Use of Fuzzy Logic for Data Fusion in a Recognized Maritime Picture

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Abstract: - The Recognized Maritime Picture (RMP) is defined as a composite picture of activity over a maritime area of interest. In simplistic terms, building an RMP comes down to finding if something is there or not, and determining what it is, what it is doing, and whether some type of follow-up action is required. The generation and maintenance of an RMP consists in part of associating contact reports from sensor sources with existing tracks or initiating new tracks. This paper presents the use of fuzzy sets in the data fusion process. The proposed approach is based on the incomplete nature of the data and uses two stages of fusion, a contact level fusion and a track level fusion. The algorithm's implementation is also presented as well as fusion specific examples with real data acquired off the East Coast of Canada.

Key-Words: - Data fusion, fuzzy set, expert system, maritime picture

1 Introduction

The Recognized Maritime Picture (RMP) is a result of all surveillance efforts, infrastructures, systems, plans or strategies from the maritime perspective. For national sovereignty purposes, the RMP areas can include the 200 NM Exclusive Economic Zone (EEZ) and for defence purposes extend well beyond. Civilian and Military maritime organizations may have access to a number of surveillance sources. The ability of a country to make full use of these systems is limited by its ability to fuse the data from all data sources in a timely, accurate, and complete manner. These systems may include, among others, the High Frequency Surface Wave Radar (HFSWR) system [1], the Electronic Intelligence (ELINT) system [2], and Surveillance Aircraft (SA) patrol.

The association of contact reports from sensor sources with existing tracks or the initiation of new tracks involves a decision-making process. This process often takes place in an environment in which the goal and the constraints are not precisely known. To deal quantitatively with imprecision, the concepts and techniques of probability theory are usually employed. The use of a probabilistic approach requires that the imprecision can be equated with randomness and that the characteristics of this randomness be reasonably well known. This is generally not the case for the generation of the RMP [3].

An alternative approach is to view the problem as fuzzy decision making and to employ the concepts and techniques of fuzzy sets [4]. The fuzzy logic technique is used to evaluate the contact to track fusion feasibility. Contact reports are sequentially associated with existing tracks or initiate new tracks. The association process makes use of positional measurement error to determine if a contact is geo-feasible with a track. It uses ship's emitter characteristics, such as Radio Frequency (RF), Pulse Duration (PD), and Pulse Repetition Interval (PRI), to determine the ElectroMAGnetic (EMAG)-feasibility. It also uses identification attributes to promote evaluated geo- and EMAG-feasibility. When all contacts have been fused into tracks, a track level fusion is performed to prevent track duplication.

This paper is structured as follows: Section 2 presents the characteristics of data to be fused, sections 3 and 4 present the contact level fusion, section 5 presents the track level fusion and section 6 discusses implementation and shows examples of fusion.

2 Data Characteristics

Data characteristics are important for the algorithm's development. The use of fuzzy logic is motivated by the imprecision of or lack of information about data. Table 1 shows the characteristics of each kind of data. Time and position are the only parameters common to all data. The Area Of Uncertainty (AOU) is sometimes not provided or inaccurate in HFSWR and SA data samples. The qualification Bad or Good for AOU does not refer to the size of the AOU but rather to the accuracy of the AOU value.

HFSWR own tracker provides a track Unique Identifier (UID). All contacts with the same UID belong to the same track. However, in some cases, contacts with different UIDs may also be associated with the same track. ELINT data provide an ELINT Notation (ELNOT) that is unique for each emitter. ELINT contacts can also be correlated using electromagnetic parameters (RF, PD, and PRI). SA provides ship's name, which can be useful for ship identification. HFSWR contacts may also have positional bias.

Only HFSWR has a sufficient rate to be considered near real time (~1 contact/min). ELINT and SA (<1 contact/hr) are not received at the operation centre in real time and can be delayed several hours.

	HFSWR	ELINT	SA
Time	Good	Good	Good
Position	Good	Good	Good
AOU	Bad	Good	Bad
Name	-	-	Good
UID	Good	-	-
ELNOT	-	Good	-
RF	-	Good	-
PD	-	Good	-
PRI	-	Good	-
Rate	Good	Bad	Bad

Table 1. Data attributes.

3 Contact-Track Membership

The determination of whether or not a contact may belong to a track is based on the Contact-Track membership [5]. The total membership value, which is a subjective measurement of the correlation between a track and a contact, is given by:

$$\mu_{\text{contact-track}} = \mu_{\text{ID}} \cdot (\mu_{\text{Geo}} \cap \mu_{\text{EMAG}}) \qquad (1)$$

where μ_{ID}, μ_{Geo}, and μ_{EMAG} are the memberships associated with ID-Feasibility, Geo-Feasibility, and EMAG-feasibility respectively. The ID-Feasibility is used to promote the intersection of Geo-Feasibility and EMAG-feasibility. The intersection of A and B is denoted by $A \cap B$ and is defined as the largest fuzzy set contained in both A and B. The resulting membership is given by:

$$\mu_{A\cap B} = \text{Min}(\mu_A, \mu_B) \qquad (2)$$

where $\text{Min}(a,b) = a$ if $a \le b$ and $\text{Min}(a,b) = b$ if $a > b$.

The union of A and B, $A \cup B$, is defined as the smallest fuzzy set containing both A and B. The membership function of $A \cup B$ is given by:

$$\mu_{A\cup B} = \text{Max}(\mu_A, \mu_B) \qquad (3)$$

where Max(a,b) = a if $a \ge b$ and Max(a,b) = b if $a < b$. A more complete discussion of fuzzy set concepts is presented in [4].

3.1 Geo-Feasibility

The computation of the contact-track μ_{Geo} is based on the overlapping area of the error ellipses (defined by the AOU) of two contacts: the contact involved itself (*c*) and the last contact belonging to the track (*tc*). If the contact *tc* is older than the contact *c*, the error ellipsis of *tc* is expanded by the distance *r* the vessel can travel at its maximum velocity as shown in Figure 1. A time limit is set on (t_c-t_{tc}) to prevent error ellipsis from expanding too much and to allow unrealistic contact fusion in a cluttered environment. This time limit and the maximum speed (v_{max}) are discussed in section 7.

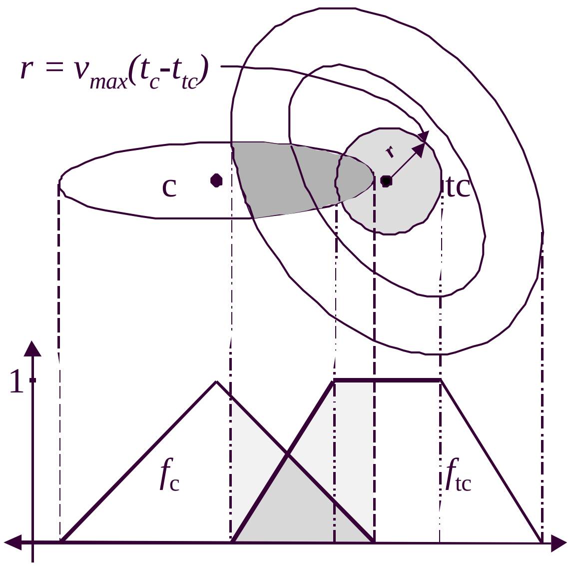

Figure 1. Time alignment and projection in one dimension of the error ellipsis functions f_{tc} and f_c.

The membership is proportional to the intersection of the two error ellipses.

$$\mu_{\text{Geo}} = \frac{\iint_S f_c f_{tc}\, dS}{\iint_S f_c\, dS} \qquad (4)$$

where f_c and f_{tc} are the functions associated with the error ellipses of the contacts c and tc, as defined in Figure 1. The surface of integration S represents the entire earth surface, but since f_c and f_{tc} are null outside the error ellipses, S could be limited to the surface of the intersection of both ellipses. The denominator is for the normalization of μ_{Geo}. When AOU is not included in an HFSWR or SA contact report, the error ellipses is estimated with a 1 NM radius circle.

3.2 EMAG-Feasibility

The EMAG-feasibility of a contact with a track depends on the similarity of EMAG parameters. ELINT contact reports provide RF, PRI, and PD. The determination of whether two signals are similar is based on the parameter's tolerance values λ_{RF}, λ_{PRI}, λ_{PD}. First, the difference between the contact RF or PD and the track corresponding parameter is calculated $X_{contact-track} = P_{contact} - P_{track}$ where P is RF or PD. Second, the membership is evaluated using:

$$\mu(X) = \begin{cases} 0 \Rightarrow |X| \geq \lambda \\ (\lambda - |X|)/\lambda \Rightarrow 0 \geq |X| < \lambda \end{cases} \quad (5)$$

For PRI, because of a miscount possibility during the detection process, a base-banding technique is applied [6]. The goal of base-banding is to multiply the candidate contact report's PRI by a factor that results in a base-band PRI closer to the average base-band PRI track. These factors are calculated as i/j, where $\{i, j \subset [1,n] : i, j, n \in \mathbb{N}\}$, to build a base-banding vector. A large value of n yields too many possible factors, which adversely impacts the association process since all PRI contact-track pairs would have $\mu_{PRI}>0$. A value of $n = 12$ is actually used, which provides 91 different factors. Using this base-banding vector, the difference vector between the contact and the PRI track is calculated.

$$\vec{X}_{contact\text{-}track} = \vec{B} \cdot \mathrm{PRI}_{contact} - \vec{I} \cdot \mathrm{PRI}_{track} \quad (6)$$

where $\vec{I}$ is the unit vector. Then the 91 memberships $\mu_{\mathrm{PRI}}^{k} = \mu(X_k)$ are calculated using equation (5). Taking the union of all PRI memberships, the membership for PRI is evaluated:

$$\mu_{\mathrm{PRI}} = \mu_{\mathrm{PRI}}^{1} \cup \mu_{\mathrm{PRI}}^{2} \cup \ldots \cup \mu_{\mathrm{PRI}}^{91} \quad (7)$$

The total EMAG membership is calculated as follows:

$$\mu_{\mathrm{EMAG}} = \mu_{\mathrm{RF}} \cap \mu_{\mathrm{PRI}} \cap \mu_{\mathrm{PD}} \quad (8)$$

If either track or contact does not have EMAG information, $\mu_{EMAG} = 1$.

3.3 ID-Feasibility

When calculating contact-track or track-track association feasibility based on ID, discrete membership values are used. Ship's name information has priority followed by track number and ELNOT. Both contact and track should have appropriate ID information, otherwise $\mu_{ID} = 0.5$.

$$\mu_{\mathrm{ID}} = \begin{cases} 0.5 & \Rightarrow \text{no ID information} \\ \mu_{\mathrm{ELNOT}} & \Rightarrow \text{no information on Name and Track number} \\ \mu_{\text{track number}} & \Rightarrow \text{no information on Name} \\ \mu_{\text{ship name}} & \Rightarrow \text{information on Name} \end{cases} \quad (9)$$

If ship's name, track number or ELNOT are the same for contact and track, the corresponding μ will be $\mu_{\text{ship name}} = 1$, $\mu_{\text{track number}} = 0.9$, and $\mu_{ELNOT} = 0.8$; else $\mu_{\text{ship name}} = 0$, $\mu_{\text{track number}} = 0.5$, and $\mu_{ELNOT} = 0.5$.

4 Contact-Track Fusion

The contact-track fusion process correlates contacts with tracks, and fuses appropriate contacts to track or initiate new tracks. The following example demonstrates the algorithm with simulated data.

Figure 2 shows the position of nine contacts in Latitude Longitude referential. The contacts are numbered with respect to their time of observation, contact 1 being the oldest and contact 9 the latest. Crosses and circles indicate that contacts have been reported by two different sensors.

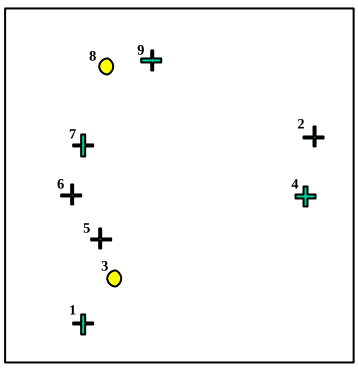

Figure 2. Example of contact position.

A matrix is built by allocating each column to a contact number and each row to a track. The first contact is allocated to track 1. A membership is evaluated for all contact-track pairs (Table 2-a, where a membership of 1 means that the contact has been allocated to the track). The contact with the highest membership is the candidate for updating the track (contact 5 in this example). Since contact 2 is anterior to contact 5 and is not the candidate for the existing track, a new track is initiated with this contact (Table 2-b, where membership of 0 means that this contact is already allocated or not feasible). Candidates for updating tracks 1 and 2 are contacts 5 and 4 respectively. Again, a new track is initiated with contact 3, which is not a candidate for any existing track. All tracks are updated at the same step. In Table 2-c contact 5 can update both tracks 1 and 3. In this case, the highest membership determines the track to be updated. Track 1 is then updated with contact 5 and track 3 with contact 6, which has the second highest membership for track 3 (Table 2-d). The process continues until all contacts are allocated to a track (Table 2-e).

a)

	1	2	3	4	5	6	7	8	9
1	1	0	0.8	0	0.9	0.5	0.6	0.5	0.7

b)

	1	2	3	4	5	6	7	8	9
1	1	0	0.8	0	0.9	0.5	0.6	0.2	0.7
2	0	1	0	0.9	0	0.1	0	0	0

c)

	1	2	3	4	5	6	7	8	9
1	1	0	0	0	0.9	0.8	0.7	0.7	0.5
2	0	1	0	0.9	0	0	0	0	0
3	0	0	1	0	0.8	0.7	0.6	0.5	0.5

d)

	1	2	3	4	5	6	7	8	9
1	1	0	0	0	1	0	0.9	0.7	0.9
2	0	1	0	1	0	0	0	0	0
3	0	0	1	0	0	1	0.8	0.8	0.8

e)

	1	2	3	4	5	6	7	8	9
1	1	0	0	0	1	0	1	0	1
2	0	1	0	1	0	0	0	0	0
3	0	0	1	0	0	1	0	1	0

Table 2. Matrix of Contact-Track allocation.

A contact updates a track by adding new information to the track attributes (first column of Table 1). If the track and contact ELNOT are the same, RF and PD are averaged while the smallest PRI is kept.

5 Track-Track Fusion

The previous contact-track fusion example results in three tracks. Track 1 includes contacts 1, 5, 7, and 9 while track 3 includes contacts 3, 6, and 8. From Figure 2 is it reasonable to think that contacts 1, 3, 5, 6, 7, and 9 belong to the same track. In other words, tracks 1 and 3 should be merged. This is the purpose of the track-track fusion. To do so, a first order fit by χ^2/ν minimization [7] for each track having at least three contacts is performed.

$$\frac{\chi^2}{\nu} = \frac{1}{n-2}\sum_i^n \frac{\left(x_i - a_0^x - a_1^x t_i\right)^2}{\partial x_i^2} + \frac{\left(y_i - a_0^y + a_1^y t_i\right)^2}{\partial y_i^2} \tag{10}$$

Where contact position $(x,y)_i$ is in latitude-longitude, ∂x_i and ∂y_i are the components of the error ellipse for the i^{th} contact, n is the total number of contacts for the fit, t_i is the time of the i^{th} contact, and a_0 and a_1 are the adjusted parameters. Then all tracks with χ^2/ν under a certain empirical threshold (to avoid curved tracks) are selected in pairs and the χ^2/ν of the fit over their combined contacts is computed. If the result is equal to or smaller than the highest χ^2/ν of the two tracks, the two tracks are fused. The track pair with the smallest χ^2/ν is fused first. The process is iterative and ends when no more tracks can be fused. Tracks with different ship's name cannot be fused. However, fused tracks can have different ELNOTs, since ships can have several emitters and different UIDs.

6 Application and Results

A software prototype has been developed [8] with the described fusion algorithm using Cortex, a new Knowledge-Based System (KBS) [9] that provides fast execution speed and easy representation of abstract data types. Cortex is implemented on a Blackboard architecture, providing advantages such as modularity, versatility, and expandability. The software includes an interface (Figure 3) that displays contact position on a map and allows contact editing when a contact is selected on the display window or in the list of contacts. Additional information like radar position, radar coverage area, oilrigs, etc. can also be displayed. The fusion process is launched through this interface.

The fusion process was tested on four sets of data. Each data set included HFSWR, ELINT, and SA and represented one day of observation. All these data were real data collected in the area of coverage of the HFSWR systems located at Cap Bonavista and Cap Race, Newfoundland, Canada. No ground truth is available for these data, the objective being the automation of the fusion process as performed manually by the operator (who does not know the ground truth either).

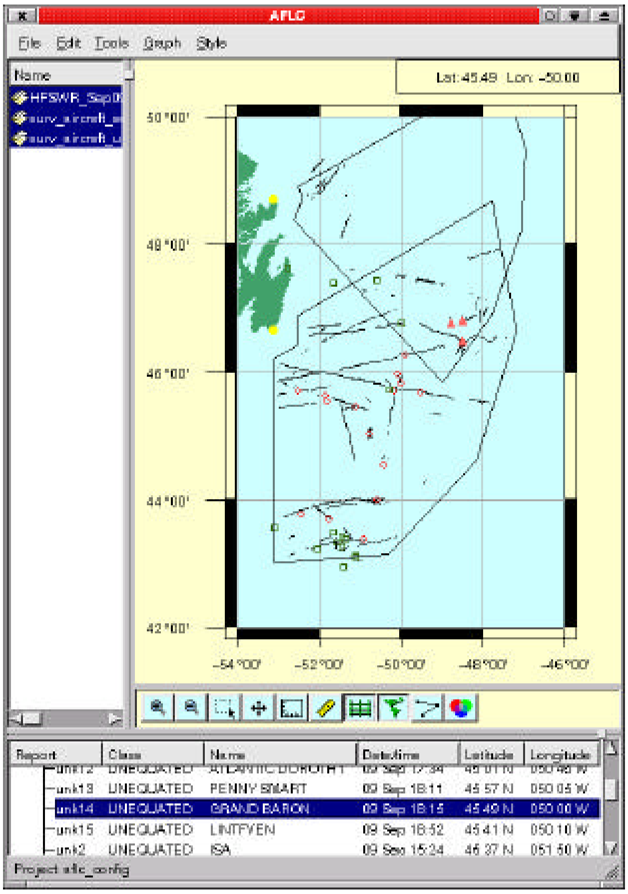

Figure 3. User Interface.

The display window of Figure 3 shows a real example of one-day radar coverage. For national security purposes, ELINT contacts are not shown and EMAG parameter tolerances will not be discussed. Two specific examples have been selected to show the two fusion stages.

The first one involves contact-track fusion only and is displayed in Figure 4. In this example, six SA contacts (red squares) are fused with tracks composed of HFSWR contacts (blue cross). The ship's name given by SA and UID given by HFSWR are shown. The four SA contacts that are not fused to any track have a too large time difference with their nearest HFSWR contacts. They could represent small ships that have not been tracked by the HFSWR. Two SA contacts are from the same ship (Sir Wilfred Grenfell) but associated with two tracks with different UIDs (SWR13106 and SWR13131). In fact these UIDs are HFSWR track numbers and the algorithm fuses all these contacts into a single track.

The second example is shown in Figure 5 and presents track-track fusion. In this picture, two groups of HFSWR contacts with different UIDs are displayed. The contact-track fusion did not fuse these contacts into a single track due to the small position difference between contacts with the same time stamps. The contact-track fusion favours fusion of contacts with the same UID and reconstructs separately the two HFSWR tracks. However, it is obvious that for some reason (sea state, false alarm, bad weather…), the HFSWR tracker starts to decorrelate the track over a short period of time (the smaller track extends over 34 minutes). With the four sets of data, 5% of the tracks reconstructed with contact-track fusion have been fused with the track-track fusion.

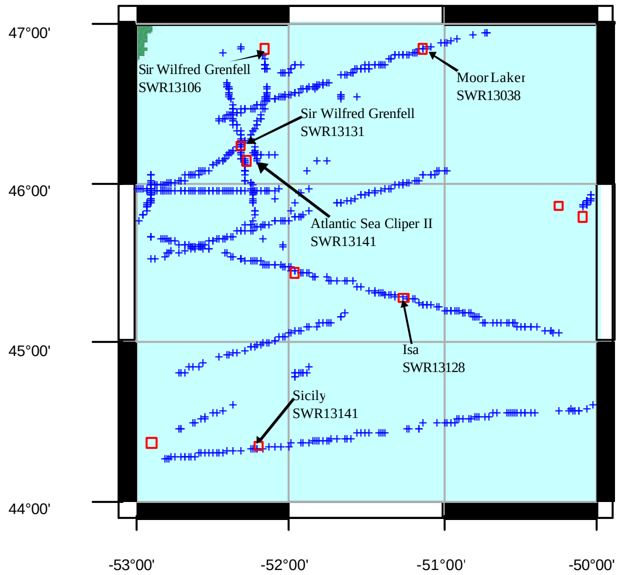

Figure 4. Contact-Track association.

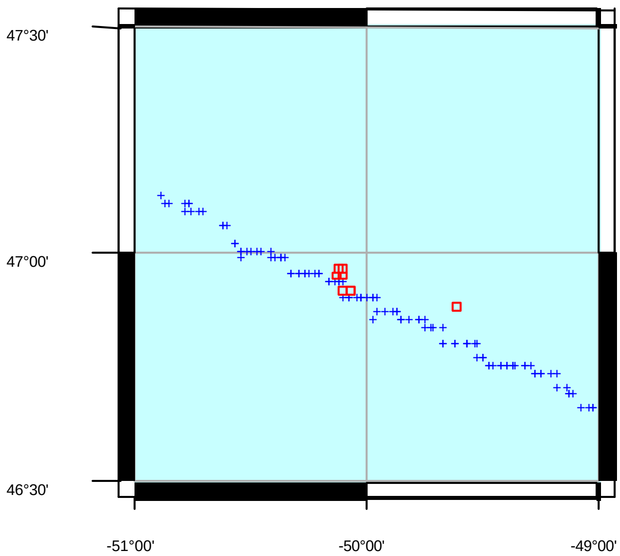

Figure 5. Track-Track association.

7 Conclusion

This paper presents an algorithm for data fusion based on fuzzy sets. Fusion is performed at two levels, contact-track fusion and track-track fusion. Data from three sources are fused - HFSWR, ELINT, and SA - to build a Recognized Maritime Picture (RMP).

This algorithm was developed and implemented into a data fusion software to study the feasibility of automation in the construction of an RMP. Four sets of data corresponding to four non-consecutive days of observation were used to test the algorithm. Results show that data fusion automation could be achieved to obtain an RMP.

The tests also show that one sensitive parameter is the maximum time difference allowed between candidate contacts and tracks. With the data used, this maximum time difference was set to 15 min when no emitter information existed and to 60 min when emitter information was available for both track and contact. This maximum time depends on the density of contacts and on the quantity of ELNOT and ship's name information.

Another sensitive parameter is the maximum speed allowed for a ship. This speed was set to 35 knots, which seems to be enough even for the quickest vessels. The overall quality of the result cannot be quantified since no ground truth exists for these data (i.e., the real number of tracks and their exact position). However, the resulting RMP is realistic and similar to those obtained by "manual" inspection and fusion.

The use of fuzzy logic leads to difficulties when several kinds of information are being compared. Taking the minimum membership implies a subjective comparison between the membership values. Since membership functions are at some point arbitrary and since the application domains are not the same, it is not possible to assert that a contact with μ_{Geo}=0.8 and μ_{EMAG}=0.7 has a better geo-feasibility than EMAG-feasibility. Varying the tolerance on EMAG parameters or the membership functions could lead to μ_{Geo}=0.75 and μ_{EMAG}=0.85.

The prototype developed using the algorithm presented in this paper gave interesting results for the automation of RMP construction. We are now further in the development of this prototype for operational evaluation of HFSWR.

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