Centralized State Estimation of Distributed Maritime Autonomous Surface Oceanographers

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Agenda

Introduction
Purpose

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

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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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- 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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Ship development

- During the project a ship was developed, using 3D modeling and rapid prototyping.
- The ship is developed as a non-planing displacement hull.

Path Planning
Considerations and Description

Considerations

- The path planner must be memory efficient.
- The path planner should consider the coastal line to be covered.
- The path planner should create an efficient path.

Straight and Turning segments

- Straight segments are generated by having a fixed minimum distance from the shore line, and then define a distance between the measuring lines. This cannot be optimized, as straight lines are, well straight lines.
- Turning segments are however more interesting, as these can be optimized.

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Theory

- The path planner is based around the Train transition problem, originally posed by [1].

[1] Arthur N. Talbot, *The Railway Transition Spiral*, 1901

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- The problem describes that a vehicle in motion, can maintain a linear angular acceleration if the amount of jerk j experienced by the ship is kept constant.
- To keep the jerk j constant, the theory defines the path using the two normalized Fresnel integrals, that when plotted produces the Euler spiral. The Fresnel integrals are given as:

$$C_F(x) = \int_0^x \cos(t^2)dt, \quad S_F(x) = \int_0^x \sin(t^2)dt \tag{1}$$

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Path Planning
Threshold definition

- The path planner is also based on the curvature of the turn the ship is to make κ. This defines if the path should consist of a transition onto a circle, or two Euler spirals (dependent on the curvature).
- The threshold $\varepsilon_{\mathsf{max}}$ is defined to be:

$$\varepsilon_{\mathsf{max}} = \frac{\kappa_{\mathsf{max}}^2}{2 \cdot \eta} \tag{2}$$

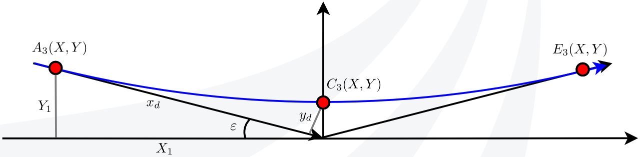
- Where η is a function described by the highest amount acceleration the ship can experience and the velocity at which it traverses this.

$$\eta = \frac{\alpha_{\mathsf{max}}}{v_{\mathsf{max}}^2} \tag{3}$$

- This function allows the ship to preserve as much energy as possible, without veering out of course.

Path Planning
3-point scenario

- The below figure shows the waypoints generated by the ship when $\varepsilon < \varepsilon_{\max}$. This consists of an inward and an outward Euler spiral.



- The waypoints are computed as follows:

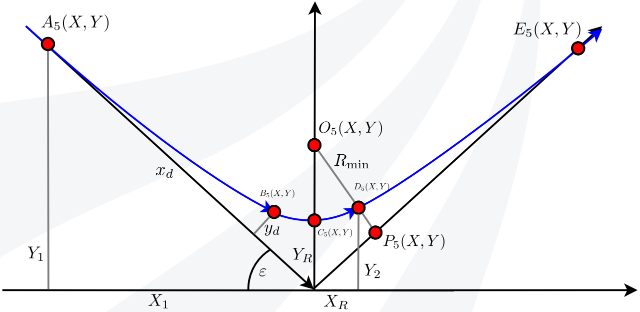
$$A_3 = (-X_1, Y_1),\ C_3 = (0, \frac{y_d}{\cos(\varepsilon)}),\ E_3 = (X_1, Y_1) \tag{4}$$

- Where X_1 and Y_1 can be computed as functions of the normalized Euler spirals, with x_d and y_d representing the length:

$$X_1 = x_d \cdot \cos(\varepsilon) + y_d \cdot \sin(\varepsilon),\ \ Y_1 = X_1 \cdot \tan(\varepsilon) \tag{5}$$

Path Planning
5-point scenario

- The below figure shows the waypoints generated by the ship when $\varepsilon > \varepsilon_{\text{max}}$. This consists of a transition from an inward Euler spiral, onto a circle and then a transition from the circle onto an outward Euler spiral.



- Adding the two points B_5 and D_5 given as:

$$B_5 = (-R_{\text{min}} \cdot \sin(\varepsilon - \varepsilon_{\text{max}}),\ Y_1 - x_d \cdot \sin(\varepsilon)) \tag{6}$$

$$D_5 = (R_{\text{min}} \cdot \sin(\varepsilon - \varepsilon_{\text{max}}),\ Y_1 - x_d \cdot \sin(\varepsilon)) \tag{7}$$

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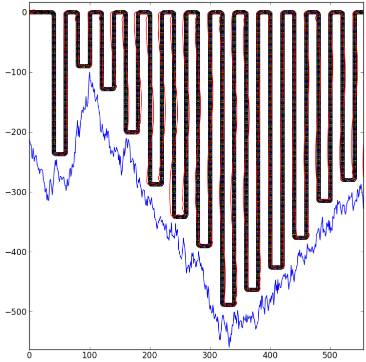
Path Planning
Verification

- To verify that the planner works properly, a random shoreline have been generated using a random walk, and a bounding box was drawn, the algorithm was then programmed to generate a shoreline, producing the following results:



- The dots on the figure represent the waypoints.

Considerations

The model is built using a top-down approach, running the main controls on a high-level interface (HLI). A low-level interface (LLI) handles the actuators and reads all the sensors. The link between these are a simplex 19.2 kbps radio link.

Top layer - HLI

Receives the sensor readings from the LLI and computes actuator set-points which are transmitted to the LLI.

Bottom layer - LLI

Receives the actuator set-points and sets these, then reads the sensors and transmit these readings back.

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Assumptions

The model is simplified to a 3-DOF model, with only motion in the x and y direction, as wel as rotation about the z-axis defined as θ. The model does not take into account the surge generated by the ship as it moves in the water, and the effects of planing is not taken into account, as the ship is not moving faster than ≈ 1 m/s. With these assumptions the following contiuous time state space model have been derived:

$$\begin{bmatrix} \dot{v} \\ \theta \\ \omega \end{bmatrix} = \begin{bmatrix} -\beta_v & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\beta_\omega \end{bmatrix} \begin{bmatrix} v \\ \theta \\ \omega \end{bmatrix} + \begin{bmatrix} m^{-1} & 0 \\ 0 & 0 \\ 0 & I^{-1} \end{bmatrix} \begin{bmatrix} F \\ \tau \end{bmatrix} \tag{8}$$

4 non-linear terms appear in the equation. Namely the β terms and the computations of the forward force F and the torque τ.

F and τ terms

The force F and torque τ are dependent on the same variables, namely the number of revolutions of the propellers n_1 and n_2. These can be computed by:

$$\begin{bmatrix} n_1^2 \\ n_2^2 \end{bmatrix} = \begin{bmatrix} C_1 & C_1 \\ C_1 \cdot l \cdot \sin(\theta_{\text{stbd.}}) & C_1 \cdot l \cdot \sin(\theta_{\text{port}}) \end{bmatrix}^{-1} \begin{bmatrix} F_{\text{desired}} \\ \tau_{\text{desired}} \end{bmatrix} \tag{9}$$

Solving for n_1 and n_2 produces:

$$n_1 = \frac{n_1^2}{\text{abs}\{n_1^2\}} \cdot \sqrt{n_1^2}, \;\; n_2 = \frac{n_2^2}{\text{abs}\{n_2^2\}} \cdot \sqrt{n_2^2} \tag{10}$$

β term

The β terms are linearized using a Taylor approximation. The constant term is removed in the reference gain of the controller.

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Optimal feedback gain and reference tracking

The optimal state feedback gain is computed by minimizing the cost function $\mathcal{J}$, given as:

$$\mathcal{J} = \int_0^{\infty} (x^T(t) \cdot Q \cdot x(t) + u^T(t) \cdot R \cdot u(t))dt \tag{11}$$

Producing the following feedback gain:

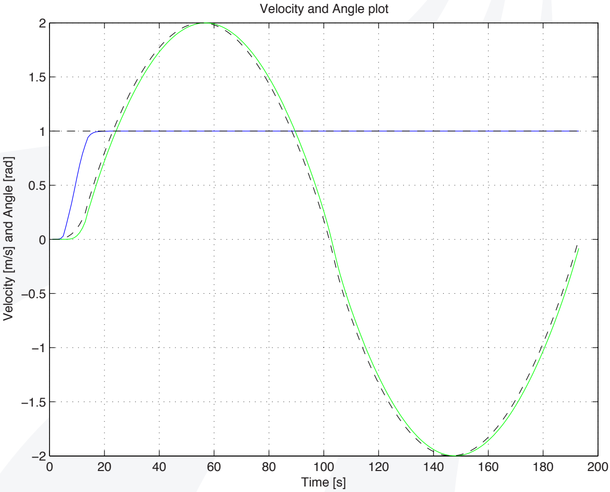
$$F_{\text{opt}} = \begin{bmatrix} 15.1668 & 0 & 0 \\ 0 & 2.5165 & 0.7134 \end{bmatrix} \tag{12}$$

The reference gain is computed by augmenting the system as in [2]., thus producing the reference gain:

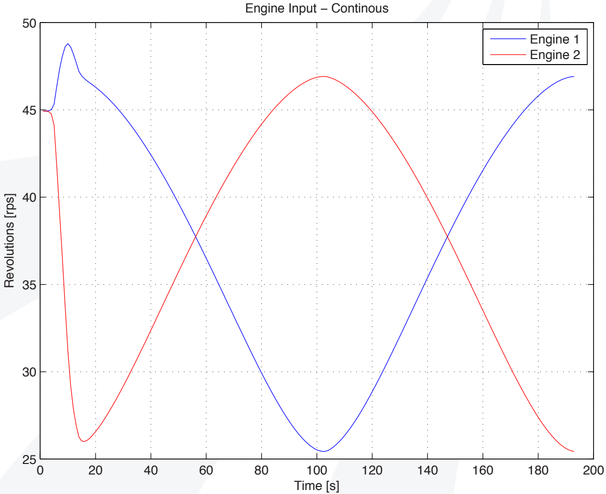
$$N_{\text{reference}} = \begin{bmatrix} 24.0668 & 0 \\ 0 & 2.5165 \end{bmatrix} \tag{13}$$

[2] Franklin et. al., *Feedback Control of Dynamic Systems*, 2010

Through simulations, the system have produced the following figures used to verify wether the controller strategy.



And testing if the conversion from desired force to revolutions work.



Estimated states and input state model

The estimated states are defined as:

$$ {}^{b}\hat{x}_k = \begin{bmatrix} x & \dot{x} & y & \dot{y} & \theta & \omega \end{bmatrix}^T \tag{14} $$

As the ship is fitted with an IMU and a GPS, the measured states becomes:

$$ v_k = \begin{bmatrix} x & \dot{x} & \ddot{x} & y & \dot{y} & \ddot{y} & \theta & \omega & \alpha \end{bmatrix}^T \tag{15} $$

Giving the state model of the system as (ts = 20 Hz):

$$ \Phi = diag\{\Phi_x, \Phi_y, \Phi_\omega\} \tag{16} $$

Where the individual Φs are given as:

$$ \Phi_{x,y,\omega}(k) = \begin{bmatrix} 1 & t_s & 0 \\ 0 & 1 & t_s \\ 0 & -\beta_{x,y,\omega} & 0 \end{bmatrix} \tag{17} $$

State Estimation
Theory - zero gaining

As the LLI and HLI are run on two seperate computers, the Kalman filter needs to filter out the measurements which are invalid. This is done by multiplying the Kalman gain $\bar{K}$ by a validity mask-matrix Λ, given as:

$$\Lambda = diag\{\lambda_x, \lambda_{\dot{x}}, \lambda_{\ddot{x}}, \lambda_y, \lambda_{\dot{y}}, \lambda_{\ddot{y}}, \lambda_\theta, \lambda_\omega, \lambda_\alpha\} \tag{18}$$

Where the λs are defined as:

$$\lambda = \begin{cases} 1 & \text{if checksum is valid} \\ 0 & \text{otherwise} \end{cases} \tag{19}$$

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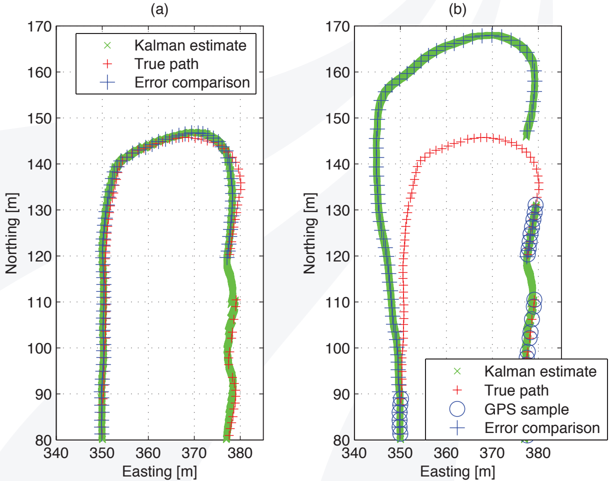
State Estimation

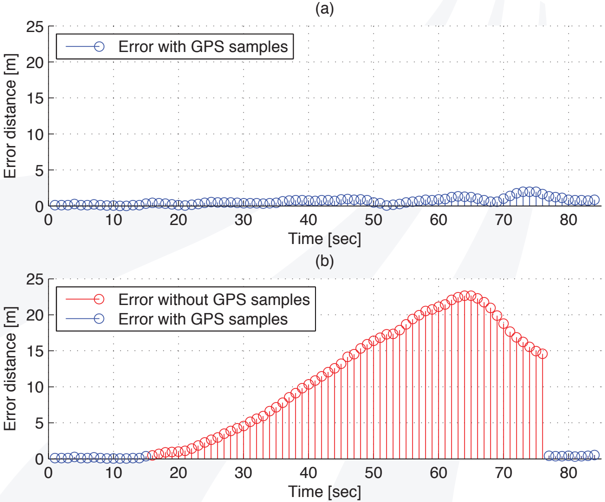
Verification of State estimator

A test of the Kalman filter, to see if it estimates lost packages was carried out producing. Figure (b) represents the case where GPS measurements are lost for 60 seconds:



State Estimation
Verification of State estimator

The absolute error of the position are depicted on the figure below:



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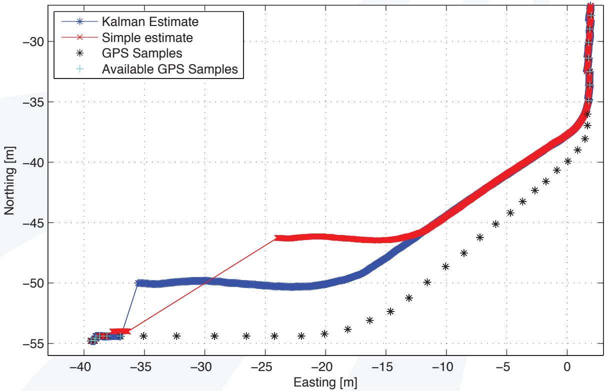
Final test

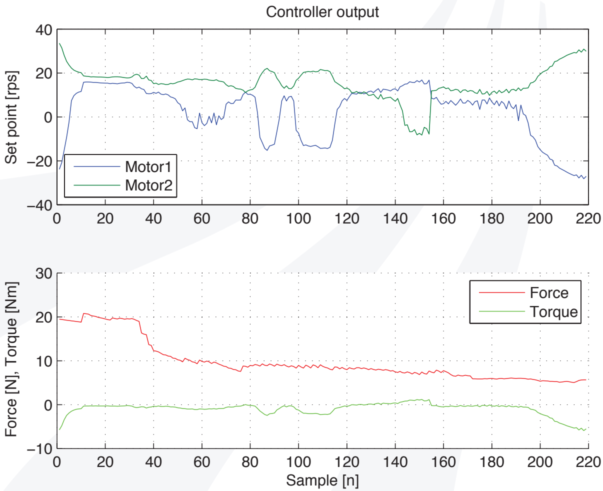
Kalman estimator verification

As the waters around Aalborg have frozen solid, final tests in water have not been carried out, however, tests on land have been carried out, producing the following:



Final test
Engine input verification

Producing the engine inputs from the controller.



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