Centralized State Estimation of Distributed Maritime Autonomous Surface Oceanographers ⋆

Rasmus L. Christensen * **Frederik Juul** * **Nick Østergaard** *
Attila Fodor * **Tudor Muresan** *

* *Department of Electronic Systems, Aalborg University, Fredrik Bajers Vej 7, 9220 Aalborg Øst, Denmark (e-mail: {ralch,nickoe,fjuul,tudor,attila}@es.aau.dk)*

Abstract: This paper considers the subject of running a centralized controller for the purpose of navigating a small Autonomous Surface Vehicle (ASV). The centralized controller is using a Kalman filter as a state predictor to improve the precision of the navigational aids mounted aboard. The work presents the design of the motion control system as well as the development of a protocol used to push through as much data on a standard 9.6 kbps data link simplex link. The performance for the algorithms developed in this project, have been tested in Limfjorden in Aalborg, and towards the end, results of these tests are shown.

Keywords: Path planning; Centralised control; Baud rates; State estimation; Marine systems; Master slave system;

1. INTRODUCTION

As up to date mapping of the coastal areas around Greenland is not available, and the process of creating these are a both time consuming and expensive task. One way to reduce both the costs and the amount of time invested in such a project could be to develop small autonomous drones to carry out this task.

These drones should be controlled by a mothership, which would utilize a simple data link, both to preserve bandwith, but also to make the duration at which the ships are able to sail as long as possible, by limiting the power consumption.

Currently the main focus of autonomous vehicles have been on aerial, ground and underwater vehicles, why there is close to no research going on about small autonomous surface vessels. An example of such a vessel is the Stingray ASV developed by Isreali Based Elbit Systems. The purpose of this vehicle is somewhat military related, where the purpose of measuring the coastal areas around Greenland are purely humanitarian,

Do not change the font sizes or line spacing to squeeze more text into a limited number of pages. Use italics for emphasis; do not underline.

1.1 Problem statement

Hypothesis 1. Is it possible to develop a centralized state estimator for use in the maritime environment using a small data link

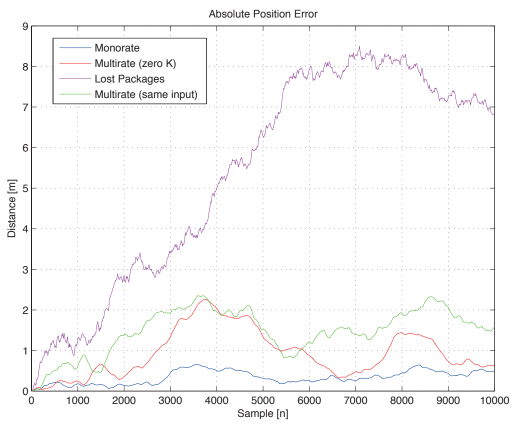

Fig. 1. Bifurcation: Plot of local maxima of x with damping a decreasing

1.2 A subsection

2. METHODS

The methods developed in this project - and the papers. 2

2.1 Path planning algorithm

The path planning algorithm1 is based around the train-track transition problem originally solved in [Talbot , 1901], which divides the path into straight and turning parts and describes the transition between these using the normalized Fresnel integral, describing an Euler spiral, which allows the ship to maintain a linear acceleration

⋆ Thanks to the has been paid for in full by the School of Information Communication and Technology.

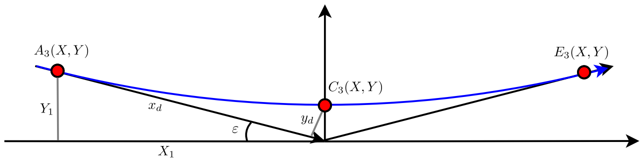

Fig. 2. Path planning when $\varepsilon < \varepsilon_{max}$, the path is composed by two identical but mirrored Euler-spirals. 3 key points are generated, denoted A_3, C_3 and E_3

through the turn, thus keeping the amount of jerk j as close to zero as possible. The two Fresnel integrals are given as in equation (1):

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

The functions two normalized Fresnel integrals produce the geometrical shape of the Euler spiral. However, the body on the track can endure only a limited amount of centripetal acceleration, which is the function of the Speed(v) and Path Curvature(κ). Vehicles have limited acceleration of heading $\dot{\kappa}_{max} = \alpha_{max}$ as well, which results in a necessary scaling (σ) of the Euler spiral:

$$A_{C_{max}} = \frac{v^2}{r} = v^2 \cdot \kappa \quad , \quad \sigma = \frac{\alpha_{max}}{v_{max}^2} \tag{2}$$

A threshold angle of turn (ε_{max})can be determined based on the vehicle parameters above:

$$\varepsilon_{max} = \frac{\kappa_{max}^2}{2\sigma} \tag{3}$$

If the angle of the turn is lower than the threshold, the turn can be completed in two similar Euler spiral stages. The 3 key points are given by the coordinate sets:

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

From where the individual coordinates can be computed by simple trigonometric equations, if the angle of the turn ε is known. x_d and y_d are the length of the scaled Euler-spiral, when the turn of the spiral equals to ε, where x_d and y_d represents the (x, y) coordinate pair of the two normalized Fresnel integral functions with the same parameter t.

$$\varepsilon = \frac{\mathrm{dx}\ F(t)}{\mathrm{dy}} \quad \rightarrow \quad [x_d, y_d] = F^{-1}(\varepsilon) \tag{5}$$

Once the angle grows larger than ε_{max} the system has to compute five key points, as the ship must transit onto a curve, and then back onto the Euler spiral ($\kappa_{Euler_{max}} = \kappa_{Arc}$) This adds the extra waypoints B_5 and D_5, the entry and exit points of the curve. The center of the circular path segment is O_5 and the radius is $R_{min} = \frac{1}{\kappa_{max}}$. The waypoints are depicted on figure (**??**), thus augmenting the waypoints to:

$$A_5 = (-X_1, Y_1),\ B_5 = (-X_2, Y_2),\ C_5 = (0, Y_R) \tag{6}$$
$$D_5 = (X_2, Y_2),\ E_5 = (X_1, Y_1) \tag{7}$$

Which is still a mirroring of points about the $x = 0$ axis, as the entry angle is the same as the exit angle. The number of equations increases, and the individual coordinates can be computed by:

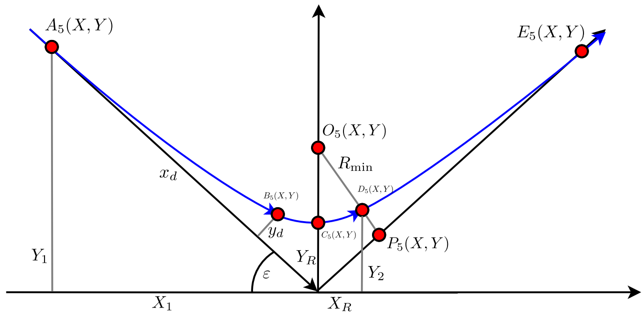

Fig. 3. Path planning when $\varepsilon < \varepsilon_{max}$, the path is approximated by a curve and only 3 sub-waypoints are generated, denoted A_5, B_5, C_5, D_5 and E_5

$$X_R = R_{\min} \cdot \sin(\varepsilon - \varepsilon_{\max}),\ P_X = X_R + y_d \cdot \sin(\varepsilon) \tag{8}$$
$$X_1 = P_X + x_d \cdot \cos(\varepsilon),\ Y_1 = X_1 \cdot \tan(\varepsilon) \tag{9}$$
$$P_Y = Y_1 - x_d \cdot \sin(\varepsilon),\ Y_2 = P_Y + y_d \cdot \cos(\varepsilon) \tag{10}$$
$$O_Y = R_{\min} \cdot \cos(\varepsilon - \varepsilon_{\max}) + Y_2,\ R_Y = O_Y - R_{\min} \tag{11}$$
$$X_2 = X_R \tag{12}$$

The resulting path in both cases can not be described explicitly, therefore a Hermite-polynom is fit to the key points. In addition, a predefined number of uniformly distributed sub-waypoints are generated on the path, based on the describing polynom. The resulting sub-waypoints are rotated and moved to their correct position in the Local-Frame, thus concluding most of the work of the local-planner. The paths between turns are straight lines, populated with the same preset density of sub-waypoints.

2.2 State estimation

To give a better estimate of position and the attitude of the craft, a Kalman filter have been implemented to improve the accuracy of the sensors mounted aboard the ship. To develop a such, the discrete time state model of the ship have been derived to be:

$$\mathbf{\Phi} = diag\{\mathbf{\Phi}_x, \mathbf{\Phi}_y, \mathbf{\Phi}_\omega\} \tag{13}$$

Where the diagonal entries $\mathbf{\Phi}_x, \mathbf{\Phi}_y, \mathbf{\Phi}_\omega$ are given by the same equation, with different entries:

$$\mathbf{\Phi}_{x,y,\omega}(k) = \begin{bmatrix} 1 & t_s & 0 \\ 0 & 1 & t_s \\ 0 & \frac{-\beta_{x,y,\omega}}{m, m, I} & 0 \end{bmatrix} \tag{14}$$

Where $\beta_{x,y,\omega}$ denotes the skin frictional drag in the x,y or ω direction respectively, m is the mass of the craft, I is the interia and t_s is the sampling time of the filter. The states to be estimated for the controller are:

$${}^{b}\hat{\boldsymbol{x}}_k = [x\ \dot{x}\ y\ \dot{y}\ \theta\ \omega]^T \tag{15}$$

The observation model of the filter does however contain more measurements, and the measurements can be given as:

$$\boldsymbol{v}_k = [x\ \dot{x}\ \ddot{x}\ y\ \dot{y}\ \ddot{y}\ \theta\ \omega]^T \tag{16}$$

The implementation of the filter is an altered version of an Linear Minimum Mean Square Error filter - the alteration lies in the Kalman gain, where a matrix mask Λ is post multiplied. This matrix mask is to zero out the

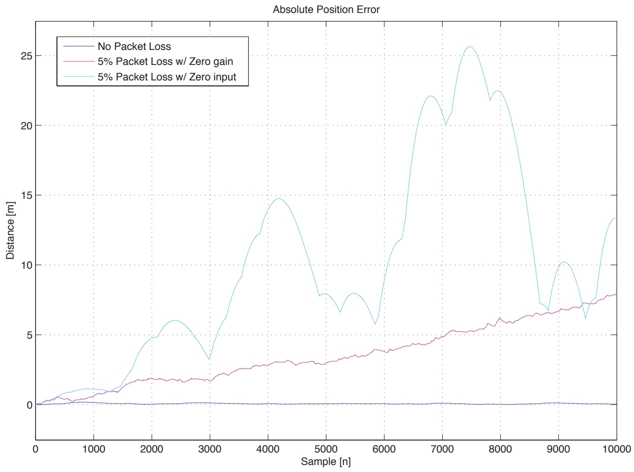

Fig. 4. Plot of the absolute position error, simulated using MATLAB and a sawtooth input to the control system running at

measurements that are invalid. This matrix mask is defined as:

$$\mathbf{\Lambda} = diag\{\lambda_x, \lambda_{\dot{x}}, \lambda_{\ddot{x}}, \lambda_{\lambda y}, \lambda_{\dot{y}}, \lambda_{\ddot{y}}, \lambda_\theta, \lambda_\omega, \lambda_\alpha\} \tag{17}$$

This ensures that when a measurement is invalid (the checksum is not true) the receiver zeros out the gain, and runs the filter on the other sensors / estimates. The individual λs are thus given as:

$$\lambda = \begin{cases} 1 & \text{if checksum is valid} \\ 0 & \text{otherwise} \end{cases} \tag{18}$$

This makes sure to zero out the measurement if a packet is corrupted instead of making the filter run on faulty data. The below figure is a simulation run in MATLAB which plots the absolute error of the position estimates of the ship for three different cases, one where the Kalman filter is running ideally with all packages available, one where the system looses 5 percent of the packages and another where the ship looses 5 percent, but gains these packages with 0 in the Kalman gain.

As all the forces are acting on the ship in the inertial body fixed frame - the

3. MATH

Some mathematics go here.

4. UNITS

5. RESULTS

5.1 Model of the ship

The model of the ASV is in continuos time given as the state space equation defined in (eq:19) - the model considers the motion of the ship with 3 degrees of freedom, movement in the x-direction, y-direction and rotation about the z-axis.

$$\begin{bmatrix} \dot{v} \\ \theta \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{-\beta_v}{m} & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & \frac{-\beta_\omega}{I} \end{bmatrix} + \begin{bmatrix} \frac{1}{m} & 0 \\ 0 & 0 \\ 0 & \frac{1}{I} \end{bmatrix} \tag{19}$$

This model is sufficient as it is only the velocity and the angle that is desired to cont as the other states are uncontrollable by the ship in its current configuration. The control strategy is to track the input reference, and use an optimal feedback gain to reach the desired values. This is done as in REFERENCE! giving the following gains:

$$F_opt = \tag{20}$$

$$N = \tag{21}$$

The above might be stupid to include?

5.2 Control verification

Running the system with just the controllers produces the following plot trying to follow a path around the parking lot.

5.3 Path planning results

Planning the path on a stretch of water in Aalborg produces the following results:

5.4 Kalman filtering verification

Filtering the above traced controller route with the Kalman filter, having the input to the system to zero, and post processing the data produces the following plot.

5.5 Combined test

Running the Kalman filter on the ship whilst in motion. As seen some packages are lost - to verify the simulator, a simulation have been run with the same amount of packages lost, and this produces the same result.

Something about the packet loss.

5.6 Other tests

Something else?

6. CONCLUSION

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

ACKNOWLEDGEMENTS

A special thank should be given to Assistant Professor Carles Navarro Manchòn, Section for Navigation and Communication, Department of Electronic Systems, Aalborg University for his help with tuning the Kalman filter.

REFERENCES

Arthur N. Talbot, *The Railway Transition Spiral* The Engeneering News Publishing Co., 1901

Appendix A. A SUMMARY OF LATIN GRAMMAR

Appendix B. SOME LATIN VOCABULARY