Centralized State Estimation of Distributed Maritime Autonomous Surface Oceanographers

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Agenda

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- Little to no research are currently devoted to maritime autonomous crafts.

Introduction

Purpose

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- During the 2012 Fukushima accident in Japan, no measurements of the spread of radioactivity was available in the coastal zones, thus relying only on estimates.

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Introduction
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- During the 2012 Fukushima accident in Japan, no measurements of the spread of radioactivity was available in the coastal zones, thus relying only on estimates.
- The coastal area around Greenland has no up-to-date baymethric maps available, and with the growing interest in Greenland (both industrially and commercially) this poses a threat to the ships going in and out of the fjords.

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Empty frame

Development
AAUSHIP.01

- The ship is designed as a non-planing deplacement craft (eg. like freight ships).

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- Vaccumformed by DD-plast in Randers and assembled in the machine shop at Aalborg University.

Development
AAUSHIP.01 Hull

Pictures of the ship.

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AAUSHIP.01 Hull

Pictures of the ship.

Development
Hardware

- Fitted with 2 x 1200W engines (totally producing around 3 HP at full thrust).
- Fitted with 6 x 3200mAh batteries (results in a mission time of around 5 hours).
- 2 counter rotating 60mm propellers.
- Inertial Measurement Unit.
- Global Positioning System.
- A 20mW 19.2 kbps radio link @470 MHz
- Arduino Mega with a custom made shield board mounted.
- Retrofitted with a hydrofoil to reduce the wake and pitch of the ship.

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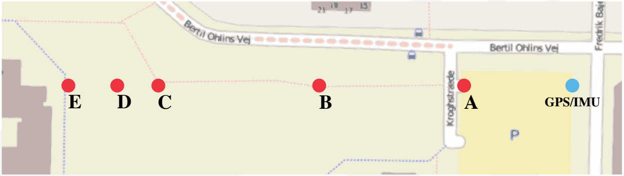
Development
Protocol

The designed protocol is given as:

Development
Distributed Control

As the protocol takes care of packet verification, the channel can be estimated by a bernoulli variable, with outcomes of a received package either a succes or a failure.



The measurements make for the following distribution of the GPS with a distance of 189 metres:

$$\lambda_{\text{gps,E}} = \begin{cases} 0.8643 & \text{for } \lambda = 1 \\ 0.1357 & \text{for } \lambda = 0 \end{cases} \quad (1)$$

And for the IMU also at 189 metres.

$$\lambda_{\text{imu,E}} = \begin{cases} 0.8689 & \text{for } \lambda = 1 \\ 0.1311 & \text{for } \lambda = 0 \end{cases} \quad (2)$$

The derivation of the Kalman filter is based around the position being equal to the last position, the change due to velocity and the change due to acceleration:

$$x[n] = x[n-1] + \dot{x}[n-1] \cdot ts + \ddot{x}[n-1] \cdot \frac{ts^2}{2} \tag{3}$$

$$\dot{x}[n] = \dot{x}[n-1] + \ddot{x}[n-1] \cdot ts \tag{4}$$

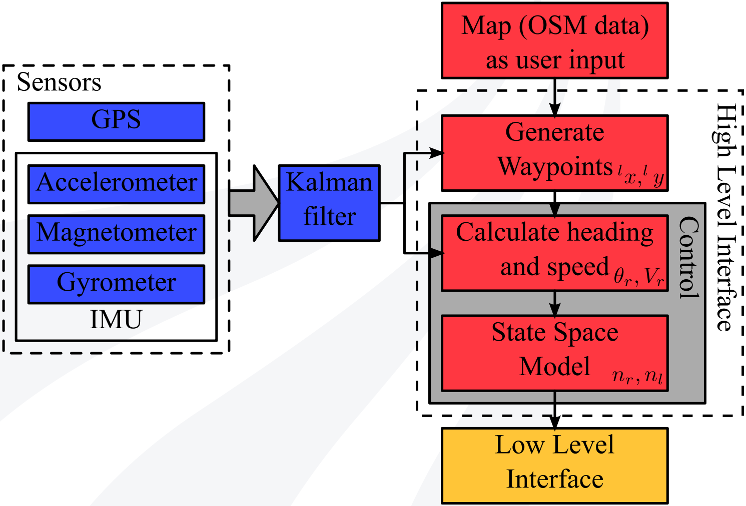
$$\ddot{x}[n] = -\beta \cdot \dot{x}[n-1] + \ddot{x}[n] \tag{5}$$

Which can be put on matrix form:

$$\begin{bmatrix} x[n] \\ \dot{x}[n] \\ \ddot{x}[n] \end{bmatrix} = \begin{bmatrix} 1 & ts & \frac{ts^2}{2} \\ 0 & 1 & ts \\ 0 & -\beta & 0 \end{bmatrix} \begin{bmatrix} x[n-1] \\ \dot{x}[n-1] \\ \ddot{x}[n-1] \end{bmatrix} \tag{6}$$

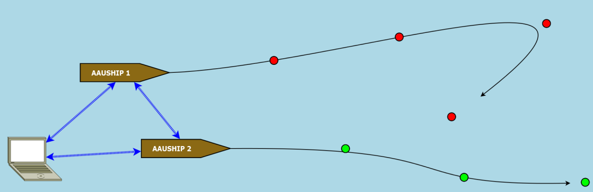
This goes for the y-axis and the rotation about the z-axis as well.

System levels

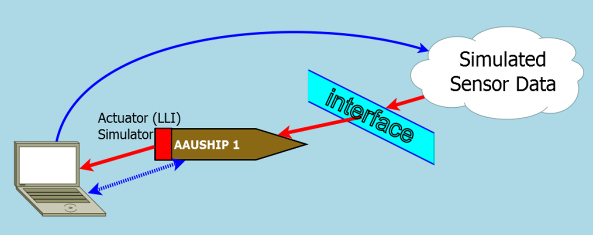


HLI features

- Model-based development that allows multiple Ship instances



- Seamlessly integrated custom Simulation environment



Waypoints and Sub-Waypoints

Waypoints

- Key points of interest, defining the **approximate path**
- Coastal information **known** $\rightarrow$ **automatic** WP generation
- Coastal information **unknown** $\rightarrow$ **manual** WP placement

Sub-Waypoints

- Specific locations that the ship must approach
- Placed in the λ_{max} surrounding of the **approximate path**
- The ship approaches each **SWP** at least to ε **follow distance**
- Each Waypoint is approached to **at least** $\lambda + \varepsilon$ distance

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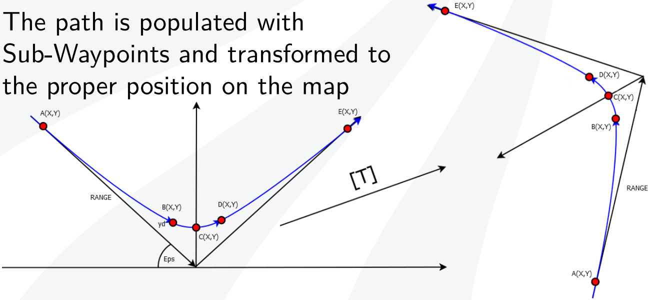
Local path planning

- Key points are determined to define an **Euler Spiral** → **Circular** → **Euler Spiral** path
- The centrifugal force affecting the body of the ship changes continuously and linearly
- The resulting sideways-movement is kept to a minimum and the control signal is better conditioned
- The path is populated with Sub-Waypoints and transformed to the proper position on the map



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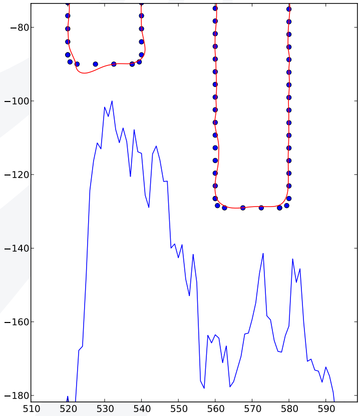
Navigation

- The ship is always heading for the next Sub-Waypoint, outside of the ε **follow distance**
- The output of the Navigator is the **reference heading** Θ_r
- The image shows a simulation of the navigation and control based on noisy inputs



Modeling
Thrust/Torque Model

The thrust generated by the engines are modeled using equation 7 which is a function of the RPS of the propellers:

$$F_{\text{stbd,port}} = \rho \cdot K_{\text{T}} \cdot D^4 \cdot |n_{\text{stbd,port}}| \cdot n_{\text{stbd,port}} \tag{7}$$

As the engines are mounted on the starboard and port side the total thrust forward is a sum of the two engines $F_{\text{total}} = F_{\text{stbd.}} + F_{\text{port}}$ and the difference between them generates a torque around the centre of rotation

$$\tau = (F_{\text{stbd.}} - F_{\text{port}}) \cdot l \tag{8}$$

Where l denotes the distance from the centre of rotation to the top of the propellers.

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Using Newtons 2nd law, the force and torque can be converted to an acceleration and an angular acceleration:

$$\ddot{x} = \frac{F_{\text{total}}}{m} \quad \ddot{\theta} = \frac{\tau}{I} \tag{9}$$

Thus allowing for the input **u** to the system to be given as:

$$\mathbf{u} = \begin{bmatrix} F_{\text{total}} & \tau \end{bmatrix}^T \tag{10}$$

And the **B** is given as the conversion from the force and torque to an acceleration and an angular acceleration respectively.

$$\mathbf{B} = \begin{bmatrix} \frac{1}{m} & \frac{1}{I} \end{bmatrix}^T \tag{11}$$

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The Dynamics of the system are given by the drag the ship experiences when moving through the water. The drag is given as:

$$F_{\text{Drag}}(\dot{x}, \dot{y}) = \frac{1}{2} \cdot \rho \cdot C_{\text{D}} \cdot \dot{x}^2 \cdot A \tag{12}$$

The formula changes when the ship is turning, as the drag then is converted into a torque - which is defined as:

$$\tau_{\text{Drag}}(\omega) = \frac{1}{2} \cdot \rho \cdot C_{\text{D}} \cdot (d \cdot (r_f^4 + r_b^4)) \cdot \omega^2 \tag{13}$$

The above can be put an matrix form as:

$$\mathbf{Ax} = \begin{bmatrix} -\beta_X & 0 & 0 \\ 0 & -\beta_Y & 0 \\ 0 & 0 & -\beta_\omega \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \tag{14}$$

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As the motion in the y-direction is uncontrollable, and the thing to be controlled is the velocity and the angle, the combined system becomes:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{15}$$

$$\begin{bmatrix} \ddot{x} \\ \dot{\theta} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} \frac{-\beta_x}{m} & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & \frac{-\beta_\omega}{I} \end{bmatrix} \begin{bmatrix} \dot{x} \\ \theta \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{1}{m} & 0 \\ 0 & 0 \\ 0 & \frac{1}{I} \end{bmatrix} \begin{bmatrix} F_{\text{total}} \\ \tau \end{bmatrix} \tag{16}$$

And the output of the system $\mathbf{y}$ becomes:

$$\mathbf{y} = \mathbf{C}\mathbf{x} + D\mathbf{u} \tag{17}$$

$$\begin{bmatrix} \dot{x} \\ \theta \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{x} \\ \theta \\ \omega \end{bmatrix} + \mathbf{0} \begin{bmatrix} F_{\text{total}} \\ \tau \end{bmatrix} \tag{18}$$

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- Optimal Control
- Reference Tracking

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Empty Frame

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Test Results
Kalman Filter

Empty Frame

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Test Results
Maiden Voyage

Empty Frame

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Empty Frame