A Joint Radar Signal Sorting Method For Multi-Radar Reconnaissance Station

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Abstract. Passive Detection Network Composed of Multi-Radar Reconnaissance Station, which can receive multiple sets of radar signal pulse descriptor word at the same time, joint signal sorting becomes an inevitable measure of such data. This paper proposes a multi-radar time-aligned association sorting method, and builds scenario close to actual conditions for testing. The results show that method can overcome the problem of partial pulse loss leading to sorting failure, and can quickly complete complex radar signal sorting in real electromagnetic environment.

1. Introduction
Radar radiation source signal sorting and identification technology research has passed the stage of characteristic parameter matching, artificial intelligence identification, D-S evidence fusion since the 1970s [2]. Commonly used feature parameter matching methods include template matching method, fuzzy matching method, gray correlation analysis method, etc. [3][3]. The feature parameter matching method directly matches the measured signal characteristic parameters with the known radar characteristic parameters in the database. This method is mainly applicable to conventional radar radiation sources whose characteristic parameters are basically unchanged. The artificial intelligence recognition method introduces the representation and inference rules of knowledge. By incorporating some empirical knowledge of experts, multiple parameters are combined to identify the radiation source. The identification method is essentially the combination of expert experience knowledge and basic radiation source signal parameters [14]. The most important feature of DS evidence theory is that the description of uncertain information adopts “interval estimation” instead of “point estimation”, which can distinguish between unknown and inaccurate information, and use DS evidence theory to sort well-selected pulse descriptors. The attribute fusion is carried out, and the radar type is discriminated by analysis and reasoning, thereby greatly improving the correct recognition probability and reducing the error probability [1][2][3].

With the development of science and technology, new phased array and ultra-wideband systems and complex modulated signal radars have emerged, making the electromagnetic signal environment composed of radar radiation sources on the battlefield increasingly complex. Modern radars often have multiple jobs. The mode corresponds to different uses and technical characteristic parameters. With the application of radar anti-interference measures such as low intercept probability and frequency agility, the radar full pulse data acquired by a single reconnaissance device presents incomplete features, resulting in the existence of sorting conclusions incomplete and even sorting failures. The multi-source
radar reconnaissance signal joint sorting technology is mainly used to complete the fusion and sorting processing of the multi-radiation source signal of the multi-reconnaissance receiving device, and form the radiation source information for guiding the electronic equipment such as radar or interference. Affected by factors such as area of action, combat radius, SNR, multipath, time-frequency aliasing, etc., each reconnaissance receiving device is sorted separately and the sorting results are different, and the video output pulses of each reconnaissance receiving device after detection are complementary. The paper studies the multi-device video output pulse signal fusion and sorting algorithm in complex electromagnetic environment to obtain better sorting results than single equipment.

2. Joint Signal Sorting

2.1. Pulse data Time Alignment

The receivers of the radar reconnaissance sensors receive the radar signal independently of each other. In the actual electromagnetic environment radar signal propagation process and the reconnaissance system signal reconnaissance processing process, there are different time delays due to the action distance and communication reasons, so the receivers there may be a time difference in reporting data time. Before multi-radar reconnaissance sensor data fusion, data from multiple receivers needs to be transformed into the same time reference system, so that the unsynchronized information is registered to the same fusion time.

A pulse description word (PDW) time alignment algorithm based on pulse repetition interval (PRI) matching, the idea is to compare the PRIs detected by different sensors, and find the time alignment positions corresponding to the maximum similarity from different PRIs. In order to facilitate understanding, the radar reconnaissance sensor group is set to sensor 1 and sensor 2, and the corresponding observation data are PRI1 and PRI2, respectively, and the corresponding errors of PRI1 and PRI2 are calculated, and the smaller the error is, the better the matching is considered. By calculating the relative values of PRI1 and PRI2 at the best matching position, the relative time of the two observation times is obtained and aligned, which is composed of five steps.

1) Select the two sets of data that need to be PRI matched: \( \{PRI1(i), i=1,2\ldots n_1\} \) and \( \{PRI2(j), j=1,2\ldots n_2\} \).

2) Make \( PRI1 \) and \( PRI2 \) in order to form an m-dimensional vector \( X1(i), \ X2(j) \):

\[
X1(i)=[PRI1(i), PRI1(i+1), L, PRI1(i+m-1)], i=1,2,L,n_1-m+1
\]

\[
X2(j)=[PRI2(j), PRI2(j+1),\ldots PRI2(j+m-1)], j=1,2,\ldots,n_2-m+1
\]

3) Take the minimum error between \( X1(i) \) and \( X2(j) \) as the best match position:

\[
er(i,j)=\min(|X1(i)-X2(j)|), i=1,2,\ldots,n_1-m+1, j=1,2,\ldots,n_2-m+1
\]

4) The number of corresponding errors in the m-dimensional vector at the best matching position within the error range is recorded as k, and calculate the similarity rate:

\[
\varepsilon = \frac{k}{m} \times 100\%
\]

5) Define the relative time \( \Delta t \) of the first group within the error range as the relative time of the two groups of messages.

\[
PRI1(i)=toa1(i+1)-toa1(i)
\]

\[
PRI2(i)=toa2(j+1)-toa2(j)
\]

\[
\Delta t=toa1(i)-toa2(j)
\]
2.2. Data Association

Based on the DS theory of fusion method \([16]\), it first needs to calculate the basic probability distribution function, reliability function and likelihood function for various data and information to be fused, and then calculate the new basic under the joint action of each evidence according to the DS combination rule. Probability assignment function, reliability function and likelihood function, and finally decide the final result according to certain rules.

Definition 1: D-S evidence theory uses a recognition framework to represent the proposition set of interest. Define the basic probability assignment function on \(U\): \(m: 2^U \rightarrow [0,1]\), Meet the following formula:

\[
\begin{align*}
  m(\emptyset) &= 0 \\
  \sum_{A \subseteq U} m(A) &= 1 
\end{align*}
\]

(8)

\(m(\cdot)\) is called the basic probability assignment on \(U\). If \(m(A) \neq 0\), then \(A\) is called a focal element, \(m(A)\) reflects the credibility of \(A\).

Definition 2: The trust function is defined as \(\text{Bel}\), also known as Lower limit function, indicates trust in \(A\).

Set function \(\text{Bel}: 2^U \rightarrow [0,1]\), And meet:

\[
\text{Bel}(A) = \sum_{B \subseteq A} m(B) \quad \forall A \subseteq U
\]

(9)

Definition 3: Set Likelihood function \(\text{Pl}: 2^U \rightarrow [0,1]\), And meet:

\[
\text{Pl}(A) = 1 - \text{Bel}(U - A) \quad \forall A \subseteq U
\]

(10)

The \(\text{Pl}\) function is also called the upper limit function or the non-refutable function, indicating the degree of trust that is not false for \(A\). It is easy to prove that the likelihood function and the trust function have the following relationship:

\[
\text{Pl}(A) \geq \text{Bel}(A)
\]

(11)

The uncertainty of \(A\) is represented by \(u(A) = \text{Pl}(A) - \text{Bel}(A)\).

The evidence theory method has its reasonable synthesis rules, referred to as the DS rule. There are two inference systems with probability assignments of \(m_1, m_2\) respectively. For subset \(A\), the DS rules for the probabilistic assignment of the two inference systems are:

\[
m(A) = \frac{\sum_{A \cap A_i = A} m_1(A_i)m_2(A_i)}{1 - K} \quad \text{def} \quad m_1(A_i) \oplus m_2(A_i)
\]

(12)

Where \(K = \sum_{A \cap A_i = \emptyset} m_1(A_i)m_2(A_i)\).

If \(K \neq 1\), then \(m\) determines a basic probability assignment. If \(K = 1\), then determine that \(m_1\) and \(m_2\) are in conflict, cannot combine basic probability assignments.

In this synthesis rule, \(A_i \cap A_j = A\) expresses \(A_i \supseteq A, i = 1, 2\). That is both \(A_i\) have ingredients that support \(A\). \(m_1(A_i)m_2(A_i)\) indicates that \(A_i\) in the two systems together support the basic probability value of \(A\), Wherein only one \(m_i\) is 0, then \(m_1(A_i)m_2(A_i)\) Will be 0, \(\sum_{A \cap A_i = \emptyset} m_1(A_i)m_2(A_i)\) represents the sum of the information supported together in the two systems. Use this to indicate that the two system support for \(A\) is reasonable. For normalization, Divide by
\[
\sum_{A \cap A_i \neq \phi} m_i(A)m_j(A_j), \quad \text{Represents the total amount of information in all systems supporting all subsets } \\
\{ \ A_i \cap A \neq \phi \ \} \quad \text{with intersections.}
\]

Total probability assignment function under the joint action of \( n \) evidences:

\[
m(A) = \begin{cases} \\
0, \\
\sum_{i=1}^{n} \prod_{A_i} m_i(A_i), & \forall A \subseteq \bigcup A_i \neq \phi \\
1 - \sum_{i=1}^{n} \prod_{A_i} m_i(A_i) \\
\end{cases}
\]

Evidence theory calculates the similarity between the characteristic attributes of a set of evidence and the attributes of each framework. The combination of DS evidence theory is used to obtain the overall similarity between the measured data and the framework for identification. Since our purpose is only to calculate and be different at the same time. The overall similarity of the signal received by the receiver can be regarded as having two recognition frames. The overall similarity between the two is calculated by calculation, and then the threshold is set. If the similarity is greater than this value, the correlation is determined.

2.3. Data Fusion

Due to the sorting algorithm and the accuracy of the measurement parameters, even the signal parameters obtained by the same radar sorting may not be exactly the same, it needs to be compared within a certain tolerance to identify, and adjust each characteristic parameter describing the same radar to a uniform value. Attribute fusion of radiation source characteristic parameters using combination rules based on D-S evidence theory, the weight coefficient is defined by the mean square error of the sorting result, finally, uniformly processed the PRI, PW, and CF parameters belonging to the same radar.

1) Carrier frequency similarity

For fixed carrier frequency radars, Define radar similarity about carrier frequency:

\[
m_j(i) = \begin{cases} \\
1 & \Delta f_i \leq f_c \\
\frac{\Delta f_i - 2f_c}{f_c} & f_c \leq \Delta f_i \leq 2f_c \\
0 & \Delta f_i \geq 2f_c \\
\end{cases}
\]

Where \( \Delta f_i \) is the difference between the carrier frequency observation and the \( i \)-th radar carrier frequency, \( f_c \) is the measurement tolerance of the Radar Reconnaissance sensor, chosen to be 4 times the measurement accuracy.

For Carrier frequency agile radar, The frequency center value is \( f_c \), frequency agility range is \( f_A \), Define radar similarity about carrier frequency:

\[
m_j(i) = \begin{cases} \\
1 & \Delta f_i \leq f_A + f_c \\
\frac{\Delta f_i - f_A - 2f_c}{f_c} & f_c \leq \Delta f_i - f_A \leq 2f_c \\
0 & \Delta f_i \geq f_A + 2f_c \\
\end{cases}
\]

2) Pulse repetition interval similarity

For the Radar of different pulse repetition periods, the definition of similarity based on PRI is
different. If the PRI type is fixed and its PRI center value is $T_i$, then the similarity is defined as follows:

$$
m_{pri}(i) = \begin{cases} 
1 & \Delta T_i \leq T_e \\
\frac{|\Delta T_i - 2T_e|}{T_e} & T_e \leq \Delta T_i \leq 2T_e \\
0 & \Delta T_i \geq 2T_e 
\end{cases} \quad (16)
$$

If the PRI type of the $i$-th Radar is a repetitive frequency difference, taking the two-parameter as an example, let the skeleton period be $T_i$, and the two-parallel repetition interval be $T_{1i}$, $T_{2i}$, then the PRI difference is $\Delta T_{ij} = |T_i - T_{ij}|,$ $j = 1, 2$. Then the similarity as follows:

$$
m_{pri}(i) = \begin{cases} 
1 & \Delta T_i \leq T_e \text{ or } \Delta T_{ij} \leq T_e \\
\frac{|\Delta T_i - 2T_e|}{T_e} & T_e \leq \Delta T_{ij} \leq 2T_e \\
\frac{|\Delta T_i - 2T_e|}{T_e} & T_e \leq \Delta T_i \leq 2T_e \\
0 & \Delta T_i \geq 2T_e 
\end{cases} \quad (17)
$$

3) Pulse width similarity

$$
m_{pw}(i) = \begin{cases} 
1 & \Delta PW_i \leq PW_e \\
\frac{|\Delta PW_i - 2PW_e|}{PW_e} & PW_e \leq \Delta PW_i \leq 2PW_e \\
0 & \Delta PW_i \geq 2PW_e 
\end{cases} \quad (18)
$$

Through the time alignment method based on PRI matching, we register the asynchronous information to the same fusion moment. Through the data association technology based on DS evidence theory, we can calculate the correlation degree of the signal received by the two receivers at the same time. After the threshold decision, we can determine whether the signal comes from the same Radar. If the overall support is greater than or equal to the threshold, then it is determined that the two pulses are from the same radar.

3. Simulation and Results

In order to be close to the actual complex electromagnetic environment, the simulation scene is shown in Figure 1. Among them, there are two radar reconnaissance sensors, namely S1 and S2, and four radar radiation sources. The Radar signal is complex and the parameters are simulated actual equipment. They are respectively by E1, E2, E3 and E4, the motion paths as shown in Figure 1.
According to the parameters of airborne early warning radar, airborne multi-function radar, shipboard air defense radar and shipborne fire control radar, using Matlab simulation software to generate mixed with four radar signal pulse description words. The parameters are shown in Table 3.1.

Table 1. Parameter of the 4 Radar mixed signal

| Radar Type                        | CF/MHz     | PW/us  | PRI feature                  |
|-----------------------------------|------------|--------|------------------------------|
| 1st Airborne Early Warning Radar | 3250       | 1.1    | multi-hop                    |
| 2nd Airborne Multi-function Radar | 9500~9900  | 2.8    | Four staggered               |
| 3rd Shipborne Air Defense Radar  | 3100~3300  | 7.1    | Sliding variable 1us/continuous 22 pulses |
| 4th Shipborne Search Radar       | 5700       | 32     |                              |

The Matlab simulation of the radar signal is shown in Figure 2 (intercepting 2 milliseconds of data).
Figure 2. Radar signal simulation

2) According to the actual situation of the actual wireless channel transmission due to the pulse increase under the multipath condition and the loss of the wireless channel transmission, the scene simulation radar signal pulse is randomly introduced. The pulse description words generated by the sensor 1 and the sensor 2 receiver are acquired to form a pulse repetition interval pulse. Group PRI1 and PRI2, time alignment of PRI1 and PRI2, calculate the relative values of PRI1 and PRI2 at the best matching position, and find the relative time of the two observation times. Integrating PRI1 and PRI2 to obtain new PRI, and the simulation results are shown in Figure 3.

Figure 3. Time alignment of Multi-radar reconnaissance sensors

3) After obtaining the multi-sensor integrated pulse repetition interval time series, then used the combination of DS evidence theory to attribute the fusion source characteristic parameters, and obtained the pulse width, repetition frequency and carrier frequency similarity parameters of the pulse descriptor word. Finally finish the radar signal sorting, simulation results shown in Figure 4.
4. Conclusions
In this paper we propose a multi-radar reconnaissance signal joint sorting technology, it adopts a PRI-based time alignment method to correlate the arrival times of pulse descriptors word of multiple passive reconnaissance nodes, forms a more comprehensive pulse repetition period time series. Using the new series to carry out CF,PRI and PW correlation, and finally complete the fusion sorting of complex radar signal.

In the Section 3 of the paper, the results show that the method can realize the fast sorting ability of radar signals in complex systems under complex electromagnetic environment.

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