{k=0}^{M-1} J(m_k) \\
\text{s.t.} \quad & \mathbf{x}_0 = \mathbf{x}_s, \quad \mathbf{x}_M = \mathbf{x}_f, \\
& \mathbf{x}_{k+1} = f(\mathbf{x}_k, m_k), \\
& m_k^p \in \left\{ \underbrace{m^1, \cdots, m^Q}_{\text{informative}}, \underbrace{m^{Q+1}, \cdots, m^{Q+B}}_{\text{basic}} \right\}, \\
& c(m_k, \mathbf{x}_k) \in \boldsymbol{\mathcal{X}}_{\text{free}}.
\end{aligned}$$

- The signals $\boldsymbol{u}_1(k), \dots, \boldsymbol{u}_Q(k)$ are used to form motion primitives.
- The ratios found in Part 1 are respected by augmenting the state vector with motion-primitive counters.

Experimental verification 1

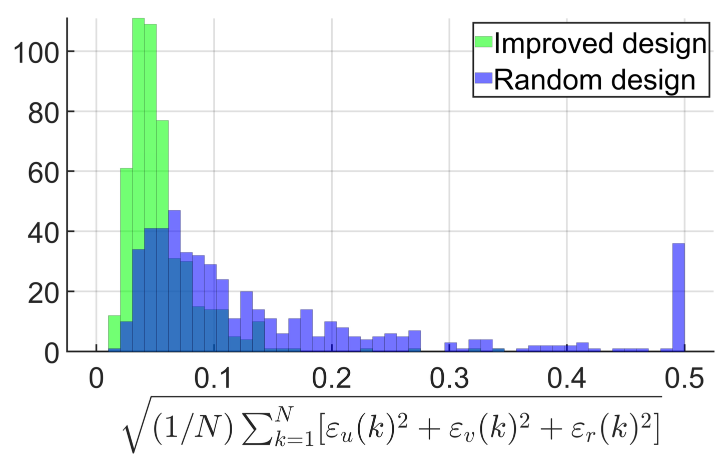
Goal: Find an informative mix of sub-experiments.

- Nonlinear 3-DOF (surge, sway, yaw rate) maneuvering model:

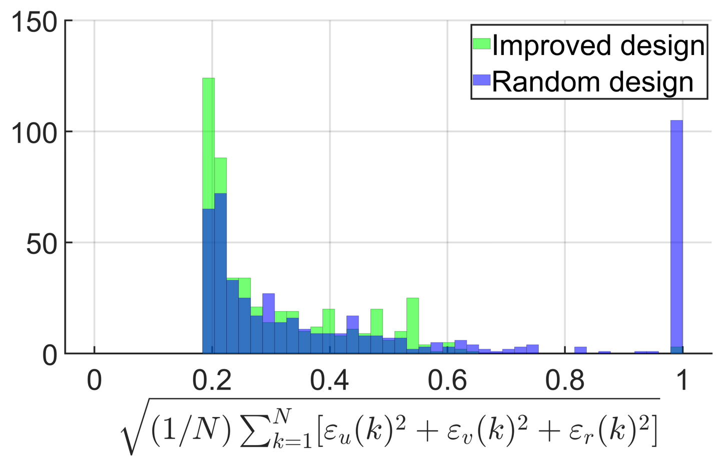
$$\begin{aligned}
u(k+1) &= u(k) + \mathcal{X}_u u_r(k) + \mathcal{X}_{u|u|} u_r(k)\left|u_r(k)\right| + \mathcal{X}_{vr} v_r(k) r(k) + \mathcal{X}_\tau \tau_x(k), \\
v(k+1) &= v(k) + \mathcal{Y}_v v_r(k) + \mathcal{Y}_{ur} u_r(k) r(k) + \mathcal{Y}_\tau \tau_y(k), \\
r(k+1) &= r(k) + \mathcal{N}_r r(k) + \mathcal{N}_{uv} u_r(k) v_r(k) + \mathcal{N}_\tau \tau_\psi(k), \\
\boldsymbol{y}(k) &= \left[u(k)\ v(k)\ r(k)\right]^T + \boldsymbol{e}(k).
\end{aligned}$$

- 11 different candidate input signals $\boldsymbol{\tau}_1(k), \dots, \boldsymbol{\tau}_{11}(k)$ (corresponding to accelerations, zig-zag maneuvers, spiral tests, etc.).
- Data collected from 55 sub-experiments (5 of each type).
- *Improved design*: Pick 6 sub-experiments that work well together.
- *Random design*: Pick 6 sub-experiments at random.
- Evaluation by comparing simulation accuracy of resulting models.

Simulated data



Model-ship data

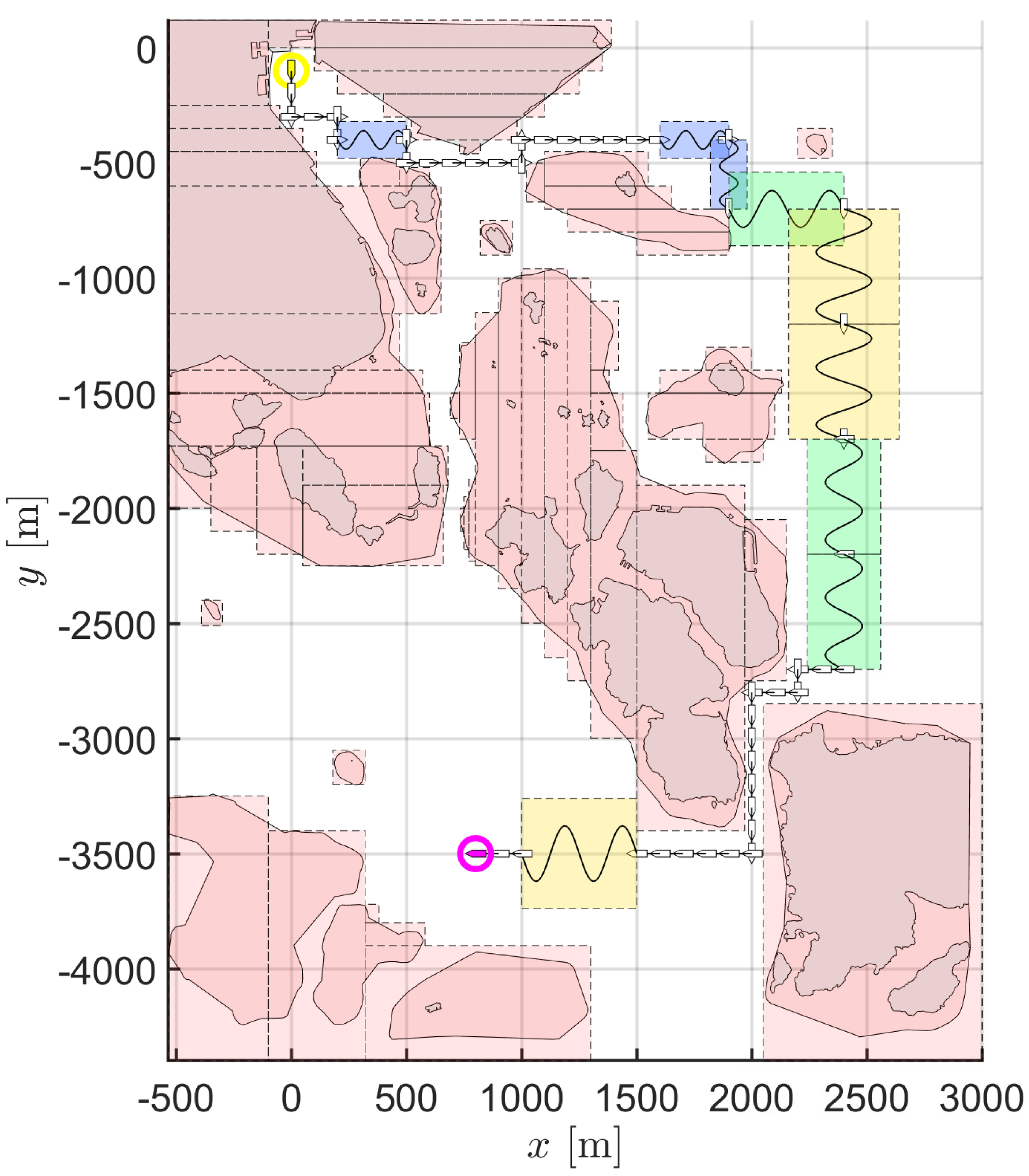


Experimental verification 2

Goal: Find a spatially feasible experiment trajectory from start (yellow) to goal (purple), where 3 informative maneuvers are used 3 times each and basic driving is performed as sparsely as possible.

- Each motion primitive is associated with a bounding box.
- Design w.r.t. a sea-depth map over the port of Helsinki.

Simulated data



Conclusion

A dictionary-based approach for experiment design for marine vessels has been explored and shows promising results on both simulated and real data. This method can be combined with a motion-planning framework to obtain a trajectory that, in addition to being informative, is spatially feasible, which is an often neglected property when planning a data-collection experiment.

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