### Centralized State Estimation of Distributed Maritime Autonomous Surface Oceanographers

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 ${\sf Modeling}$ 

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### Introduction

autonomous crafts.

▶ Little to no research are currently devoted to maritime

Purpose



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### Introduction

Purpose



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

▶ 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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Purpose



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

- 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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# Development AAUSHIP.01



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

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# Development AAUSHIP.01



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Developed using rapid prototyping techniques.

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Engine model



- ► The ship is designed as a non-planing deplacement craft (eg. like freight ships).
- ▶ Developed using rapid prototyping techniques.
- ► Developed in Rhinoceros<sup>TM</sup>using a lofting techniques.

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- ► Examined and the process iterated.

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

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# Development AAUSHIP.01 Hull



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Pictures of the ship.

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Pictures of the ship.



► 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



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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:

$$\lambda_{\mathsf{gps},\mathsf{E}} = \left\{ \begin{array}{ll} 0.8643 & \text{for } \lambda = 1\\ 0.1357 & \text{for } \lambda = 0 \end{array} \right. \tag{1}$$

And for the IMU also at 189 metres.

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

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### Development Kalman Filter



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:

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

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

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

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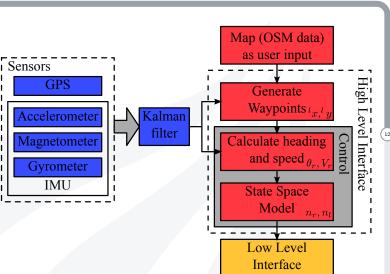
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### System levels





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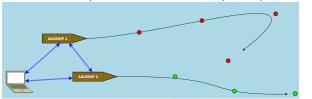
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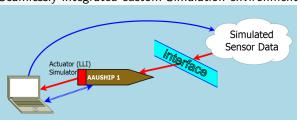
### **HLI** features



► Model-based development that allows multiple Ship instances



► Seamlessly integrated custom Simulation environment



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## Waypoints and Sub-Waypoints



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#### Path Planning

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### Waypoints

- ▶ Key points of interest, defining the approximate path
- ► Coastal information **known** → **automatic** WP generation
- ► Coastal information **unknown** → **manual** WP placement

### Sub-Waypoints

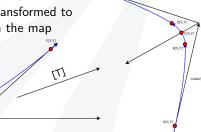
- Specific locations that the ship must approach
- ▶ Placed in the  $\lambda_{max}$  surrounding of the approximate path
- $\blacktriangleright$  The ship approaches each **SWP** at least to  $\varepsilon$  **follow distance**
- ▶ Each Waypoint is approached to at least  $\lambda + \varepsilon$  distance

## Local path planning



- $\blacktriangleright$  Key points are determined to define an **Euler Spiral**  $\rightarrow$ **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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Path Planning

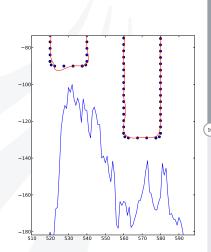
Engine model

## Navigation



### **Navigation**

- ► The ship is always heading for the next Sub-Waypoint, outside of the  $\varepsilon$  follow distance
- ▶ The output of the Navigator is the reference heading  $\Theta_r$
- ► The image shows a simulation of the navigation and control based on noisy inputs



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

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

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

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

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# Modeling Thrust/Torque Model



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  $\mathbf{u}$  to the system to be given as:

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

And the  ${\bf B}$  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:

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

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

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

The above can be put an matrix form as:

$$\mathbf{A}\mathbf{x} = \begin{bmatrix} -\beta_{X} & 0 & 0 \\ 0 & -\beta_{Y} & 0 \\ 0 & 0 & -\beta_{\omega} \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix}$$
(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:

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

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

And the output of the system **y** becomes:

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

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

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► Optimal Control ► Reference Tracking

### Control Implementation

**Empty Frame** 



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**Empty Frame** 

### Test Results Maiden Voyage

**Empty Frame** 



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**Empty Frame**