Navigation of large cruise liners built by Meyer Werft, Germany

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Abstract: The shipyard *Meyer Werft* at Papenburg (Germany) is building cruise liners for customers from all over the world. However, Papenburg is connected to the North Sea only by the river Ems. Consequently, the navigation of the first 36 km of each large vessel poses a serious problem. The position and orientation of the ship must be computed accurately at all times. At the moment, we use GPS, mariner compass and a tilt sensor for data collection. Most critical is the rolling of the ship due to wind forces and maneuvers. This could be properly treated using a Kalman filter.

Introduction

The shipyard *Meyer Werft* at Papenburg (Germany) is world famous for building large luxury cruise liners. Papenburg is suituated in the German province of East Frisia, close to the Dutch border. Each year two or three cruise liners are built by *Meyer Werft*. At the moment (September 2008), the *Celebrity Solstice* is docked at Papenburg. The 315 metre long and 37 metre wide cruiseliner has 1,426 cabins for about 2,852 passengers. According to the shipyard, this vessel, built for *Celebrity Cruises* (Miami/USA), is the largest cruise liner ever built in Germany.

Figure 1: Celebrity Solstice (Meyer Werft 2008)

However, Papenburg is connected to the North Sea only by the river Ems. This river is relatively small: Only 80 m³ of water flow into the North Sea each second. This is no more than 1/30 of the outflow of the neighbouring river Rhine.

This makes the transportation of a finished cruise liner up to the North Sea a serious problem. The trip is only possible as a result of the huge Ems barrier construction, which allows the water level in the river to be raised by 2.70 metres. The 476 metre long barrier building permits the transportation of ships up to a draught of 8.50 metres (*Celebrity Solstice* has a draught of 8 metres).

Figure 2: Ems barrier

The cruise liners are towed by tugboats stern first. A bridge passage is most critical, namely the passage through *Jann-Berghaus-Bridge* near Leer. This bascule bridge must be opened, and it

provides just as much space as needed for the large cruise liners to pass through.

Figure 3: Jann-Berghaus-Bridge

Inland navigation and hydrostatics and ship dynamics

Modern maritime navigational sensors are

1. Differential GPS or Differential GNSS antennas and receivers, also multi-antenna systems

2. Faser optical gyro(s)

We use the faser optical gyro HYDRINS made for maritime applications by iXSea (2008). The roll and pitch (see below) accuracy of this gyro is specified by the manufacturer to an RMS value of 0.01 degrees. This order of magnitude has been confirmed by Röttger (2008).


Figure 4: INS-Systems HYDRINS and OCTANS III made by iXSea (Röttger 2008)

The navigation of a ship at a river is harder than at open sea for the following reasons:

1. Obviously there are stronger accuracy requirements.

2. It is more likely that signals of navigation satellites at low elevation are blocked by obstacles.

3. Extrusion of water is disturbed by coastlines and river bottoms, which requires more skill in precise ship steering

The hydrostatics of a ship is governed by two forces: force of weight F_G and force of buoyancy F_B. The resultant of both forces, if not vanishing, causes a „righting" torque τ.
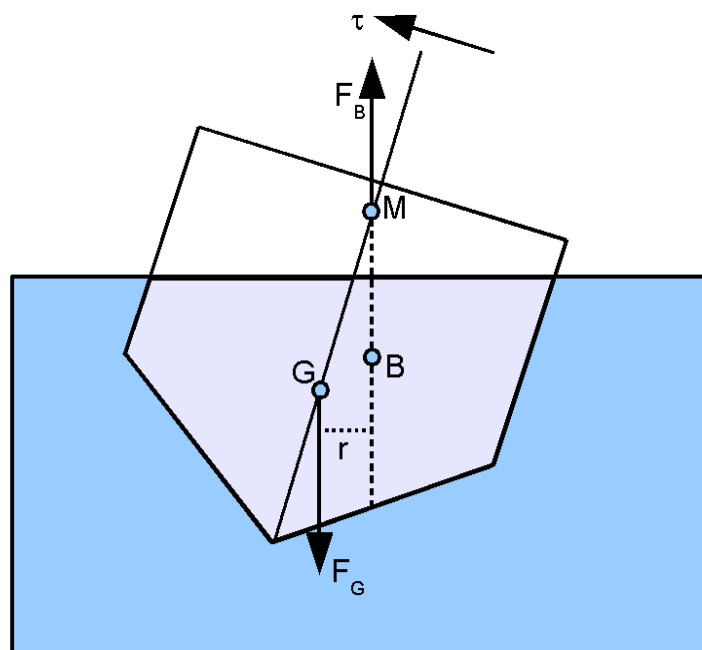
Figure 5: *G*: Mass center of the ship, *B*: Centre of buoyancy or centre of immersed bulk (point through which passes the resultant of all upward forces by which a ship floating freely in still water is suspended), *M*: Metacenter (point where all lines of buoyant force intersect).

It holds

$$\tau = F_B \cdot r$$

Like any ship, a cruise liner is always a little tilted, mainly in transversal (crosswise to driving direction). This is for two reasons:

1. Trimming (i.e. adjustment of a boat's loading so as to change its attitude in the water): This can be done by shifting fuel, water, or supplies.

2. Wind forces: The ship is tilted in leeward (downwind) direction.

3. Maneuvering forces: They are created mainly by towing forces and bow thrusters (i.e. propulsion devices built into the bow of a ship to enhance its maneuverability).

The last two forces are time variable, causing the ship to „sway" transversally. This movement is called „rolling" in maritime navigation. The roll angle is the transversal tilt angle. For cruise liners passing through the river Ems it can assume absolute values up to 3 degrees.

Test data set obtained from AIDAbella

AIDAbella is a cruise liner, towed to the North Sea via Ems at March 27th, 2008. It is a little smaller than *Celebrity Solstice* (draught 7.30 metres).

One GPS antenna has been used for positioning. It was placed 44 metres above water level.

The test data set is taken from the passage through *Jann-Berghaus-Bridge*, where nautic maneuvering is required, causing strong roll movements. The data set contains 348 data records of a measurement frequency of 1 Hz. The roll angle is displayed in figure 6. It shows a strong harmonic oszillation with a period of 20.6 seconds. The average is not zero, but 0.39 degrees.
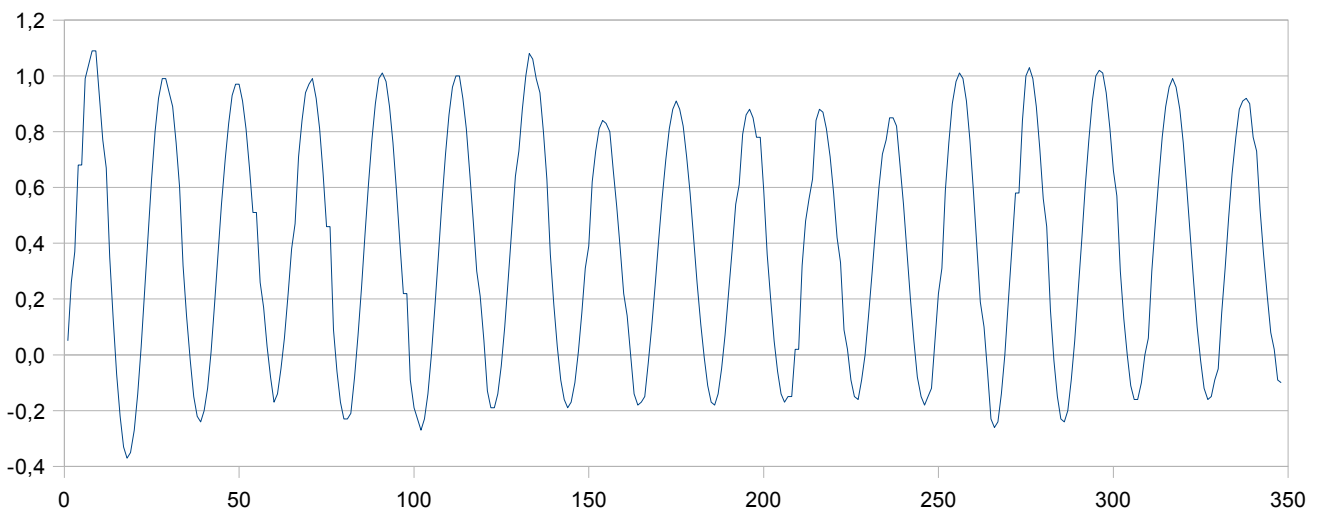
Figure 6: Roll angle of *AIDAbella* [degrees] vs. time [seconds].

First we reduce the effect of rolling in the GPS coordinates assuming that the roll axis is at water level. The result is given in figure 7. It is clearly visible that a strong effect of rolling is left in the transversal component of the motion, while in the longitudinal (in driving direction) component we mainly observe a deceleration from 0.77 m/s (0.39 knots) to 0.73 m/s (0.37 knots).

Unfortunately, no information on the maneuvers applied by the crew is available.
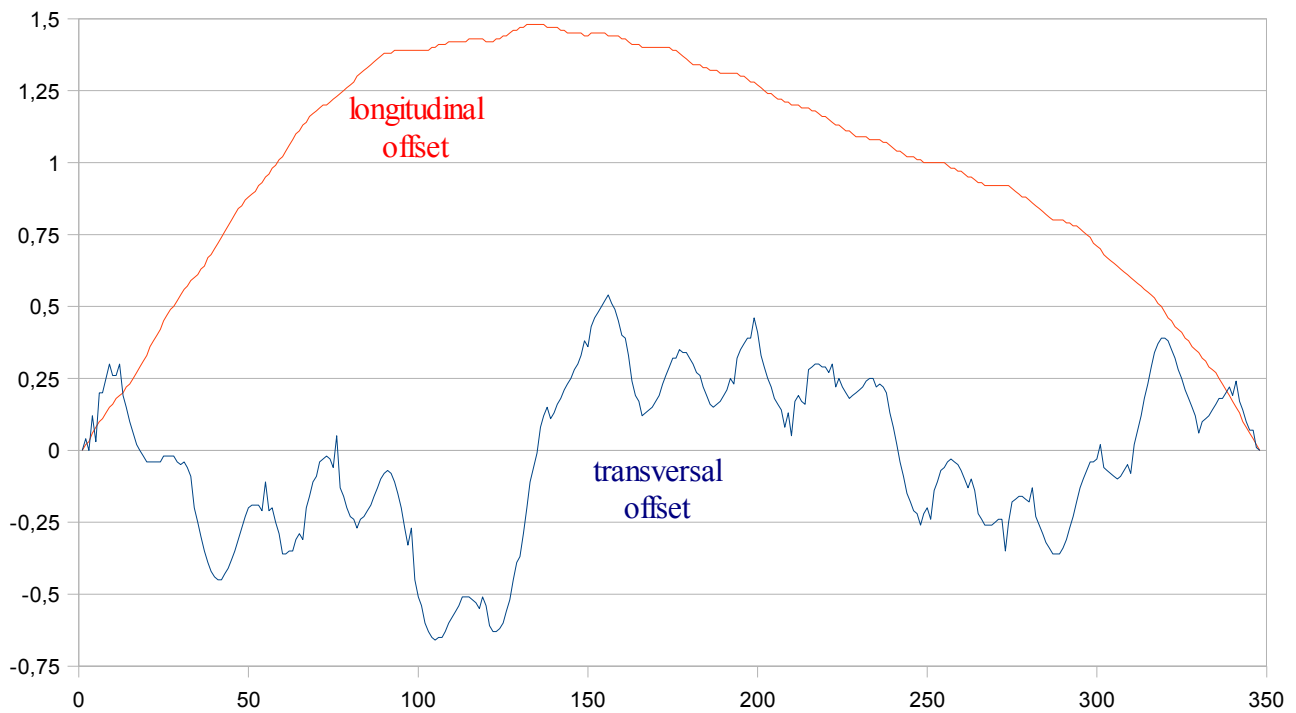
Figure 7: Position [metres] of the ship relative to a virtual ship in regular motion simultanuously passing through the first and last point vs. time [seconds]

Matched filtering

The task is now to split signal and noise. The desired signal is the position of the ship unaffected by rolling and measurement noise. The noise is the superimposed effect of rolling plus the typical measurement noise. Everything must be computable in real time.

A number of methods are available to solve this problem. In general, a solution can only be achieved by assuming some properties of signal and noise. The success will depend on how well these assumptions are fullfilled.

We start with three simple assumptions:

1. The signal is a smooth function of time, due to the inertness of the ship. For simplicity reasons we consider a cubic spline function.

2. The effect of rolling depends linearly on the observed roll angle shifted by some lag parameter τ.

3. The measurement noise is Gaussian white noise (GWN).

Based on these assumptions we can model our observed transversal offset (lower curve in figure 7) as follows:

observed transversal offset (t) = cubic spline (t) + e · roll angle (t-τ) + GWN (t)

The parameters of the spline function as well as e and τ are to be estimated. This leads us to a simple least squares curve fitting procedure.

Finally we want to estimate the position and motion of the ship, i.e. the signal, in present time:

estimated transversal offset (t_{now}) = cubic spline (t_{now})

For this estimation it is not necessary to consider all observed data obtained so far, but only those from the recent past. Observed data older than some time span Δt_{fit} will only deteriorate the estimate because it is more likely that maneuvers have been applied in the meantime. Therefore, we decide to fit the observed offset data invoking a piecewise linear weighting function

$w(t) = max(0 , t - t_{now} + \Delta t_{fit})$.

It will turn out that the optimal time span Δt_{fit} is so short that no actual cubic spline is required, but only a cubic polynomial:

observed transversal offset (t) = $a + b \cdot t + c \cdot t^2 + d \cdot t^3 + e \cdot$ roll angle (t-τ) + GWN (t)

In the driving direction we will proceed accordingly, except that we do not need to include the roll effect:

observed longitudinal offset (t) = $a' + b' \cdot t + c' \cdot t^2 + d' \cdot t^3 + GWN$ (t)

Results obtained for the test data

We will test the procedure based on the data set obtained from *AIDAbella*. As a measure of success we will compute the deviation of the predicted track of the ship from the observed track over the last full roll period of 21 s. Consequently, these data are excluded from the observed data. We test various time spans Δt_{fit} and obtain the following results:

Estimated lag parameter $\tau = 2.17$ seconds.

Time span Δt_{fit}	Weighted RMS of transversal fit	Weighted RMS of lateral fit	Maximum deviation of predicted track
20 s	0.03 m	0.06 m	0.59 m
30 s	0.05 m	0.02 m	0.65 m
50 s	0.11 m	0.03 m	0.74 m
70 s	0.23 m	0.04 m	0.20 m
100 s	0.40 m	0.06 m	0.89 m
130 s	0.54 m	0.07 m	1.21 m
160 s	0.61 m	0.10 m	1.28 m
200 s	0.85 m	0.21 m	1.05 m

It is clearly visible that short time spans of data fitting give better results. In figure 8 we present two curve fittings. Note that older data are less well fitted than newer data due to the chosen weighting function.
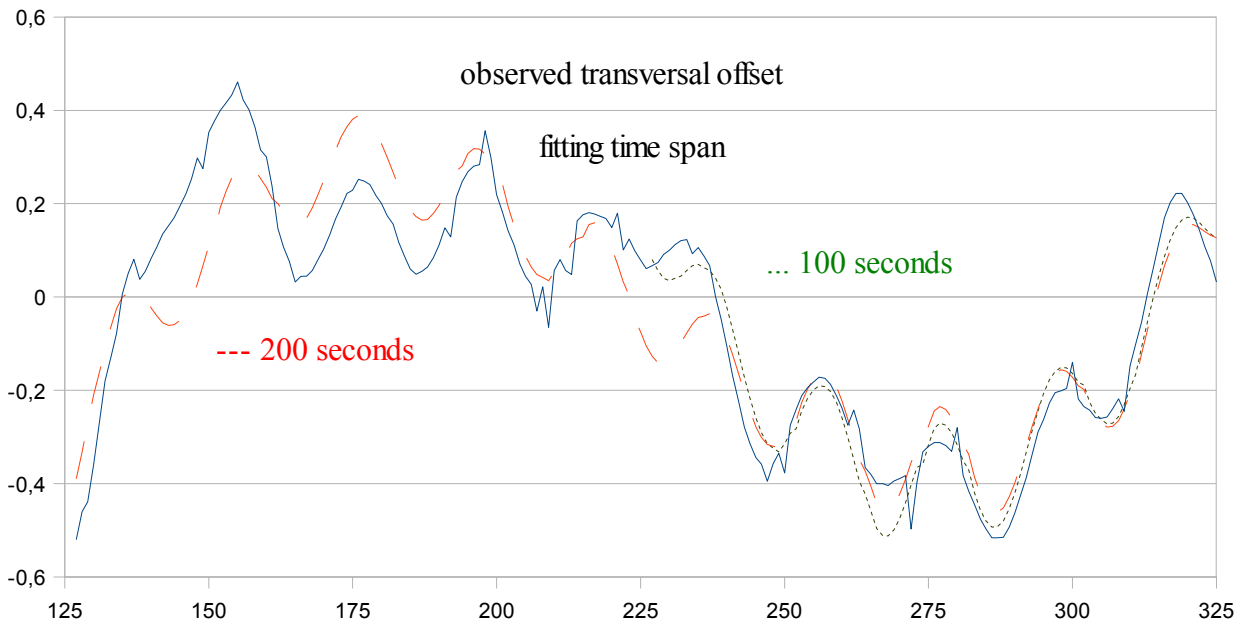
Figure 8: Curve fitting of transversal offset [metres] when using a fitting time span of 100 or 200 seconds.

Figure 9 shows how the track of the ship is predicted. The prediction to the near future is relatively good when using short fitting time spans. Note that the observed track of the ship does contain the effect of rolling.
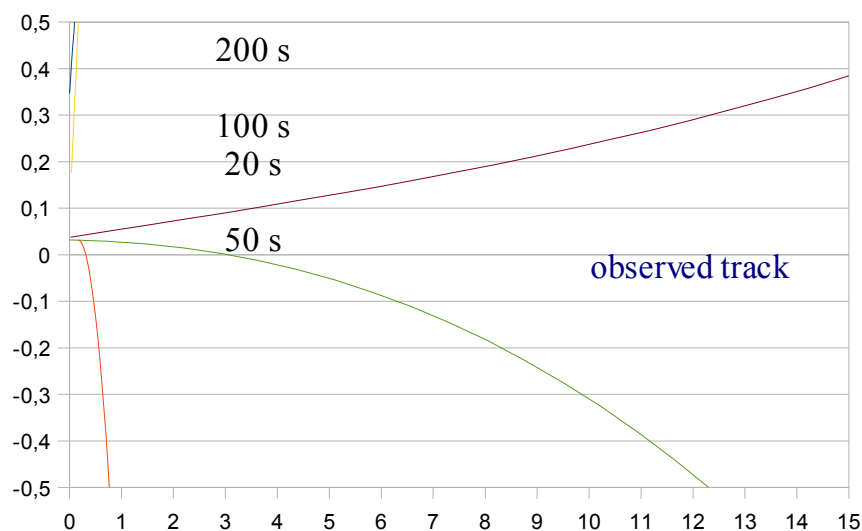
Figure 9: The observed track of the ship vs. predicted tracks [metres] when using various fitting

time spans. Note that the scalings in lateral (left => right) and transversal (up <=> down) directions differ by a factor of 10.

Summarizing, we state that matched filtering is a workable method, but it does not account for the physical reasons of the observed phenomena. When doing so, we can hope to improve the results.

Kalman filtering: State equations

The proper mathematical toolbox for the solution of problems posed in the framework of navigational sensor integration is the toolbox of Kalman filtering. It contains tools for optimal filtering of noisy sensor outputs obtained in a dynamical system. We cannot give an introduction into this field, but we refer to Grewall et al. (2001, pp. 179-264).

In order to apply Kalman filtering, one has to build a model of the dynamical system and to define the statistical properties of measurements taken in this system. The closer this model is to reality, the better will be the results of Kalman filtering.

In our case, the dynamical system is the ship together with the forces acting on it. We could build a highly complex model of the ship and its movement, but since we have at the moment only limited measurements, such a filter would not work.

It is better to restrict ourselves to the simplest model: In transversal direction, the ship is considered a damped and disturbed harmonic resonator. Its behavoiur is described by the diffential equation

$$\frac{d^2}{dt^2}\xi + \frac{2}{\tau}\frac{d}{dt}\xi + \left(\omega^2 + \frac{1}{\tau^2}\right)\xi = w_\xi(t)$$

where ξ is the roll angle. By $w_\xi(t)$ we express the resultant of all disturbing torques acting on the ship in lateral direction as a function of time. τ is the damping time constant (time for the amplitude to decay from unity down to $1/e=0.367879...$) and ω is the resonant frequency in units of radians per second, both related to the case of no disturbances ($w_\xi=0$). In this case the solution is well known to be

$$\xi(t) = \xi_0 \exp(-t/\tau)\sin(\omega t + \phi_0)$$

with integration constants ξ_0, ϕ_0 determined from suitable initial conditions. This formula describes the undisturbed damped harmonic resonator.

Besides the roll movement, we must consider a lateral drift movement, expressed as the lateral position η of the mass center G of the ship relative to the rigid Earth:

$$\frac{d^2}{dt^2}\eta = w_\eta(t)$$

By $w_\eta(t)$ we express the resultant of all disturbing accelerations acting on G.

Next, we express these equations as a system of first order differential equations. By substituting

$$x_1 := \xi, \quad x_2 := \frac{d}{dt}\xi, \quad x_3 := \eta, \quad x_4 := \frac{d}{dt}\eta$$

we obtain

$$\frac{d}{dt}\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ -\omega^2 - 1/\tau^2 & -2/\tau & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} + \begin{pmatrix} 0 \\ w_\xi \\ 0 \\ w_\eta \end{pmatrix} .$$

Also in the inhomogeneous case $w_\xi, w_\eta \neq 0$ we are able to express the general solution of this set of equations, but the full expression is very clumsy. In principle, it takes the form matrix

$$x = \Phi x_0 + w_0$$

where Φ is the state transition matrix, x_0 is the initial state of the system and w_0 considers the effect of the disturbances. This gives rise to the state equation of a time dicrete dynamical system:

$$x_k = \Phi_{k-1} x_{k-1} + w_{k-1}, \quad k = 0, 1, 2, ...$$

Up to now we have tacitly assumed that the disturbances can be characterized by a Gaussian process, as usually required in Kalman filtering. Problems can arise from non-stochastic disturbances like constant wind forces. If they are known, it is simple to introduce them.

The next problem is to define suitable initial covariance matrices for the w-vector. We leave it unsolved at the moment.

Kalman filtering: Measurement equations

The system is accessible to a set of time-discrete measurements z_k related to the state vector x_k by a linear equation

$$z_k = H_k x_k + v_k$$

where H_k is the measurement sensitivity matrix and v_k is a vector of measurement errors. The index k refers to the number of epoch.

When building a Kalman filter we must now define the matrices and vectors involved. If the roll angle can be observed directly by INS, like in the test data set, we would immediately have

$$z_{kl} = x_{kl} + v_{kl}$$

If we observe the movement of the ship by GPS using an antenna in height h above G, we would

get the equation

$$z_{k2} = x_{k3} + \sin(x_{k1}) \cdot h + v_{k2} \approx x_{k3} + x_{k1} \cdot h + v_{k2}$$

In this case the matrix $\boldsymbol{H}_k$ would read

$$H = \begin{pmatrix} 1 & 0 & 0 & 0 \\ h & 0 & 1 & 0 \end{pmatrix}$$

From knowledge of measurement accuracies we can easily define suitable initial covariance matrices for the *v*-vector.

Adaptive Kalman filtering

For the practical application of Kalman filtering we need the parameters τ, ω and h. In ship dynamics we often have little knowledge of such values, least of all of τ. Moreover, these values may be time variable. For example, *G* is not a fixed point since fuel and other objects are moving on board the ship. In this case we augment the state vector to become

$$x = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ \tau \\ \omega \\ h \end{pmatrix}$$

This method is known as **adaptive** Kalman filtering. The unknown parameters are estimated in the framework of Kalman filtering. However, there are disadvantages:

1. The solution becomes more and more underdetermined. More measurements are required.

2. The state equations take a nonlinear form. Linearization of Kalman state equations is possible in the framework of extended Kalman filtering, but introduces additional linearization errors.

At the moment, we do not have enough data to perform adaptive Kalman filtering. In the future, we will try to obtain such data and we will further investigate the method.

Conclusions

We have shown a simple and workable procedure that accounts for the effect of rolling, when navigating large cruise liners from Papenburg to the North sea. In the future, this fully deterministic approach should be replaced by some optimal filtering technique like (adaptive) Kalman filtering.

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