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Radar and Automatic Identification System Track Fusion in an Electronic Chart Display and Information System

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This paper presents the results of research on the fusion of tracking radar and an Automatic Identification System (AIS) in an Electronic Chart Display and Information System (ECDIS). First, the concept of these systems according to the International Maritime Organization (IMO) is described, then a set of theoretical information on radar tracking and the fusion method itself is given and finally numerical results with real data are presented. Two methods of fusion, together with their parameters, are examined. A proposal for calculating the covariance matrix for radar and AIS data is also given, and the paper ends with conclusions.

KEY WORDS

1. Radar. 2. Automatic Identification System. 3. Integrated navigation. 4. ECDIS

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1. INTRODUCTION. The main task for the officer in charge of a navigational watch at sea is to navigate the vessel safely to her destination. Thus, one of the most critical issues is to avoid collision situations with other ships. Knowing the movement parameters of observed targets is crucial for this. Traditionally, these parameters have been obtained by visual observation; however, with the development of technology, new sensors have appeared on the navigational bridge. Two of the most important sensors in terms of target observation are tracking radar and the Automatic Identification System (AIS).

Tracking radar is the most important sensor used for so-called tactical navigation. It is currently used on most merchant vessels, giving independent information about the movements of targets around the ship. It calculates the target's movement vector based on radar observation. Special tracking algorithms allow determination of the course and speed of the targets, taking into account range and bearing measurements. The most advanced International Maritime Organization (IMO) standard for a radar

Table 1. Accuracy requirements for radar tracking according to IMO (2004).

Time of steady motion	Relative course	Relative speed	Closest Point of Approach (CPA)	Time to CPA (TCPA)	True course	True speed
1 min: tendency	11°	1·5 kn or 10 %	1·0 Nm	–	–	–
3 min: prediction	3°	0·8 kn or 1%	0·3 Nm	0·5 min	5°	0·5 kn or 1%

device providing target tracking at sea is the Automatic Radar Plotting Aid (ARPA). Functional requirements for tracking radars were developed by the IMO in 1979, and the latest requirements were provided in 2004 (IMO, 2004) and have been mandatory from 2008. The accuracy requirements are presented in Table 1.

Radar is commonly used as the primary source of information in the avoidance of collision situations. The main deficiencies of this method are the delay in tracking, mostly during manoeuvres, and the lack of target identification (Kazimierski, 2013).

The other system, AIS, was intended to be a Very High Frequency (VHF) platform for broadcasting information about vessels. According to IMO requirements (IMO, 2000), each ship of more than 300 GT (gross tonnage, a measure of the ship's overall internal volume) has to be equipped with an AIS transceiver, which can transmit the ship's own data and also receive information from other vessels. The data include dynamic information, such as course, speed and position, voyage-related information (destination), as well as static information such as the vessel's name, call sign and dimensions. Thus, accurate information about other ships, together with identification, is transmitted. The main issue is that strategic data comes from external sensors, instead of independent observations with the ship's own sensor, as in the case of radar. Each sensor malfunction on the target ship results in incorrect data, which are transmitted on air. AIS in anti-collision processes has been used by many researchers, e.g. Hsu et al. (2009), Mou et al. (2010), Hansen et al. (2013), Silveira et al. (2013) and Last et al. (2014).

In practice, both systems (tracking radar and AIS) are used simultaneously, and fusion of their data has to be carried out. Thus, one of the key aspects of modern maritime navigation is data integration. It is essential that the officer in charge of the navigational watch receives reliable and accurate complex information from the various sensors available on board the vessel. Different systems are being developed independently, and new systems using integrated data are also appearing. The first example of such a system is an Electronic Chart Display and Information System (ECDIS), which was introduced at the end of the twentieth century. The main idea was to present navigational information with the background of an Electronic Navigational Chart (ENC). With time, the system has been developed, and new functionalities have arisen. In addition, methods to present collision situations around the ship have been evolving. The basis for this is fusion of data from tracking radar and AIS (Kazimierski, 2013). The ECDIS, which is often part of an Integrated Navigation System (INS), is nowadays the most important platform for fusion. Radar–AIS fusion is also a basis for navigational decision support systems, as demonstrated by Borkowski and Zwierzewicz (2011), Borkowski (2012), Pietrzykowski et al. (2012), Kazimierski and Wawrzyniak (2014), Stateczny and Bodus-Olkowska (2014) and Zhao et al. (2014).

This paper presents the main problems and concepts of tracking radar–AIS data fusion from the ECDIS's point of view. First, the ECDIS itself is described, based on IMO requirements. Next, a description of radar target tracking algorithms is given. Then, the most popular fusion concepts are presented. Finally, a numerical experiment is shown in which a comparison of two approaches and a proposal of their modification are given.

2. ECDIS ACCORDING TO THE IMO.

The ECDIS is currently widely used on vessels all over the world, in many cases, substituting traditional paper charts (with adequate backup arrangements). The newest requirements for the ECDIS are given by the IMO in Resolution MSC.232(82), which was adopted in 2006 (IMO, 2006). According to these requirements, the ECDIS is a navigation information system that displays selected information from a System of Electronic Navigational Charts (SENC) with positional information from navigation sensors to assist the mariner in route planning and route monitoring. On request, additional navigation-related information may be displayed. The ECDIS may be implemented on board as a dedicated standalone workstation or as a multifunctional workstation, as part of an INS.

2.1. *Main functions.*

The primary function of the ECDIS is to contribute to safe navigation. More detailed functions given in the requirements are related mostly to navigational charts. According to these, the ECDIS should:

- Be capable of displaying all chart information necessary for safe and efficient navigation;
- Facilitate simple and reliable updating of the ENC;
- Reduce the navigational workload in comparison to using a paper chart;
- Provide appropriate alarms or indications with respect to the information displayed or malfunction of the equipment.

Display of the ENC should follow IMO and International Hydrographic Organization (IHO) standards. From the anti-collision point of view, it is important that requirements for displaying other navigational information are also given. These also include radar and AIS data.

2.2. *Display of target data.*

Although the ECDIS is focused on presenting chart information, display of other navigational information for enhancing navigational safety is also allowed. The most important data included in the Resolution are radar and AIS data. According to IMO (2006), these data can be transferred from systems that are compliant with suitable IMO standards and added to the display. However, they should not degrade SENC information (standardised database with chart information) and should be clearly distinguishable from it. The possibility of removing radar/AIS data by a single operator action, if needed, should be ensured. No further requirements are stated.

Radar information transferred to the ECDIS can include both radar image and/or tracked target information. It is crucial that the added navigational information should use a common reference system with the SENC. The radar image and the position from the position sensor should both be adjusted automatically for antenna offset from the conning position.

It can be noticed while analysing the requirements for the ECDIS that they focus mostly on chart display. AIS and radar are only mentioned in reference to other

IMO documents such as those of the International Electrotechnical Commission (IEC, 2008). In fact, the concept of integration presented in IEC (2008) assumes only target association and selection of one of the targets: radar or AIS. It can be seen that no advanced fusion algorithms are needed to fulfil these requirements, except harmonized criteria for the association. Nevertheless, presentation of integrated radar–AIS information on the ECDIS screen is commonly used and plays an important role in modern navigation.

3. RADAR TARGET TRACKING ALGORITHMS.

While the task of obtaining plots and target data in the AIS is simple, because it is an external sensor and there are not many possibilities of adjusting it, it may become an important issue for radar. IMO requirements for radar tracking are to give accuracy figures. More detailed tests for checking the requirements are presented in IEC 62388 (IEC, 2013). However, none of these documents gives precise algorithms for tracking; this is left to the industrial manufacturers. Thus, each manufacturer has the possibility to introduce its own tracking methods.

The most commonly used algorithm for radar target tracking in maritime radars is the Kalman Filter or its modifications, e.g. the Extended Kalman Filter. In the following paragraph, the Kalman Filter algorithm for radar tracking of ships is presented. Because these methods suffer from a sudden decrease of accuracy during object manoeuvres, other numerical approaches have been proposed. They can be generally described as multiple model filters, but can also be divided into more specific groups. The main idea of these is to choose the best for the present situation of elementary Kalman filters. This can be done via adaptive estimation, decision-based methods or other multiple model approaches such as the Interacting Multiple Model (IMM) filter (Tuzlukov, 2013), by using interval Kalman filtering (Motwani et al., 2013) or another solution (Malleswaran et al., 2013; Wang et al., 2013a).

An interesting alternative for numerical methods is artificial neural networks. Promising results were obtained using these methods during 15 years of research carried out at the Maritime University of Szczecin. Out of the many network structures studied, the General Regression Neural Network (GRNN) performed particularly well (Stateczny, 2002b; Stateczny and Kazimierski, 2006). The research (Stateczny and Kazimierski, 2008a) showed that owing to considerable differences in dynamics, uniform rectilinear motion and non-linear motion require the application of different GRNN parameters. Thus, a concept of multiple model neural filters arose (Kazimierski et al., 2012; Kazimierski and Stateczny, 2012; Kazimierski and Zaniewicz, 2014) for radar and sonar tracking. Results of verification research presented in Stateczny and Kazimierski (2008b) have shown that neural filters are real competition for commercially used filters, especially during target manoeuvres.

Apart from the tracking method, it is essential that the most reliable positioning method is used for plotting radar information. This task means mostly extraction of targets from the radar screen. Another interesting alternative can be shown here for traditionally used pulse radars, Frequency Modulated Continuous Wave (FMCW) radar, which are particularly good for inland waters and short distances (Adamski et al., 2000; Kulpa, 2001, 2003; Kulpa et al., 2000).

The research carried out so far has proved radar usefulness for comparative navigation (Stateczny, 2002a, 2004) and for spatial sensor planning (Lubczonek, 2008; Lubczonek and Stateczny, 2009; Stateczny and Lubczonek, 2014) or other spatial

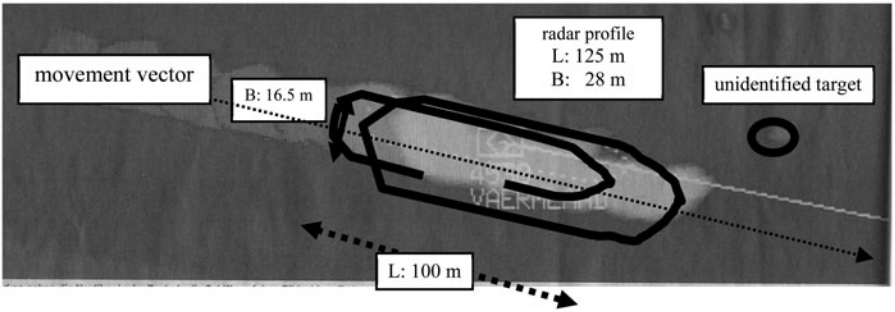

Figure 1. Discrepancies between radar and AIS images (Kazimierski and Stateczny, 2011).

analysis (Wang et al., 2013b). It is also worth mentioning that neural networks are nowadays more often used in navigation, in general, e.g. seabed modelling (Stateczny, 2000; Lubczonek and Stateczny, 2003; Lubczonek, 2004; Stateczny and Wlodarczyk-Sielicka, 2014; Wawrzyniak and Hyla, 2014).

4. AIS–RADAR FUSION CONCEPT.

The need for fusion of AIS and radar data arises from the diversity of both systems. In Figure 1, a screenshot from VTS in Hamburg is presented, which briefly shows the major differences between the two systems.

It cannot be allowed that the officer on watch gets two different movement vectors for one target – one from AIS transmission and one estimated from radar bearing and range measurements. Both are two-dimensional movement vectors, but owing to the specifics of each system, some differences are observed. This leads directly to sensor fusion. In general, two major concepts of AIS–radar fusion can be presented, namely decentralised and centralised approaches. In the first one, complex information is first calculated in each sensor and then provided to a fusion algorithm, where it is integrated with established rules. In the second one, raw measurements from the sensor are transmitted for further processing to the fusion module. In the case of the ECDIS, it is more convenient to use the decentralised concept. For the ECDIS, radar and AIS are just an external source of data, and creating an additional filter in the ECDIS for centralised fusion is pointless. The decentralised approach based on the Kalman Filter algorithm is also the most popular in the literature (e.g. Matzka and Altendorfer, 2008; Kazimierski and Stateczny, 2011).

The first step for all fusion algorithms is target association, and this step often generates most of the problems. Various algorithms for this task are also implemented, including numerical calculations, grey theory or fuzzy logic. Proposed solutions and a survey on association problems can be found in, for example, Kazimierski (2013).

4.1. *Problems of association.*

Differences between tracking radar and AIS concepts cause tracks to be received from both systems, which, although describing the same target, are of a different nature. Therefore, it is not a trivial problem to properly associate radar and AIS tracks. The following main problems in the association process can be identified (Stateczny and Kazimierski, 2013):

- Lack of time synchronisation between measurements in both systems;
- Various time intervals of measurements;

- Different speeds and courses (dualism);
- Lack of identification of radar targets;
- Large differences in position accuracies;
- Target representation – size of radar echo in relation to point AIS targets.

Most of these problems can be solved using methods presented in the literature (e.g. Kazimierski, 2013), and their description is beyond the scope of this paper. However, it is worth mentioning that the values used for track fusion are already an approximation of data and not real measurements. Many of the problems are caused by inaccuracies in the radar target tracking methods briefly presented above.

In Kazimierski (2013), a three-step algorithm was proposed for radar–AIS data association. In this approach, three association criteria were proposed:

- Position;
- Movement vector;
- History.

The first one is the most natural; however, it might happen that there is more than one target in the vicinity, so it is good to also check target movement. In addition, it may be necessary to confirm the association tendency in a period of time, thus, the criterion of history is also used.

The idea of association is to create a gate around the target data. The crucial task is then to determine a proper size of this gate. It has to be small enough to avoid false association, but large enough to include system errors. It can be said that a distance of three to four cables should be enough for position correlation (Stateczny and Kazimierski, 2013), and the movement vector gate can be established based on IMO accuracy requirements for radar tracking.

4.2. *Track fusion algorithms.* When the tracks are received and associated, a process of track fusion begins. It is assumed that the state vector and covariance are known from both systems (radar and AIS) and that they describe the same target. Various algorithms for track fusion are presented in the literature (e.g. Gan and Harris, 2001; Yang et al., 2006; Hill et al., 2010). From these, the most popular appear to be

- Simple fusion;
- With the use of cross-covariance.

In the simple fusion algorithm presented in, for example, Matzka and Altendorfer (2008) or Liggins et al. (2009), the fusion is a weighted average of elementary estimates (x), where the weights are computed directly from the covariance (P). For radar–AIS tracking of one target, the fusion equation has the form:

$$x = \left(P_r^{-1} + P_a^{-1}\right)^{-1}\left(P_r^{-1}x_r + P_a^{-1}x_a\right), \tag{1}$$

with an error covariance matrix of the form

$$P = \left(P_r^{-1} + P_a^{-1}\right)^{-1}. \tag{2}$$

The case of calculating fusion with cross-covariance is more complicated, and in a classical form, it requires more information from elementary filters. According to Matzka and Altendorfer (2008), the fusion for two sensors can be calculated as follows:

$$x = x_a + W(x_r - x_a) \tag{3}$$

Where

$$W = (P_a - P_{ar})U_{ar}^{-1} \tag{4}$$

$$U_{ar} = P_a + P_r - P_{ar} - P_{ar}^{-1} \tag{5}$$

and P_{ar} is the cross-covariance matrix, calculated recursively with the use of the Kalman Filter matrices of elementary filters. Such a solution is useless if only the estimated value and its covariance are known and no more details about elementary filters are given. This is a situation similar to the one in the ECDIS, where no information about tracking filters is transmitted, only the values. This situation also can happen if methods other than the Kalman Filter are used, such as the previously mentioned neural method. Thus, a method of approximation of the cross-covariance matrix by the Hadamard product of input matrices was proposed by Matzka and Altendorfer (2008):

$$P_{ar} = \rho(P_a \bullet P_r)^{1/2} \tag{6}$$

where ρ is an effective correlation coefficient, determined empirically. In this research, a value of 0·4 is adopted, following Kazimierski and Stateczny (2011).

An interesting approach, often used in the literature, is to fuse even more than two sensors using the Probabilistic Data Association Filter (PDAF) method and its mutations and developments. The filter is described thoroughly in Liggins et al. (2009) and its implementation can be found in Kwiatkowski et al. (2011).

5. NUMERICAL EXPERIMENTS.

The idea of this research was to verify the described algorithms with real data. For this purpose, dedicated software was prepared and data on a vessel was registered. The data included raw AIS and radar National Marine Electronics Association (NMEA) strings. It was then played back off-line with various filters (methods) applied. The main goal was to compare simple fusion with a cross-covariance fusion algorithm and to propose values for covariance. An ECDIS environment was assumed, i.e. only the values of the state vector received from external sensors (radar and AIS) are known. For track association, a three-step algorithm, consisting of position association, track association and history correlation was performed, as by Kazimierski (2013). Thus, the targets were assumed to be associated, and only track fusion was examined in this research.

5.1. *Research concept.*

The research focused on analysis of methods and variance matrices. Three stages of the research were proposed:

- Comparison of fusion algorithms;
- Comparison of variation matrices;
- Length of sliding window analysis.

The state vector was formulated as:

$$x = [BE, D, COG, SOG]^T \tag{7}$$

where *BE* is the true bearing to the target (angle between north and the line connecting the ship to the target, in degrees), *D* is the distance from the ship to the target (in nautical miles), *COG* is the course over the ground of the target (in degrees), *SOG* is the speed over ground of the target (in knots). After the association process, both vectors were synchronized and COG and SOG were known for both sensors.

All the values in the state vector were treated as independent measurements. Thus, the variance matrices in the first stage had the form of a diagonal matrix:

$$P = diag\left({\sigma_{BE}}^2, {\sigma_D}^2, {\sigma_{COG}}^2, {\sigma_{SOG}}^2\right) \tag{8}$$

For the radar, particular values were taken, following IMO requirements:

$$P_r = diag(4, 2500, 25, 0{\cdot}25) \tag{9}$$

For the AIS target, particular values were taken based on the so-called relative accuracy:

$$P_a = diag(0{\cdot}04, 225, 9, 0{\cdot}0001). \tag{10}$$

5.2. *Research scenario.* The research was performed in prepared software in VisualBasic.Net. The software allows implementation of any fusion method and easy adjustment of its parameters. Data for the scenarios can be simulated, imported off-line from files or received on-line via serial ports. In the research, the data were imported from previously recorded files.

Data for the research were recorded on research-school ship *Nawigator XXI* in the southern Baltic Sea. NMEA strings from tracking radar and from AIS were recorded and then played back in the software. The scenario presented in this paper included radar and AIS observation of ferry *Wolin* with a Length Over All (LOA) of 189 m and GT of almost 23 000 tonnes. Two hours of observation were recorded, with the *Nawigator XXI* remaining stationary. The trace of the target received from the AIS is presented in Figure 2.

Analysis of the influence of the length of sliding window was carried out in the third stage of the research.

6. RESEARCH RESULTS.

The results of the research are presented in the following subsections.

6.1. *Comparison of fusion algorithms.* In this stage, fusion using two methods – simple fusion and cross-covariance – was examined. The variance matrix was stated based on IMO requirements as in Equations (9) and (10). A comparison of course estimation is presented in Figure 3.

During analysis of Figure 3, it can be noticed that the estimated fusion is much closer to the AIS data, as these data are much more accurate. The graph is also more smoothed than the radar graph. However, both fusions deviate slightly towards the radar course, thus following its values. This observation confirms that both fusion methods are performing the task according to assumptions. It can also be noticed that the cross-covariance method relies more on the covariance matrix, because this fusion is closer to AIS data.

6.2. *Comparison of variances.* In the second stage of the research, the influence of the covariance matrix values was examined. Apart from those stated in Equation (8), a modification of the covariance matrices was proposed. The values in the state vector

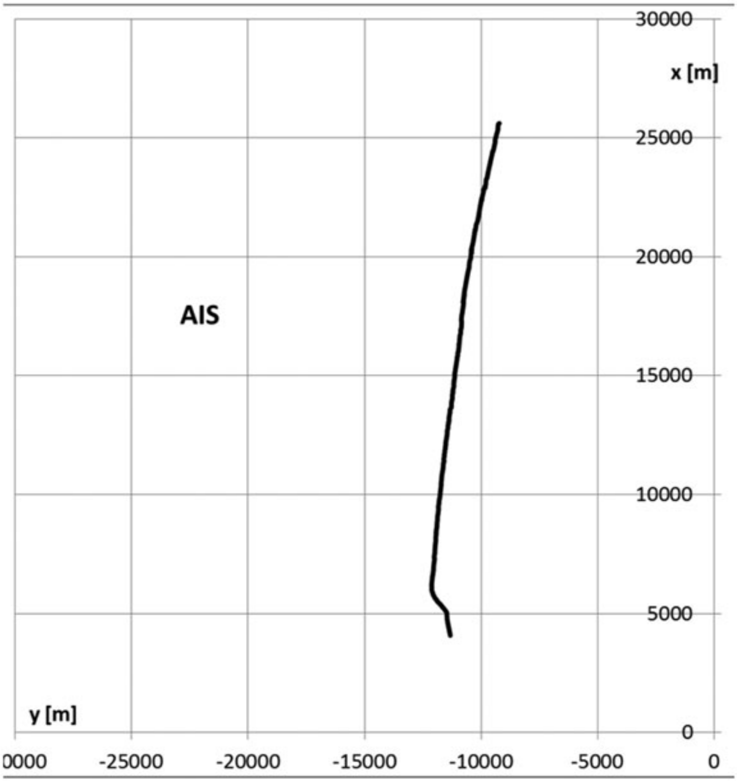

Figure 2. Trace of AIS target in the experiment, relative to own ship position.

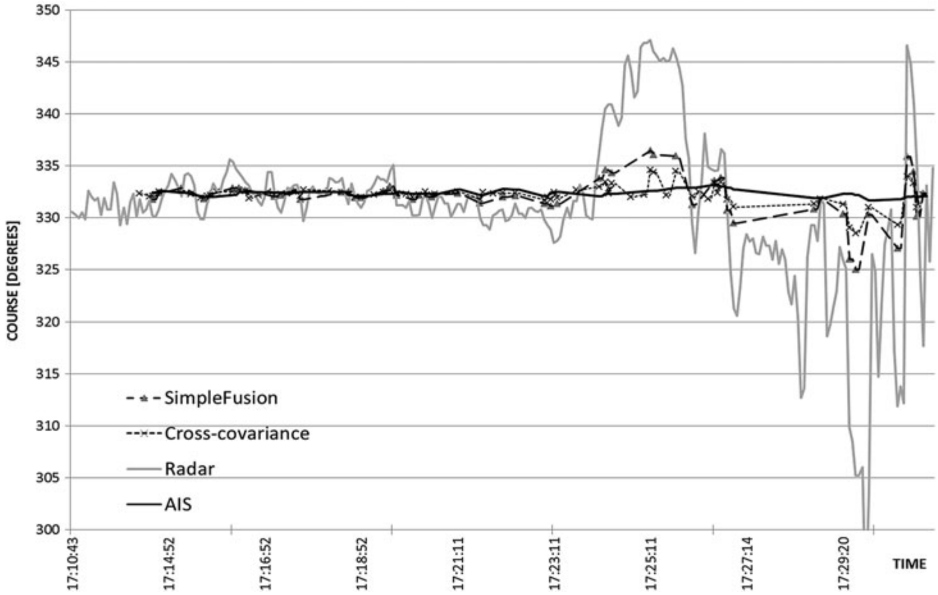

Figure 3. Comparison of course estimated with different fusion methods.

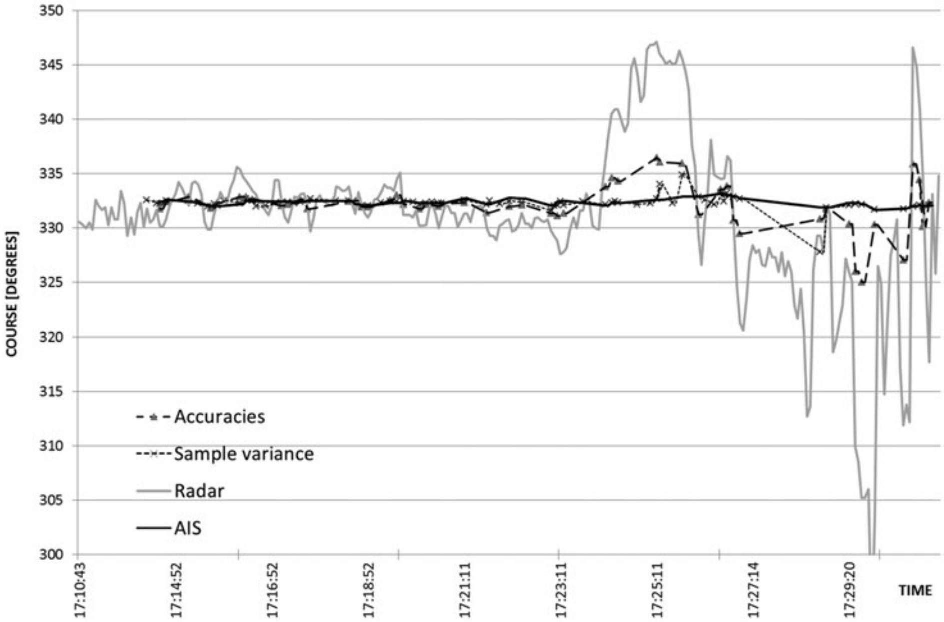

Figure 4. Comparison of course estimated with different variances for simple fusion.

were treated as samples of the variable measurements. Thus, sample variances for the set of values over a sliding window were proposed as items in the covariance matrices:

$$P_v = diag(var(BE_{k-l}:BE_k), var(D_{k-l}:D_k), var(COG_{k-l}:COG_k), var(SOG_{k-l}:SOG_k)) \tag{11}$$

where l is the length of the sliding window. To retain the influence of sensor accuracy, the covariance matrix used in this stage of research was a Hadamard product of Equations (8) and (10), resulting in the matrix:

$$\begin{aligned} P = diag(&\sigma_{BE}{}^{2*} var(BE_{k-l}:BE_k), \sigma_D{}^{2*} var(D_{k-l}:D_k), \sigma_{COG}{}^{2*} var(COG_{k-l}:COG_k), \\ &\sigma_{SOG}{}^{2*} var(SOG_{k-l}:SOG_k)) \end{aligned} \tag{12}$$

The results are shown in Figure 4. The covariance matrix, based on dynamic measurements of variance is called ‘sample variance’ in the figure, and it is also examined, as well as the covariance matrix based on accuracies. In Figure 4, the graph labelled ‘accuracies’ is the same as in the case of Figure 3, and the line labelled ‘sample variance’ shows the case where simple fusion is used but a covariance matrix is calculated according to Equation (12), and the length of the sliding window is set to ten. It can be noticed that fusion in this case is more subjected to AIS as the more accurate sensor. At the beginning, when the radar values are significantly varying, fusion is almost equal to AIS, but when the AIS data begin to vary, the fusion deviates into radar, yet remaining more smoothed, almost like AIS data. This interesting feature might be used for detecting temporary errors of any sensor. However, the problem

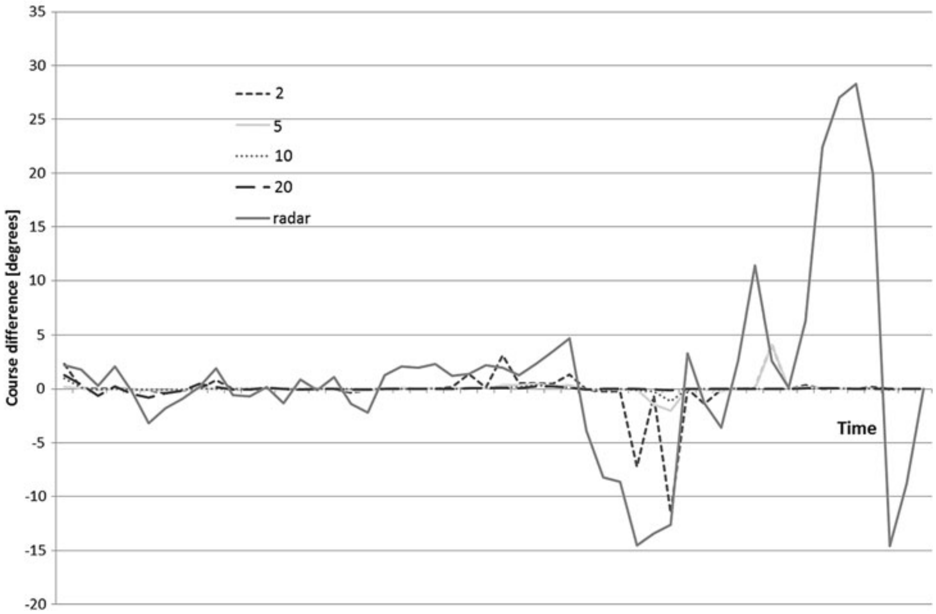

Figure 5. Comparison of course differences for different sliding window lengths.

of manoeuvres might occur. For better analysis of this issue, another research step is proposed, in which the influence of the length of the window is analysed.

6.3. *Length of sliding window analysis.* In this stage, the research focused on analysing the influence of the size of the sliding window. Simple fusion is used with a covariance matrix based on sample variance and the sliding window length varies. Four values were used: 2, 5, 10 and 20, and the results are presented in Figure 5. The graph shows the difference between the AIS course and the fusion/ radar course.

Based on Figure 5, it can be noticed that the most different from the AIS is the radar, and that all the fusion values are relatively close to the AIS values. However, it may be observed that for smaller values, the line for fusion becomes closer to the radar line. It can be thus concluded that the shorter the single window is, the more fusion is sensitive to changes. For very small values, e.g. 2, fusion jumps rapidly. On the other hand, for values of more than 20, the fusion results are almost the same as for the AIS, and the influence of the radar is minimised. It can be assumed that the optimal length of the sliding window is somewhere between 10 and 20.

7. CONCLUSIONS.

Theoretical and empirical research of target data fusion from tracking radar and an AIS in an ECDIS were presented in this paper. First, theoretical aspects, including ECDIS functionalities, radar and AIS characteristics, were given. Then, the most popular concepts of fusion were presented, and finally, practical results of numerical experiments were described.

The empirical research was carried out with the use of real target data recorded on a research ship from radar and an AIS. Two different methods of decentralised fusion were examined. It was assumed that, like in real environments, only the measurements from NMEA strings were known. Thus, the covariance matrix had to be estimated. Two approaches were proposed. In the first approach, the covariance matrix was calculated based on IMO accuracy requirements. In the second approach, the covariance matrix was calculated from variances of measurements in state vectors over a sliding window. The influence of the sliding window length was also examined.

The basic conclusions of the research are that:

- Parameters of the covariance matrix have an important influence on the fusion process: both examined algorithms of fusion are, in fact, some kind of weighted average, thus the weights, derived from the covariance matrix, are of vital importance.
- Applying dynamic values in the covariance matrix allows better adjustment of the algorithm to a situation.
- Too large sliding windows for the covariance matrix results in fusion, which is almost equal to the AIS.
- Too small sliding windows for the covariance matrix results in a "jumping" vector.

In general, it can be said, based on the research, that a correctly selected sliding window should allow a movement vector with approximately AIS accuracies that is sensitive to radar changes, to be obtained. This may be of importance, especially in the case where AIS data are sparse. On the other hand, fusion with a properly set sliding window should allow detection of AIS errors. It is expected that fusion will then give results that are closer to radar. However, this expectation requires further empirical research. The other direction for future research is to examine fusion during target manoeuvres, which is usually the biggest problem in tracking at sea, as well as tracking in heavy traffic conditions.

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