Krzysztof Jaskólski

**AUTOMATIC IDENTIFICATION SYSTEM (AIS) DYNAMIC DATA ESTIMATION BASED ON DISCRETE KALMAN FILTER (KF) ALGORITHM**

**ABSTRACT**

Due to the safety reason, the ship movement on the littoral area should be monitored, tracked, recorded and stored. Automatic Identification System (AIS) is the perfect tool to ensure this requirement. The limit probability for the AIS dynamic data availability can be limited by the lack of Global Position System (GPS) signal, heading (HDG) and rate of turn (ROT) data in position report. Availability of data link is an additional limitation. For this purpose, it is possible to attach the Discrete Kalman filter (KF) for the position, and course estimation. Coordinate estimation in the absence of a transmission link can improve the quality of AIS service at Vessel Traffic Service (VTS) stations. This article presents Kalman filtering algorithm to improve the possibilities of ship motion tracking and monitoring in the TSS (Traffic Separation Scheme) and fairways area. Only 39 iterations were presented to familiarize how the Kalman filter algorithm works. The archival data from 2006 were used deliberately. During that time, there were problems with the AIS availability service. With the use of measurements series from those years, it is easier to observe the effectiveness of Kalman filter in absence of AIS data.

**Key words:**
AIS, Kalman filter, AIS data estimation.

**INTRODUCTION**

At present, according to increased maritime transport, we pay particular attention to the safety aspect. The downsizing of crew forced the introduction of new
technological solutions for safety navigation. It is possible to define the coordinates of your own ship. In relation to the other ships you must rely on navigation systems. One of the commonly used systems for this purpose is AIS. Unfortunately, AIS developers did not meet integrity, availability and reliability expectations. Therefore, appropriate steps must be taken to minimize the risk of unreliable information. Over the years, a number of articles have been published about AIS data integrity and availability. Looking for a solution to the reliability problem of navigation systems presented in [5, 7], it is proposed to use the discrete KF to estimate coordinates for AIS position reports.

STATE OF KNOWLEDGE ON THE DISCRETE KALMAN FILTER ALGORITHM

The Kalman filter estimates a process by using a form of feedback control: the filter estimates the process state at some time and then obtains feedback in the form of (noisy) measurements. The equations for the Kalman filter fall into two groups: time update equations and measurement update equations. The time update equations are responsible for projecting forward (in time) the current state and error covariance estimates to obtain the a priori estimates for the next time step. The measurement update equations are responsible for the feedback — i.e. for incorporating a new measurement into the a priori estimate to obtain an improved a posteriori estimate.

The time update equations can also be thought of as predictor equations, while the measurement update equations can be thought of as corrector equations. Indeed the final estimation algorithm resembles that of a predictor-corrector algorithm for solving numerical problems as shown below in figure 1 [11].

![Fig. 1. The ongoing discrete Kalman filter cycle [11]](image-url)
The equations for the time and measurement updates are presented below. According to formula (1), (2) discrete Kalman filter time update equations are:

$$\hat{x}_k^- = A \cdot \hat{x}_{k-1} + B \cdot u_k + w_{k-1},$$  \hspace{1cm} (1)

where:
- $\hat{x}_k^-$ — estimated state vector;
- $A$ — transition matrix;
- $\hat{x}_{k-1}$ — previous estimated state vector;
- $B$ — output matrix;
- $u_k$ — control variable vector;
- $w_{k-1}$ — previous state noise matrix

and

$$P_k^- = A \cdot P_{k-1} \cdot A^T + Q,$$ \hspace{1cm} (2)

where:
- $P_k^-$ — process error covariance;
- $P_{k-1}$ — previous state process covariance;
- $A^T$ — transpose of a matrix;
- $Q$ — process noise covariance.

The state and covariance matrix estimates forward from time step $k-1$ to step $k$.

According to formula (3), (4), (5), discrete Kalman filter measurement update equations are presented below:

$$K_k = P_k^- \cdot H^T \cdot (H \cdot P_k^- \cdot H^T + R)^{-1},$$ \hspace{1cm} (3)

where:
- $K_k$ — Kalman gain;
- $H^T$ — transpose of simply transformation matrix;
- $H$ — simply transformation matrix;
- $R$ — sensor noise covariance

and

$$\hat{x}_k = \hat{x}_k^- + K_k \cdot (z_k - H \cdot \hat{x}_k^-),$$ \hspace{1cm} (4)

where:
- $\hat{x}_k$ — a posteriori estimate of the state at step $k$;
- $\hat{x}_k^-$ — a priori estimated state;
- $z_k$ — actual measurement vector

and

$$P_k = (I - K_k \cdot H) \cdot P_k^-,$$ \hspace{1cm} (5)
where:

\[ P_k \] — process error covariance matrix;

\[ I \] — identity matrix;

\[ P_k^- \] — process error covariance ahead.

1. The first task during the measurement update is to compute the Kalman gain \( K_k \).
2. The next step is to actually measure the process to obtain \( z_k \) and then to generate an a posteriori state estimate by incorporating the measurement as in equation \( \hat{x}_k \) (4). Again equation (4) \( \hat{x}_k \) a posteriori state estimate as a linear combination of an a priori estimate \( \hat{x}_k^- \) and a weighted difference between an actual measurement \( z_k \) and a measurement prediction \( H \cdot \hat{x}_k^- \) [11].

The final step is to obtain an a posteriori error covariance estimate via equation (5). Figure 2 offers a complete picture of the operation of the filter [11].

Because most of vessels navigating in TSS and fairways and by the shortest route we may assume that vessels navigating along linear path, thus the first algorithm will use the linear movement description. The second algorithm will use Kalman filtering.
LINEAR ALGORITHM FOR SHIP MOVEMENT PREDICTION

According to technical specification [3] every vessels equipped with AIS receiver transmits position report about its movement. These selected data are presented in table 1.

Tab. 1. Selected data of AIS Position Report [3]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Message ID</td>
<td>Identifier for this Message 1, 2 or 3.</td>
</tr>
<tr>
<td>User ID</td>
<td>Unique identifier such as MMSI number.</td>
</tr>
<tr>
<td>Rate of turn</td>
<td>0 to +126 = turning right at up to 708° per min or higher; 0 to –126 = turning left at up to 708° per min or higher; Values between 0 and 708° per min coded by ROT AIS = 4.733 SQRT(ROT sensor) degrees per min where ROT sensor is the Rate of Turn as input by an external Rate of Turn Indicator (TI). ROT AIS is rounded to the nearest integer value. +127 = turning right at more than 5° per 30 s (No TI available); –127 = turning left at more than 5° per 30 s (No TI available); –128 (80 hex) indicates no turn information available (default). ROT data should not be derived from COG information.</td>
</tr>
<tr>
<td>Speed over ground</td>
<td>Speed over ground in 1/10 knot steps (0–102.2 knots) 1 023 = not available, 1 022 = 102.2 knots or higher.</td>
</tr>
<tr>
<td>Longitude</td>
<td>Longitude in 1/10 000 min (±180°, East = positive (as per 2’s complement), West = negative (as per 2’s complement). 181 = (6791AC0h) = not available = default).</td>
</tr>
<tr>
<td>Latitude</td>
<td>Latitude in 1/10 000 min (±90°, North = positive (as per 2’s complement), South = negative (as per 2’s complement). 91°(3412140h) = not available = default).</td>
</tr>
<tr>
<td>Course over ground</td>
<td>Course over ground in 1/10 = (0–3599). 3600 (E10h) = not available = default. 3 601-4 095 should not be used.</td>
</tr>
<tr>
<td>Time stamp</td>
<td>UTC second when the report was generated by the electronic position system (EPFS) (0–59, or 60 if time stamp is not available, which should also be the default value, or 61 if positioning system is in manual input mode, or 62 if electronic position fixing system operates in estimated (dead reckoning) mode, or 63 if the positioning system is inoperative).</td>
</tr>
</tbody>
</table>

If vessel is on the way, moored, at anchor, we know its speed over ground \( (V) \) in knots, course over ground \( (\psi) \), geographic position \( (\varphi, \lambda) \). For the research purpose \( \psi' \) was converted to \( \frac{m}{s} \) according to formula (10), and geographic position was converted to Cartesian coordinates \( (x, y) \) according to formula (6), (7), (8), (9) [2]. Finally, coordinates will be presented with the use a 2-dimensional Cartesian coordinate system — The Universal Transverse Mercator (UTM).
With the use of ellipsoid WGS-84 parameters, estimate the square of the first eccentric \(e^2\) [1]

\[
e^2 = \frac{a^2 - b^2}{a^2},
\]

(6)

where:
\(a\) — semi-major axis;
\(b\) — semi-minor axis

and

\(a = 6378137,0\ m;\)
\(b = 6356752,3\ m.\)

Determine the radius of curvature for the first vertical circle \(N\) [1]

\[
N = \frac{a}{\sqrt{1 - e^2 \sin^2 \phi}}
\]

(7)

where
\(\phi\) — latitude.

Then, the Cartesian coordinates take the form [1]:

\[
X = (N + h) \cdot \cos \phi \cdot \cos \lambda;
\]

(8)

\[
Y = (N + h) \cdot \cos \phi \cdot \sin \lambda;
\]

(9)

\[
Z = [N - (1 - e^2) + H],
\]

(10)

where:
\(H\) — height of the point ‘P’;
\(\lambda\) — longitude.

According to formula (10), speed over ground given in [kt] should be converted to [m/s]

\[
V' \left[\frac{m}{s}\right] = 0.514(4) \cdot V[kt],
\]

(11)

where
\(V'\) — speed over ground in \(\left[\frac{m}{s}\right]\)

and

\[
\omega' \left[\frac{\circ}{min}\right] = \frac{\text{rot} \left[\frac{\circ}{min}\right]}{60},
\]

(12)

where
\(\omega'\) — rate of turn in \(\left[\frac{\circ}{s}\right]\).
According to $\Delta t = 10$ s observations, AIS data were presented in table 2.

<table>
<thead>
<tr>
<th>observation number</th>
<th>time [s]</th>
<th>$\Delta t$</th>
<th>$X$ [m]</th>
<th>$Y$ [m]</th>
<th>$\varphi$ [°]</th>
<th>$V'$ [m/s]</th>
<th>$\omega$ [°/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6062445</td>
<td>4368335</td>
<td>3.8</td>
<td>5.2</td>
<td>0.13</td>
</tr>
<tr>
<td>1</td>
<td>11</td>
<td>11</td>
<td>6062500</td>
<td>4368343</td>
<td>5.1</td>
<td>5.2</td>
<td>0.12</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>9</td>
<td>6062556</td>
<td>4368351</td>
<td>6.3</td>
<td>5.2</td>
<td>-0.10</td>
</tr>
<tr>
<td>3</td>
<td>29</td>
<td>9</td>
<td>6062600</td>
<td>4368359</td>
<td>5.3</td>
<td>5.4</td>
<td>0.35</td>
</tr>
<tr>
<td>4</td>
<td>39</td>
<td>10</td>
<td>6062655</td>
<td>4368367</td>
<td>8.8</td>
<td>5.3</td>
<td>-0.12</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>11</td>
<td>6062711</td>
<td>4368375</td>
<td>7.6</td>
<td>5.5</td>
<td>-0.42</td>
</tr>
<tr>
<td>6</td>
<td>60</td>
<td>10</td>
<td>6062766</td>
<td>4368383</td>
<td>3.4</td>
<td>5.5</td>
<td>0.33</td>
</tr>
<tr>
<td>7</td>
<td>71</td>
<td>11</td>
<td>6062822</td>
<td>4368391</td>
<td>6.7</td>
<td>5.5</td>
<td>-0.29</td>
</tr>
<tr>
<td>10</td>
<td>99</td>
<td>28</td>
<td>6062988</td>
<td>4368422</td>
<td>3.8</td>
<td>5.3</td>
<td>0.50</td>
</tr>
<tr>
<td>11</td>
<td>110</td>
<td>11</td>
<td>6063043</td>
<td>4368430</td>
<td>8.8</td>
<td>5.4</td>
<td>-0.07</td>
</tr>
<tr>
<td>14</td>
<td>140</td>
<td>30</td>
<td>6063210</td>
<td>4368454</td>
<td>8.1</td>
<td>5.7</td>
<td>-0.08</td>
</tr>
<tr>
<td>15</td>
<td>149</td>
<td>9</td>
<td>6063254</td>
<td>4368462</td>
<td>7.3</td>
<td>5.6</td>
<td>-0.11</td>
</tr>
<tr>
<td>17</td>
<td>170</td>
<td>21</td>
<td>6063365</td>
<td>4368484</td>
<td>6.2</td>
<td>5.4</td>
<td>0.06</td>
</tr>
<tr>
<td>19</td>
<td>191</td>
<td>21</td>
<td>6063487</td>
<td>4368501</td>
<td>6.8</td>
<td>5.8</td>
<td>-0.28</td>
</tr>
<tr>
<td>20</td>
<td>200</td>
<td>9</td>
<td>6063542</td>
<td>4368509</td>
<td>4.0</td>
<td>5.4</td>
<td>0.47</td>
</tr>
<tr>
<td>31</td>
<td>311</td>
<td>111</td>
<td>6064152</td>
<td>4368604</td>
<td>8.7</td>
<td>5.9</td>
<td>-0.52</td>
</tr>
<tr>
<td>34</td>
<td>339</td>
<td>28</td>
<td>6064307</td>
<td>4368628</td>
<td>3.5</td>
<td>5.6</td>
<td>0.5</td>
</tr>
<tr>
<td>35</td>
<td>350</td>
<td>11</td>
<td>6064373</td>
<td>4368643</td>
<td>8.5</td>
<td>5.7</td>
<td>0.43</td>
</tr>
<tr>
<td>36</td>
<td>360</td>
<td>10</td>
<td>6064429</td>
<td>4368651</td>
<td>12.8</td>
<td>5.8</td>
<td>-0.28</td>
</tr>
<tr>
<td>38</td>
<td>379</td>
<td>19</td>
<td>6064540</td>
<td>4368667</td>
<td>10.0</td>
<td>5.9</td>
<td>-0.10</td>
</tr>
</tbody>
</table>

According to observation numbers and interval of recorded data, it is easy to observe the limitation of VHF data link availability and the latency of AIS position reports.

For the linear algorithm, coordinates might be estimated as follows:

$$X_k = X_{k-1} + \Delta X; \quad (13)$$

$$Y_k = Y_{k-1} + \Delta Y, \quad (14)$$

where:

$X_{k-1}, Y_{k-1}$ — coordinates for the previous moment — AIS data;

$\Delta X, \Delta Y$ — shift coordinates in x and y axis.

If [4]

$$\Delta X = \frac{a_x \Delta t^2}{2}; \quad (15)$$

$$\Delta Y = \frac{a_y \Delta t^2}{2}$$

and [9]

$$a_x = \frac{V' k \cos (\varphi_k + \omega_k \Delta t) - \cos (\varphi_{k-1})}{\Delta t}; \quad (17)$$
\[ a_y = \frac{V'_k \cdot \sin(\psi'_k + \omega'_k \Delta t) - \sin(\psi_{k-1})}{\Delta t}, \]  

(18)

where:

- \( a_x, a_y \) — acceleration in \( x \) and \( y \) axis;
- \( \omega'_k \) — rate of turn;
- \( V' \) — speed over ground;
- \( \psi \) — course over ground.

**DISCRETE KALMAN FILTERING ALGORITHM FOR SHIP MOVEMENT PREDICTION**

The Kalman filter has been the subject of extensive research and application, particularly in the area of autonomous or assisted navigation. This is a recursive algorithm responsible for discrete linear dynamic process estimation. The algorithm is responsible for minimize the mean of the squared error. Due to the reason discrete KF might be applied for ship movement estimation [11].

For \( k \) iteration, and for 2 dimension model the state vector \( X_i \) is

\[
X_i = \begin{bmatrix} \begin{bmatrix} x_k \\ y_k \\ V'_k \cdot \cos(\psi'_k) \\ V'_k \cdot \sin(\psi'_k) \end{bmatrix} \end{bmatrix},
\]

(19)

where:

- \( x_k, y_k \) — UTM coordinates;
- \( V'_k \cdot \cos(\psi'_k), V'_k \cdot \sin(\psi'_k) \) — linear speed in \( x \) and \( y \) axis.

For the initial state

\[
X_0 = \begin{bmatrix} 0 m \\ 0 m \\ 0 m/s \\ 0 m/s \end{bmatrix}.
\]

For the 1 iteration

\[
X_1 = \begin{bmatrix} 6062445 m \\ 4368335 m \\ 5,2 m/s \\ 0,3 m/s \end{bmatrix}.
\]
The transition matrix for 2 dimension model is presented according to formula [4]:

\[
A = \begin{bmatrix}
1 & 0 & \Delta t & 0 \\
0 & 1 & 0 & \Delta t \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix},
\] (20)

where \(\Delta t = 10\) s — interval between current and previous measurements.

To estimate predicted state matrix \(\hat{x}_k\), the product of output matrix \(B\) and control variable vector \(u_k\) for 2 dimension model is presented as follow

\[
B \cdot u_k = \begin{bmatrix}
a_x \cdot \frac{\Delta t^2}{2} [m] \\
a_y \cdot \frac{\Delta t^2}{2} [m] \\
a_x \cdot \Delta t [m/s] \\
a_y \cdot \Delta t [m/s]
\end{bmatrix}.
\] (21)

If there are no information about imperfection of measuring sensors for observed vessel via AIS, noise in the process vector \(w_{k-1}\) for the previous iteration is

\[
w_{k-1} = \begin{bmatrix}
0 [m] \\
0 [m] \\
0 [m/s] \\
0 [m/s]
\end{bmatrix},
\]
then predicted state matrix \(\hat{x}_k\) is

\[
\hat{x}_k = A \cdot \hat{x}_{k-1} + B \cdot u_k + w_{k-1},
\] (22)

where

\(\hat{x}_{k-1}\) — previous state vector.

To estimate previous state process covariance matrix \(P_{k-1}\), following assumption were adopted for the first 5 iterations.

If

\[
\sigma_x = 10 \ m, \ \sigma_y = 10 \ m, \ \sigma_x' = 0.5 \ \frac{m}{s}, \ \sigma_y' = 0.5 \ \frac{m}{s}
\]
and if

\[
P_{k-1} = \begin{bmatrix}
\sigma_x^2 & \text{cov}(x, y) & \text{cov}(x, V_x) & \text{cov}(x, V_y) \\
\text{cov}(y, x) & \sigma_y^2 & \text{cov}(y, V_x) & \text{cov}(y, V_y) \\
\text{cov}(V_x, x) & \text{cov}(V_x, y) & \sigma_x'^2 & \text{cov}(V_x, V_y) \\
\text{cov}(V_y, x) & \text{cov}(V_y, y) & \text{cov}(V_y, V_x) & \sigma_y'^2
\end{bmatrix},
\] (23)
then
\[
P_{k-1} = \begin{bmatrix}
100 \, m^2 & 100 \, m^2 & 5 \, m^2/s & 5 \, m^2/s \\
100 \, m^2 & 100 \, m^2 & 5 \, m^2/s & 5 \, m^2/s \\
5 \, m^2/s & 5 \, m^2/s & 0.25 \, m^2/s^2 & 0.25 \, m^2/s^2 \\
5 \, m^2/s & 5 \, m^2/s & 0.25 \, m^2/s^2 & 0.25 \, m^2/s^2 \\
\end{bmatrix}.
\]

For estimate previous state process covariance matrix \( P_{k-1} \) according to formula (23) for \( k=5+i \) iteration, elements of the \( P_{k-1} \) matrix are presented below [6]:

\[
\sigma_x^2 = \Delta t^2 \cdot [\sigma_v \cdot \cos(\psi_{k-1})]^2 + \Delta t^2 \cdot [\sigma_{\psi} \cdot V_k \cdot \cos(\psi_k)]^2; \quad (24)
\]
\[
\sigma_y^2 = \Delta t^2 \cdot [\sigma_v \cdot \sin(\psi_{k-1})]^2 + \Delta t^2 \cdot [\sigma_{\psi} \cdot V_k \cdot \cos(\psi_k)]^2; \quad (25)
\]
\[
\sigma_{vx}^2 = [(\sigma_v \cdot \cos(\psi_k))^2 + [\sigma_{\psi} \cdot V_k \cdot \sin(\psi_k)]^2; \quad (26)
\]
\[
\sigma_{vy}^2 = [(\sigma_v \cdot \sin(\psi_k))^2 + [\sigma_{\psi} \cdot V_k \cdot \cos(\psi_k)]^2; \quad (27)
\]
\[
cov(x,y) = \text{cov}(y,x) = \frac{1}{2} \cdot \Delta t^2 \cdot \sin(2 \cdot \psi_k) \cdot [\sigma_v^2 - (\sigma_{\psi} \cdot V_k)]; \quad (28)
\]
\[
cov(x,V_x) = \text{cov}(V_x, x) = \Delta t \cdot \cos(\psi_k)^2 \cdot [\sigma_v^2 - (\sigma_{\psi} \cdot V_k)]; \quad (29)
\]
\[
cov(y, V_y) = \text{cov}(V_y, y) = \Delta t \cdot \sin(\psi_k)^2 \cdot [\sigma_v^2 + (\sigma_{\psi} \cdot V_k)]; \quad (30)
\]
\[
cov(V_x, V_y) = \text{cov}(V_x, V_y) = \frac{1}{2} \cdot \sin(2 \cdot \psi_k) \cdot [\sigma_v^2 + (\sigma_{\psi} \cdot V_k)]; \quad (31)
\]
\[
cov(y, V_x) = \text{cov}(V_x, y) = \frac{1}{2} \cdot \Delta t \cdot \sin(2 \cdot \psi_k) \cdot [\sigma_v^2 - (\sigma_{\psi} \cdot V_k)]; \quad (32)
\]
\[
cov(x, V_y) = \text{cov}(V_y, x) = \frac{1}{2} \cdot \Delta t \cdot \sin(2 \cdot \psi_k) \cdot [\sigma_v^2 - (\sigma_{\psi} \cdot V_k)]. \quad (33)
\]

If process noise covariance \( Q \)
\[
Q \equiv P_{k-1}, \quad (34)
\]

then process error covariance \( P_k^- \) for 2 dimension model is calculated according to formula (2).

If simply transformation matrix \( H \) is presented as follow
\[
H = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix} \quad (35)
\]

and sensor noise covariance matrix \( R \) is calculated in every iteration, where diagonal values are variances of last 5 measurements of coordinates and velocity.
\[ R = \begin{bmatrix} \sigma_x^2 & 0 & 0 & 0 \\ 0 & \sigma_y^2 & 0 & 0 \\ 0 & 0 & \sigma_x^2 & 0 \\ 0 & 0 & 0 & \sigma_y^2 \end{bmatrix}, \quad (36) \]

then Kalman gain \( K_k \) is calculated in every iteration according to formula (3).

If actual measurement vector \( z_k \) is presented as follow

\[ z_k = \begin{bmatrix} x_k [m] \\ y_k [m] \\ V'_k \cdot \cos(\psi_k) [m/s] \\ V'_k \cdot \sin(\psi_k) [m/s] \end{bmatrix}, \quad (37) \]

then a posteriori estimate of the state at step \( k \) \( \hat{x}_k \) is estimated according to formula (4).

Finally, if identity matrix takes form

\[ I = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (38) \]

then process error covariance matrix \( P_k \) is calculated according formula (5).

If coordinates are unavailable, then course over ground for \( k \) iteration is calculated according to formula [6]

\[ \psi_k = \text{atan} \left( \frac{y_k - y_{k-1}}{x_k - x_{k-1}} \right), \quad (39) \]

and linear speed over ground in \( x \) and \( y \) axis is calculated according to formulas:

\[ V'_k^x = \cos(\psi_k) \cdot V_k [m/s]; \quad (40) \]
\[ V'_k^y = \sin(\psi_k) \cdot V_k [m/s]. \quad (41) \]

**RESEARCH OUTCOMES**

Measurement experiment has been conducted in area Gulf of Gdansk. The archival data from 2006 were used deliberately. Only 39 iterations with the use of Discrete Kalman Filtering Algorithm were carried out to reduce VHF AIS data link unavailability. The research outcomes of AIS and KF data fusion to improve availability of VHF AIS data link were presented in table 3.
Tab. 3. The research outcomes of AIS and KF data fusion

<table>
<thead>
<tr>
<th>( i )</th>
<th>( t ) [s]</th>
<th>( y ) [m]</th>
<th>( x ) [m]</th>
<th>( \psi_{\text{est}} ) [°]</th>
<th>( \Delta \psi )</th>
<th>( \Delta x ) [m]</th>
<th>( \Delta y ) [m]</th>
<th>( M_{x,y} ) [m]</th>
<th>( M_{V} ) [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>4368335</td>
<td>6062445</td>
<td>3,8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>14,1</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>4368339</td>
<td>6062497</td>
<td>8,3</td>
<td>-3,2</td>
<td>4,0</td>
<td>3,0</td>
<td>14,1</td>
<td>0,7</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>4368350</td>
<td>6062554</td>
<td>8,1</td>
<td>-1,8</td>
<td>1,0</td>
<td>2,0</td>
<td>14,1</td>
<td>0,7</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>4368355</td>
<td>6062607</td>
<td>10,3</td>
<td>-5</td>
<td>4,0</td>
<td>-7,0</td>
<td>10,5</td>
<td>0,5</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>4368362</td>
<td>6062659</td>
<td>8,3</td>
<td>0,5</td>
<td>5,0</td>
<td>-4,0</td>
<td>10,8</td>
<td>1,0</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>4368373</td>
<td>6062711</td>
<td>8,1</td>
<td>-0,5</td>
<td>2,0</td>
<td>0,0</td>
<td>10,8</td>
<td>1,1</td>
</tr>
<tr>
<td>6</td>
<td>60</td>
<td>4368382</td>
<td>6062766</td>
<td>8,3</td>
<td>-4,9</td>
<td>1,0</td>
<td>0,0</td>
<td>10,8</td>
<td>1,1</td>
</tr>
<tr>
<td>7</td>
<td>70</td>
<td>4368391</td>
<td>6062822</td>
<td>8,1</td>
<td>-1,4</td>
<td>0,0</td>
<td>0,0</td>
<td>10,8</td>
<td>1,1</td>
</tr>
<tr>
<td>8</td>
<td>80</td>
<td>4368399</td>
<td>6062876</td>
<td>8,1</td>
<td>-1,4</td>
<td>0,0</td>
<td>0,0</td>
<td>10,8</td>
<td>1,1</td>
</tr>
<tr>
<td>9</td>
<td>90</td>
<td>4368405</td>
<td>6062931</td>
<td>8,1</td>
<td>-1,4</td>
<td>0,0</td>
<td>0,0</td>
<td>10,8</td>
<td>1,1</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>4368420</td>
<td>6062988</td>
<td>8,1</td>
<td>-4,3</td>
<td>2,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>11</td>
<td>110</td>
<td>4368429</td>
<td>6063043</td>
<td>8,3</td>
<td>0,5</td>
<td>1,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>12</td>
<td>120</td>
<td>4368437</td>
<td>6063096</td>
<td>8,3</td>
<td>0,5</td>
<td>1,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>13</td>
<td>130</td>
<td>4368445</td>
<td>6063149</td>
<td>8,3</td>
<td>0,5</td>
<td>1,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>14</td>
<td>140</td>
<td>4368453</td>
<td>6063210</td>
<td>8,3</td>
<td>-0,2</td>
<td>1,0</td>
<td>0,0</td>
<td>11,1</td>
<td>1,1</td>
</tr>
<tr>
<td>15</td>
<td>150</td>
<td>4368462</td>
<td>6063254</td>
<td>10,3</td>
<td>-3</td>
<td>0,0</td>
<td>0,0</td>
<td>11,1</td>
<td>1,1</td>
</tr>
<tr>
<td>16</td>
<td>160</td>
<td>4368471</td>
<td>6063309</td>
<td>10,3</td>
<td>-3</td>
<td>0,0</td>
<td>0,0</td>
<td>11,1</td>
<td>1,1</td>
</tr>
<tr>
<td>17</td>
<td>170</td>
<td>4368483</td>
<td>6063365</td>
<td>10,3</td>
<td>-4,1</td>
<td>1,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>18</td>
<td>180</td>
<td>4368493</td>
<td>6063418</td>
<td>10,3</td>
<td>4,1</td>
<td>1,0</td>
<td>0,0</td>
<td>11,3</td>
<td>1,1</td>
</tr>
<tr>
<td>19</td>
<td>190</td>
<td>4368501</td>
<td>6063487</td>
<td>10,3</td>
<td>-3,5</td>
<td>0,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>20</td>
<td>200</td>
<td>4368510</td>
<td>6063542</td>
<td>8,3</td>
<td>-4,3</td>
<td>-1,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>21</td>
<td>210</td>
<td>4368518</td>
<td>6063595</td>
<td>8,3</td>
<td>4,3</td>
<td>1,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>22</td>
<td>220</td>
<td>4368522</td>
<td>6063650</td>
<td>8,3</td>
<td>4,3</td>
<td>1,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>23</td>
<td>230</td>
<td>4368526</td>
<td>6063703</td>
<td>8,3</td>
<td>4,3</td>
<td>1,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>24</td>
<td>240</td>
<td>4368534</td>
<td>6063765</td>
<td>8,3</td>
<td>4,3</td>
<td>1,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>25</td>
<td>250</td>
<td>4368541</td>
<td>6063810</td>
<td>8,3</td>
<td>4,3</td>
<td>1,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>26</td>
<td>260</td>
<td>4368549</td>
<td>6063863</td>
<td>8,3</td>
<td>4,3</td>
<td>1,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>27</td>
<td>270</td>
<td>4368557</td>
<td>6063917</td>
<td>8,3</td>
<td>4,3</td>
<td>1,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>28</td>
<td>280</td>
<td>4368565</td>
<td>6063970</td>
<td>8,3</td>
<td>4,3</td>
<td>1,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>29</td>
<td>290</td>
<td>4368573</td>
<td>6064023</td>
<td>8,3</td>
<td>4,3</td>
<td>1,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>30</td>
<td>300</td>
<td>4368579</td>
<td>6064076</td>
<td>8,3</td>
<td>4,3</td>
<td>1,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>31</td>
<td>310</td>
<td>4368597</td>
<td>6064152</td>
<td>8,3</td>
<td>0,4</td>
<td>7,0</td>
<td>0,0</td>
<td>10,7</td>
<td>1,1</td>
</tr>
<tr>
<td>32</td>
<td>320</td>
<td>4368607</td>
<td>6064210</td>
<td>8,3</td>
<td>0,4</td>
<td>7,0</td>
<td>0,0</td>
<td>11,1</td>
<td>1,1</td>
</tr>
<tr>
<td>33</td>
<td>330</td>
<td>4368617</td>
<td>6064268</td>
<td>8,3</td>
<td>0,4</td>
<td>7,0</td>
<td>0,0</td>
<td>11,4</td>
<td>1,1</td>
</tr>
<tr>
<td>34</td>
<td>340</td>
<td>4368627</td>
<td>6064307</td>
<td>8,3</td>
<td>-4,8</td>
<td>1,0</td>
<td>0,0</td>
<td>11,4</td>
<td>1,1</td>
</tr>
<tr>
<td>35</td>
<td>350</td>
<td>4368641</td>
<td>6064374</td>
<td>12,8</td>
<td>-4,3</td>
<td>2,0</td>
<td>-1,0</td>
<td>11,1</td>
<td>1,1</td>
</tr>
<tr>
<td>36</td>
<td>360</td>
<td>4368651</td>
<td>6064428</td>
<td>8,1</td>
<td>4,7</td>
<td>0,0</td>
<td>1,0</td>
<td>11,1</td>
<td>1,1</td>
</tr>
<tr>
<td>37</td>
<td>370</td>
<td>4368660</td>
<td>6064486</td>
<td>8,1</td>
<td>4,7</td>
<td>0,0</td>
<td>1,0</td>
<td>11,3</td>
<td>1,1</td>
</tr>
<tr>
<td>38</td>
<td>380</td>
<td>4368667</td>
<td>6064540</td>
<td>8,1</td>
<td>1,9</td>
<td>0,0</td>
<td>0,0</td>
<td>11,3</td>
<td>1,1</td>
</tr>
</tbody>
</table>

\( i \) — iteration number  
\( x, y \) — UTM coordinates estimated with the use of KF algorithm  
\( \psi_{\text{est}} \) — course over ground estimated with the use of KF algorithm coordinates  
\( \Delta x, \Delta y \) — difference between AIS and KF estimated coordinates  
\( \Delta \psi \) — difference between AIS and KF estimated course over ground  
\( M_{x,y} \) — mean error of coordinates  
\( M_{V} \) — mean error of speed over ground
Dark grey lines on table 3 presents updated data with the use of discrete Kalman filtering algorithm. The use of the Kalman filter was intended to improve the availability of AIS dynamic information displayed on the Vessel Traffic Service (VTS) stations. The research outcomes for the discrete KF estimation for Cartesian Coordinates were presented on figure 3.

![UTM coordinates for the AIS data and estimated coordinates (UTM) with the use of discrete Kalman filtering algorithm](image)

Estimated course over ground (est. $\psi[^{\circ}]$) was calculated according the formula (39). The scores of course estimation were presented on table 3. The differences between AIS data course and KF estimated course were presented on figure 4. The course differences did not exceed 5 degrees. The outcomes repeatability for the iteration number 21-30 is the result of the data generated by the Kalman filter algorithm.
Fig. 4. The difference between AIS course over ground and estimated course over ground with the use of discrete Kalman filtering algorithm [own study]

Coordinate differences for the x and y direction with the maximum 7 m difference were presented on figure 5. According to the research scores, maximum differences were typical for the first five iterations, where KF algorithm did not work and after AIS signal appearance, for 31 iteration.

Fig. 5. Differences between AIS and KF estimated \((x, y)\) coordinates [own study]
Similar proportion can be observed for mean error of coordinates calculation according to formula

\[ M_{xy} = \sqrt{\sigma_x^2 + \sigma_y^2}. \]  

(42)

An outcome scores for the mean error of coordinates were presented on figure 6.

---

An opposite outcome scores for the mean error of speed over ground were presented on figure 7 and calculated according the formula

\[ M_V = \sqrt{\sigma_{Vx}^2 + \sigma_{Vy}^2}. \]  

(43)

---

![Figure 6. Mean error of estimated coordinates [own study]](image1)

![Figure 7. Mean error of estimated speed over ground [own study]](image2)
CONCLUSION

Discrete Kalman filter algorithm seems to be a good tool for update position in case of AIS dynamic data unavailability. Only 39 iterations were presented to demonstrate the principle of discrete Kalman Filter. According to investigation scores, Kalman Filter application decrease the mean error of coordinates up to 10 meters. The essential factor affecting the correct Kalman filter operation is the appropriate estimation of the sensor noise covariance matrix $R$ and process noise covariance $Q$.

In the research studies, registered AIS position reports (from 2006) were used. Position reports were collected in area of VTS ZATOKA. An incomplete archive position reports has been selected deliberately to set the purpose of use Discrete Kalman Filter algorithm. Kalman Filter algorithm did not work for the first 5 iterations. This is easily noticeable for the estimated errors, for individual iterations.

REFERENCES


ESTYMACJA DANYCH DYNAMICZNYCH AUTOMATYCZNEGO SYSTEMU IDENTYFIKACJI (AIS) W OPARCIU O ALGORYTM DISKRETNEGO FILTRU KALMANA (KF)

STRESZCZENIE

Dla zapewnienia bezpieczeństwa żeglugi ruch jednostek pływających w rejonie wód wewnętrznych i w strefie przybrzeżnej powinien być monitorowany i rejestrowany, najlepiej w postaci cyfrowej. Doskonałym narzędziem do tego celu jest automatyczny system identyfikacji (AIS). Dostępność danych dynamicznych AIS może zostać jednak zredukowana z powodu braku dostępu do systemów pozycjonowania (GPS) oraz braku danych o kursie (HDG) i prędkości kątowej (ROT) w raportach pozycyjnych. Niedostępność łącza komunikacyjnego w paśmie VHF jest dodatkowym ograniczeniem systemu. W celu estymacji danych dotyczących pozycji i kursu statku w czasie, gdy dane te nie są dostępne, można zastosować dyskretny filtr Kalmana (KF). Estymacja współrzędnych w przypadku braku łącza komunikacyjnego wynikającego z ograniczeń dostępności systemu AIS podnosi jakość serwisu zarządzania ruchem statków (VTS). W artykule zaprezentowano 39 iteracji filtru Kalmana. Celowo zastosowano dane archiwalne z 2006 roku, albowiem w tych rejestracjach występują wyraźne przerwy w strumieniu danych. Rzecz w tym, że efektywność zaproponowanego rozwiązania łatwo zaobserwować, jeśli zostaną zastosowane serie pomiarowe z okresu, gdy występowaly problemy z dostępnością serwisu AIS.

Słowa kluczowe:
AIS, filtr Kalmana, estymacja danych AIS.