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Multisource Information Adaptive Fuzzy Logic Correlator for 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 process of data fusion is absolutely critical to the production of an RMP An indecipherable picture is worse than no picture at all, regardless of how many contacts are on the plot This paper presents an information fusion system that correlates and fuses information from sensor data sources. Instead of fusing source data directly, this fusion system, named Adaptive Fuzzy Logic Correlator (AFLC), fuses information from two communication systems, the TACELINT and the OTH Gold. The correlator is implemented with the Cortex expert system developed by Lockheed Martin Canada. The AFLC also provides a file editor that can edit and display contacts over any region of interest, and set fuzzy membership function.*

Keywords: Information fusion, fuzzy logic, expert system, maritime picture.

1 Introduction

The RMP is a result of all surveillance efforts, infrastructure, 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 defense purpose extend well beyond. Civilian and Military maritime organization 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, the Electronic Intelligence (ELINT) system, and surveillance aircraft

This paper discusses the AFLC, which fuses information from two communication systems, the TACELINT [1] and the OTH Gold [2] These communication protocols are used to broadcast data from sensor systems. In this project, TACELINT is used to broadcast sensor data from an ELINT source while OTH Gold is used to broadcast sensor data from two coastal HFSWRs or from ship navigation systems The information that has to be correlated and combined does not follow exact and deterministic statistical models, as is the case with sensor data. We refer to the AFLC system of this project as a Multiple Information Fusion (MIF) system as opposed to the better known Multi-Source Data Fusion (MSDF) system

The AFLC operates in batch mode. It first fuses contacts to tracks based on feasibility and then proceeds to track association to minimize track duplication due to biases between dissimilar information sources Correlation is based on identity attributes and fuzzified geo-feasibility and electromagnetic data.

Section 2 presents some mathematical techniques used by the AFLC system. Sections 3 and 4 present the main algorithms of the AFLC and their implementation

2 The fuzzy logic techniques

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 known precisely To deal quantitatively with imprecision, we usually employ the concepts and techniques of probability theory The use of a probabilistic approach requires that the imprecision can be equated with randomness and that the characteristics of this randomness are 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][5]. The application of fuzzy decision making does not imply that the process is fuzzy but rather that one or more of the goals or constraints of the decision process are fuzzy A fuzzy set is a class of objects in which there is no sharp boundary between those objects that belong to the class and those that do not A more precise definition may be stated as follows.

Let X = {x} denote a collection of objects (points) denoted generically by x. Then a fuzzy set A in X is a set of ordered pairs

$$A = \{(x, \mu_A(x))\}, \text{ with } \quad x \in X \qquad (1)$$

Where $\mu_A(x)$ termed the membership of x in A, and μ_A:X→M is a function from X to a space M called the membership space When M contains only two points, 0 and 1, A is non-fuzzy and its membership function becomes identical to the characteristic function of a non-fuzzy set

In this project M is the interval [0, 1] with 0 and 1 representing, respectively, the lowest and highest grades of membership Thus, a fuzzy set A can be defined by associating with each object x a number between 0 and 1, which represents its grade of membership in A.

We present here basic fuzzy set concepts that will be used later in this paper

Normality: A fuzzy set is normal if and only if the supremum of $\mu_A(x)$ over X is unity A non-empty subnormal fuzzy set can be normalized by dividing each $\mu_A(x)$ by the supremum of $\mu_A(x)$ In this report, all fuzzy sets will be normal

Intersection. 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 membership is given by:

$$\mu_{A \cap B}(x) = \mathrm{Min}(\mu_A(x), \mu_B(x)), \qquad x \in X \qquad (2)$$

Where $\mathrm{Min}(a,b) = a$ if $a \le b$ and $\mathrm{Min}(a,b) = b$ if $a > b$

Union: 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

$$\mu_{A \cup B}(x) = \mathrm{Max}(\mu_A(x), \mu_B(x)), \qquad x \in X \qquad (3)$$

Where Max(a,b) = a if $a \ge b$ and Max(a,b) = b if $a < b$.

3 The Adaptive Fuzzy Logic Correlator

OTH Gold and TACELINT reports are made of several contacts that provide ship information for a given time at a given position This information can be grouped into three sets of attributes identification (ID), positional (Geo), and electromagnetic (EMAG). The correlation in AFLC is based on these three sets

All contacts are first ordered in time. Then the first contact (the oldest) creates the first track, the track being initiated with the parameters of this first contact The next step is to find the best candidate to update this track. When a candidate is found, a check is made to see if each track has its own candidate (which is obviously true when there is only one track) If several tracks have been created, the same contact could prove to be the best candidate for more than one track In this case, the candidate-track pair with the highest feasibility is kept and the algorithm is prohibited from associating the contact with the other tracks New candidates are then found for tracks that lost their first candidate The process is repeated until each track has its own unique candidate

After the candidate selection is performed, a check is made to see if the oldest free contact is older than all candidates A free contact is a contact that is not allocated to a track and is not a candidate If this check is positive, then a new track is created with this free contact The process is repeated until the oldest unallocated contact is a candidate.

If there is no possible candidate for a track (i.e., no free contact could feasibly update this track), then the track is pending. Otherwise, the track can be updated. All non-pending tracks are updated at the same time. This means that each track must have its own candidate or must be pending before the update is done. The process is repeated until no unallocated contacts are left.

Finally track-track correlation is performed. All track-track pairs with compatible identity attributes are evaluated for possible fusion

3.1 ID-Feasibility

Although OTH Gold and TACELINT messages can provide several ship ID attributes (name, class, pennant number, flag, ELINT notation, etc.), few are included in the messages we used HFSWR records only ship positions and does not provide any ID information. However we used the track number given by the HFSWR's own tracker as an ID attribute. Our TACELINT provides ELINT notation, but since this attribute is related to the ship radar and several ships may have the same radar, this attribute is not unique to a ship. If one ship has several radars then several reports of this ship could also have different ELINT notations Surveillance aircraft are the best source of ship ID attributes. They generally provide ship name, category and flag, however, we only used ship name from these messages since each ship has its own name

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

$$\mu_{ID} = \begin{cases} 0.5 & \Rightarrow \text{no ID information} \\ \mu_{ELNOT} & \Rightarrow \text{no information on Name and Track number} \\ \mu_{track\ number} & \Rightarrow \text{no information on Name} \\ \mu_{ship\ name} & \Rightarrow \text{information on Name} \end{cases} \quad (4)$$

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

3.2 Geo-Feasibility

The computation of the contact-track positional membership is based on the overlapping area of the error ellipses 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

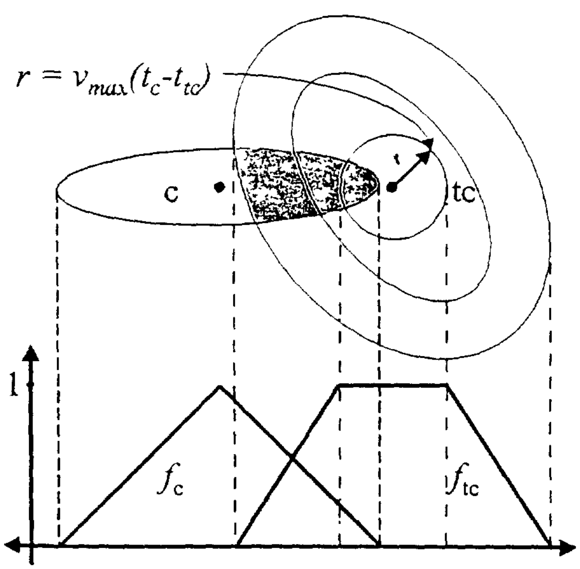

Figure 1 Time alignment and projection in one dimension of the error ellipsis functions f_{tc} and f_c

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

$$\mu_{Geo} = \frac{\iint_S f_c f_{tc} \, dS}{\iint_S f_c \, dS} \quad (5)$$

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 nulls outside the error ellipses, S could be limited to the intersection's surface of both ellipses. The denominator is for the normalization of μ_{Geo}

3.3 EMAG-Feasibility

The EMAG-feasibility of a contact with a track depends on the similarity of EMAG parameters. The TACELINT message provides Radio Frequency (RF), Pulse Repetition Frequency (PRI), and Pulse Duration (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:

$$\mu(X) = \begin{cases} 0 \Rightarrow |X| \geq \lambda \\ (\lambda - |X|)/\lambda \Rightarrow 0 \geq |X| < \lambda \end{cases} \quad (6)$$

For PRI, because of a miscount possibility during the detection process, a base-banding technique is applied[1] 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 $\{i, j \subset [1,n] \quad i, j, n \in \square\}$, 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 $\mu_{PRI}>0$ For the AFLC, a value of $n = 12$ is used, which provides 91 different factors. Using this base-banding vector, the differences vector between the contact and the PRI track is calculated.

$$\vec{X}_{contact-track} = \vec{B} \ \mathrm{PRI}_{contact} - \vec{I} \cdot \mathrm{PRI}_{track} \quad (7)$$

Where I is the unit vector. Then the 91 memberships $\mu_{PRI}^{k} = \mu(X_k)$ are calculated using the same function as for RF and PD Taking the union of all PRI memberships the membership for PRI is evaluated.

$$\mu_{PRI} = \mu_{PRI}^{1} \cup \mu_{PRI}^{2} \cup \ldots \cup \mu_{PRI}^{91} \quad (8)$$

The total EMAG membership is calculated as follows

$$\mu_{EMAG} = \mu_{RF} \cap \mu_{PRI} \cap \mu_{PD} \quad (9)$$

3.4 Contact Selection and Track Update

Correlation is represented by a total membership value that includes the three previous membership evaluations The membership value, which is a subjective measurement of the correlation between a track and a contact, is given by

$$\mu_{contact\text{-}track} = \mu_{ID}\ (\mu_{Geo} \cap \mu_{EMAG}) \qquad (10)$$

The contact, among all n contacts, that has the highest membership with the m^{th} track becomes the candidate of this track

$$\mu_{candidate} = \mu_{contact^1\text{-}track^m} \cup \mu_{contact^2\text{-}track^m} \cup \ldots \cup \mu_{contact^n\text{-}track^m} \qquad (11)$$

If the fused contact has ID information that is missing in the track, this information updates the track. For ELINT, the RF and PD tracks are updated following this rule:

$$P_{track} = (P_{contact} + N\ P_{track})/(N+1) \quad \text{for } 1 \le N \le 10 \qquad (12)$$

Where P is RF or PD This way the RF and PD tracks are smoothed by the last ten values of the correlated contacts The PRI track is updated by taking the maximum value of the contact and the PRI track

$$PRI_{track} = \text{Max}(PRI_{contact}, PRI_{track}) \qquad (13)$$

3.5 Track Association

A first order fit by χ^2/ν minimization[6] for each track having at least three contacts is performed.

$$\frac{\chi^2}{\nu} = \frac{1}{n-2}\left\{\sum_{q=x,y}\sum_{i}^{n}\left(\frac{q_i-(a_0^q+a_1^q t_i)}{\sigma_i}\right)^2\right\} \qquad (14)$$

Where q is one of the two orthogonal referential axes (here q is either along the longitude or along the latitude at each contact position $(x,y)_i$), σ_i is the composant in the orthogonal referential 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^q and a_1^q are the adjusted parameters. Then all tracks with χ^2/ν under a certain empirical threshold (to avoid curved tracks) are selected in pair and the χ^2/ν of the fit over their combined contacts is computed. If the result is equal or smaller to 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 together

4 Implementation of AFLC with Cortex

Lockheed Martin Canada has developed Cortex, a new Knowledge-Based System (KBS) [7] that provides fast execution speed and easy representation of abstract dat types. Cortex is programmed using C++ to take advantag of the speed of a compiled language and the benefits of a object-oriented programming language such as dat abstraction, class inheritance, information hiding, etc Cortex not only offers the tools to solve complex problem in the field of Artificial Intelligence; it also serves as powerful run-time engine on which complex application can be developed more easily. Cortex is implemented on Blackboard architecture, providing advantages such a modularity, versatility, and expandability

The main Cortex components comprise the data types the agents, the Blackboard, and the Blackboard controlle Within Cortex, all objects of a given problem o application are represented by *data types*. These dat types can symbolize simple numbers, arrays or structures or more complex and abstract objects These data type can be created, deleted, or transformed by *agents*. Th agent's role is to fulfil the computational or procedur tasks of the application. Each agent is designed to act on specific data type and produce (or modify) another specifi data type (which can be different or similar to the inpu data type) The various data types contained in th application are instantiated and reside on the so-calle Blackboard. The Blackboard can be understood as shared memory space containing the instances of th various data types, which can be accessed by all agents i the system. The remaining component of Cortex is th Blackboard controller, whose main task is to schedule an execute the processing tasks within the application b continuously monitoring the state of the Blackboard an associating the data with their corresponding agents.

AFLC has two data types. The first is named *Conta* and represents the structure of a contact. Each conta selected by the user through the Graphical User Interfac (GUI) instantiates a *Contact* data type when the correlatio process is launched. The second data type is *Track* an represents the fusion information of several contacts. Th occurrence of a *Contact* data type triggers the three agen *Gate ID*, *Evaluate EMAG*, and *Evaluate Position* (se Figure 2) These agents evaluate the fusion possibility all *Contacts* with all *Tracks*. A *Contact* instantiation ca create a new track by triggering the *Create Track* agen When all *Contact-Track* fusion possibilities have be evaluated, the *Elect Candidate* agent selects one uniq *Contact* to be fused to each *Track*. The *Update Tra* agent starts when all non-pending *Tracks* have their ow updating *Contact*. A *Track* may have no *Conta* candidate. In this case the *Track* status is pending Th same process is repeated until all *Contacts* have created *Track* or have been fused to an existing one.

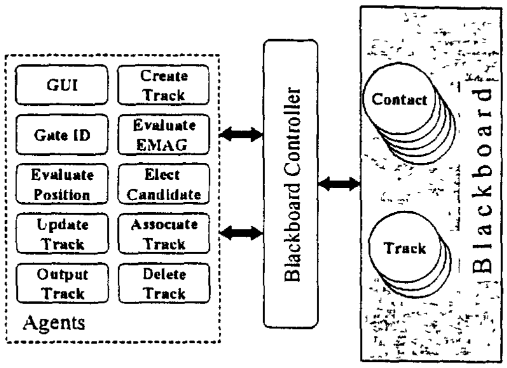

Figure 2. AFLC implementation with Cortex

When the *Contact-Track* fusion is finished, the *Track-Track* fusion is performed with *Associate Track* agent. If a *Track* cannot be fused to any other *Track*, it is terminated and outputted in OTH Gold format by the *Output Track* agent.

With Cortex it is possible to run agents on separate threads The *GUI* agent starts running the user interface when the AFLC is launched. This interface presents information about OTH Gold and TACELINT files, displays contact positions of selected files on the map, and allows contact editing when a contact is selected on the display window or in the list of contacts (Figure 3). Additional information like radar position, radar coverage area, oilrigs, etc. can also be displayed The correlation process is launched through this interface.

5 Application and results

Three data samples were used for the fine-tuning and analysis of the AFLC. All these data sample are based on actual data collected in the area of coverage of the HFSWR systems located at Cap Bonavista and Cap Race, Newfoundland Canada. One sampling is a TACELINT buffer while the other two are OTH-Gold buffers All the HFSWR and Surveillance Aircraft (SA) input data sent to the AFLC system are plotted in the display window of Figure 3 For national security purposes TACELINT inputs are not shown and EMAG parameter tolerances will not be discussed.

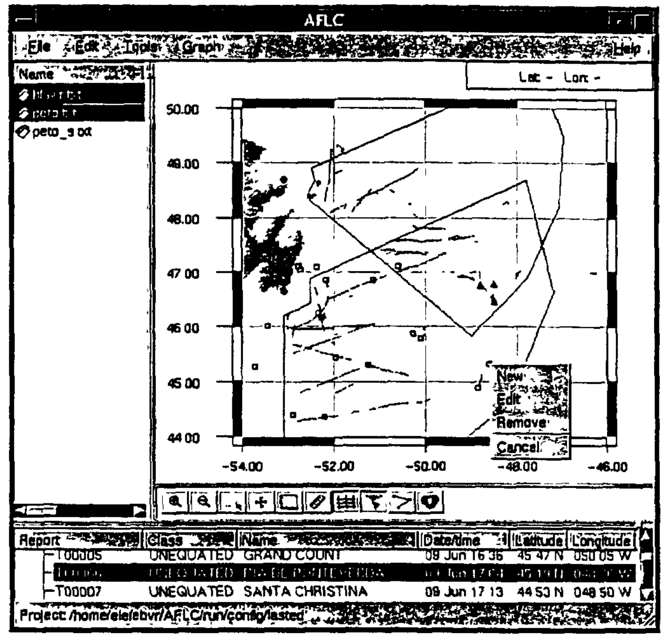

Figure 3. AFLC user interface

The HFSWR sample consists of 2467 contacts in OTH Gold format divided into 153 sets with the same Unique Identifier (UID). The surface wave radar system's own algorithm provides these UIDs

A surveillance aircraft provided a sample consisting of 19 contacts in OTH Gold format. Among these, 15 provide the ship name. Category, type and flag are also provided for most contacts.

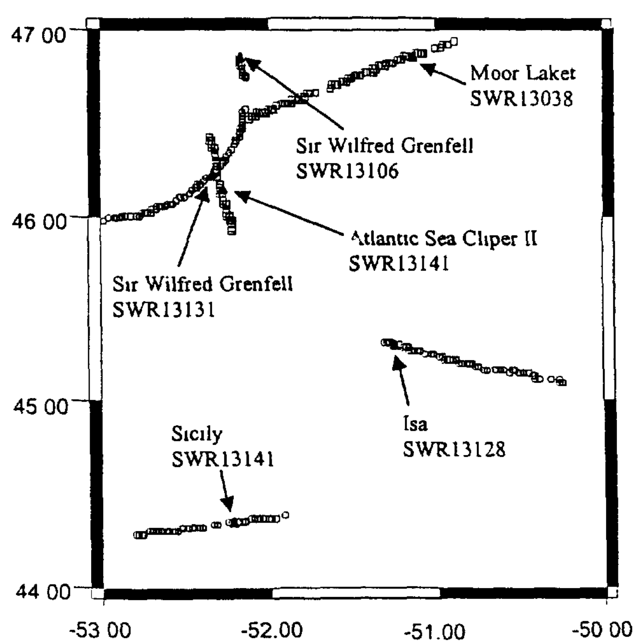

Figure 4 HFSWR-SA Data association.

When the three data files (HFSWR, TACELINT, and SA) are submitted to the AFLC system, the correlator associates contacts with tracks from different sources. The association process highly depends on the maximum time difference allowed for association between a track at time t_k and a contact at time t_n. Most contact-track associations were sensitive to this time limit. This limit was set to 60 min. if track and contact have emitter information and to 15 min if not. When emitter information exists EMAG membership has a contribution in the total membership allowing to relax the time constrain. Otherwise the time gap should be reduce to prevent excessive association in cluttered region. The remarks on AFLC association hereinafter are based on a run with these optimized time limits for the data available.

Of the 19 SA contacts, seven were from the HFSWR detection zone and five were fishing ships that had irregular motion, which prevented them from being tracked by the HFSWR. The seven remaining contacts were from ships transiting the region and were suitable for tracking. Six were correctly associated by the AFLC system with a HFSWR track shown in Figure 4. Only one was not associated with a track constructed from HFSWR contacts This was a ship which appeared to have had its position reported with a wrong time, since no HFSWR track was found surrounding it at the reported time. For any fusion of information or sensor data, a correct reported time is an indispensable condition for successful fusion.

The track-track fusion appears to be useful for TACELINT-HFSWR association. Indeed, without track-track fusion some tracks are duplicated as if the fusion was incomplete Considering only HFSWR and SA data, from the 105 tracks produced 13 track associations are made reducing the total number of tracks to 92.

6 Conclusion

The correlator of the ALFC system performs well within the constraints of the data used. HFSWR contacts are associated with respect to their UID, and TACELINT and SA contacts are fused to them. Only large time or position alignment incompatibilities prevent contacts from being fused to the rest of the other kinds of data One sensitive parameter is the maximum time difference allowed between candidate contacts and tracks. With the current data, this maximum time difference is set to 15 min when no emitter information exists and to 60 min when emitter information are available for both track and contact. This maximum time depends on the density of contacts and on the quantity of ELNOT and ship name information. Another sensitive parameter is the maximum speed allowed for a ship This speed is actually set to 35 knots, which seems to be enough even for the most rapid vessels The overall quality of the result cannot be quantify since no ground truth exist for these data (i.e. the real number of track and their exact position) However, this system was develop to study the feasibility of automation in the construction of RMP when data are incomplete and dissimilar In this sens, results are promising.

The use of fuzzy logic leads to some 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.

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