Real-time Sensing and Visualization of Electromagnetic Situation Based on Multi-source Information Fusion

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Abstract. It is of great significance for real-time sensing and visualization of electromagnetic situation to grasp the battlefield situation. The most important procedure is to deal with multi-source mass electromagnetic perception data and realize the point to space electromagnetic situation data refactoring. The basic idea of this paper is to estimate the electromagnetic field intensity of any concerned position by space domain fusion of multi-source data fusion after time domain fusion. Firstly, the Grubbs criteria is used in the pretreatment of single sensor data, and then the Bootstrap re-sampling methods is used for single sensor information fusion. This method can eliminate the vagueness and uncertainty of a mass of sensing data in a short period of time. Secondly, by the D-S evidence theory, the multi-sensor perceptual data combined with the wave propagation model and expert information are fused, and finally the prediction of space electromagnetic situation data is reconstructed. Finally, calculation examples of single sensor fusion and multi-sensor fusion are given to illustrate that the developed methods can increase the credibility of the reconstructed electromagnetic situation.

1. Introduction
As the widely use of electronic equipment and electronic countermeasures equipment, the battlefield electromagnetic environment becomes increasingly complex. The realization of sensing and visualization of Electromagnetic situation would enhance the EW operation discussion or other activities greatly[1]. Electromagnetic situation sensing belongs to the research category of high-level information fusion. It is not only the subsequent and deepen of battlefield target extraction, but also the premise of combat mission distribution and resource scheduling[2]. Multi-source data fusion technology has been applied to signal detection, recognition and positioning of radiation source[3][4][5], spectrum perception[6] and battlefield electromagnetic environment monitoring, etc. Heterogeneous information processing and fusion of huge amounts information form single sensor are the key problems. The fusion framework of battlefield electromagnetic perception was designed in article [2] based on high-level information fusion principle, and then the situational perception and fusion processing and application service technology are studied in detail to provide support to the operation command decision. In [7] multiple features are got from the image sensor and are fused to an integrated feather, then the feather is used in target recognition. The problems that conventional multi-user cooperative spectrum sensing ignores the difference of environments and Dempster-Shafer evidence theory combining rule neglects the extent of evidence conflicts ware solved in article [8], and then a spectrum sensing algorithm based on improved D-S evidence theory is proposed. A weighted
cooperative spectrum sensing algorithm based on D-S evidence theory (DS-WCSS) was proposed by Zhou [9].

In the process of electromagnetic situational sensing and visualization, a huge number of sensory data to be deal with in order to realize point to surface data refactoring. Then the lack of monitoring sites is compensated and the inversion of electromagnetic environment is achieved. After pretreatment on the sensor data, including time proofreading, target combined, fault-tolerant processing of the reconnaissance data, multi-sensor multi-target and multi-cycle measure data are obtained. Based on that, the Bootstrap re-sampling method is used for the fusion of single sensor monitoring information in time domain, then the D-S evidence theory is used for the fusion of multi-sensor perceptual data in space domain.

2. Time domain fusion of single sensor monitoring data
As the spectrum scanning speed is fast, a great deal of electromagnetic monitoring data can be obtained by each sensor in a short period of time. The sensory information represents the instantaneous or tiny fragments situation of electromagnetic environment. Those fuzzy and uncertain spectrum sensing data need to be fused to state the electromagnetic environment.

2.1. outlier data eliminate based on Grubbs criteria
The statistical method is employed for data processing within a minimal available time slice. The Grubbs criteria is firstly used to eliminate the influence of outlier data which is far away from the true value, and then remaining datum are approximately obey the normal distribution. After that the true state of the current spectrum perception state is estimated by statistical inference. Suppose the equal precision and independent monitor value of the field strength and other parameters in a short period of time are obtained as \( x_1, x_2, \ldots, x_n \), then sort the measured value in sequence as \( x_1 \leq x_2 \leq \cdots \leq x_n \), as the measured value \( x_i(i = 1, 2, \ldots, n) \) is normal distribution, then

\[
\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \quad \sigma^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2
\]

(1)

According to the principle of order statistics, define Grubbs statistics \( g_i = \left| \frac{x_i - \bar{x}}{\sigma} \right| (i = 1 \text{ or } n) \).

Given confidence level \( \alpha = 0.05 \text{ or } \alpha = 0.01 \), the critical value of Grubbs statistics which is \( g_{n, \alpha} \) can be obtained by table look-up, and \( P[g_i \geq g_{n, \alpha}] = \alpha \) is a low probability event. To measure the top value \( x_i(i = 1 \text{ or } n) \) and its Grubbs statistics \( g_i \), if \( g_i \geq g_{n, \alpha} \), then the statistic \( g_i \) is with significant differences to the distribution, \( x_i \) is a dubious value and should be deleted. Otherwise, the corresponding \( x_i \) is without error, and it should be retained.

2.2. Fusion estimation of sensing datum based on Bootstrap method
Repeat the above process, and ultimately get electromagnetic monitoring data without outliers as \( X = \{X_1, X_2, \ldots, X_N\} \), after that Bootstrap method is employed for spectrum sensing data fusion. The Bootstrap re-sampling is a statistical inference method proposed by Efron[11]. Only the given observation information is depended by this method, while other assumptions or added new observations is independent. The difficulties of data limitations and calculation robustness can be overcome, and the efficiency of estimation or inference methods can be greatly increased.

If the observation \( X = \{X_1, X_2, \cdots, X_N\} \) are from the unknown population distribution \( F \), \( R(X, F) \) is a selected random variables in advance, the basic steps of electromagnetic sensing data fusion based on Bootstrap are as follows:
Step1 construct empirical distribution function of the sample observations \( X = \{X_1, X_2, \ldots, X_N\} \), the weight of each point \( X_i \) of \( F_X(X) \) is \( \frac{1}{N}, i = 1, 2, \ldots, N \);

Step2 Resample from \( F_X(X) \) and get the Bootstrap sample \( X_i^* \sim F_X(X) \), and call \( X^* = \{X_1^*, X_2^*, \ldots, X_n^*\} \) as the Bootstrap sample. The core of Bootstrap method is to use Bootstrap sample to estimate the statistical properties of the unknown probability measure. The method does not assume that observation data conform to a particular form of distribution, but directly sample by the empirical distribution, and it belongs to the category of nonparametric method. We can get the resample by Monte Carlo as follows:

1) sample with the empirical distribution\(^{[11]}\), produce any decimal number between 0~1, \( U \sim U(0,1) \), define \( p = (n-1)U \) and \( I = \lfloor p \rfloor + 1 \), and then the first resample is \( X_i^* = X_i + (p - I + 1)(X_{i+1} - X_i) \), cycle until the sample number is \( N \).

2) Bayes Bootstrap re-sampling\(^{[10]}\): generate \( N \) sequences of random vector group \( V_{(i)}, \ldots, V_{(n)} \) distributed as Dirichlet \( D(1, \ldots, 1) \). each group of sequences generated as follows: assume \( v_{1}, \ldots, v_{n-1} \) is a uniform independent identically distribution sequence on \([0, 1]\), then rearrange it and we can get order statistic sequence \( V_{(1)}, \ldots, V_{(n)} \). let \( v_{(0)} = 0 \), \( v_{(n)} = 1 \), then the joint distribution of \( V_i = v_{(i)} - v_{(i-1)} \) \( i = 1, \ldots, n \) is \( D_1(1, \ldots, 1) \), \( V = (V_1, \ldots, V_n) \) is the needed random vector. then use occurrence probability as the weighted factor to get the estimated parameter, then a set of estimated samples is got, repeat the process to generate the other renewable samples.

Step3 use Bootstrap distribution \( R^* = R(X^*, F_X) \) to approximate the distribution \( R(X, F) \). s from point view of parameter statistical, \( F_X(X) \) is the maximum likelihood estimation of \( F(X) \), it is a discrete distribution, \( X^* \sim F_X \) and the possible value is \( \{X_1, X_2, \ldots, X_N\} \).

It can be seen that once the sample observations \( X \) is given, \( F_X(X) \) can be set, and thus get the Bootstrap sample, further the Bootstrap distribution can be obtained, and then the statistical inference can be carried on.

If \( M \) times of Monte Carlo simulation is done and each time the electromagnetic estimate from the Bootstrap re-sample is \( \hat{e}_k^* = E(X^*) \), then

\[
\hat{e}_{\text{mean}}^* = \frac{1}{M} \sum_{k=1}^{M} \hat{e}_k^* , \quad \text{var}(\hat{e}^*) = \frac{1}{M-1} \sum_{k=1}^{M} (\hat{e}_k^* - \hat{e}_{\text{mean}}^*)^2
\]

Under the limited samples, to estimate the distribution density and its parameters directly is an ill-posed problem. It is difficult to estimate accurately on condition of small sample, thus we turn to the Bootstrap method to calculate the estimated bias. in addition, the small sample size is in commonly 10 or so, when the sample is too little, the credibility is not high. If the timeliness demand of situational analysis is higher, the particle filter technology should be used to modify the weight of the particle dynamically through continuous sampling and re-sampling, then the estimated results will approach the real state of electromagnetic environment.

3. Space domain fusion of multi-source monitoring data
As the spectrum monitoring stations adopt coarse-grained, large-area separation and dispersion stations, it cannot effectively cover all concerned area. After time domain fusion, as the multiple source spectrum field sensing information are complementary or redundancy, the certainty and reliability of the information can be improved. During the process from multipoint monitoring information to the spatial spectrum field intensity data reconstruction, many factors such as topography, geomorphology, distance, frequency are involved. In the following paper, based on the
wave propagation prediction and the expert experience knowledge, the space distribution of electromagnetic situation is got by the D-S evidence theory.

3.1. wave propagation prediction model

Electromagnetic situation is calculated based on the calculation of wave propagation of radiation sources within a designated area. It is important to choose the appropriate radio waves propagation models. Radio waves propagation characteristics depends both on the transmission medium structural characteristic and the waves characteristic. Propagation medium characteristics of space and time mainly refers to the medium complex refractive index including dielectric constant, permeability and electrical conductivity, and it is the root of time and space changes of radio waves propagation characteristics. Thus, it is very important to collect and observe the local media characteristics, such as spatial distribution, time change and boundary condition. Wave propagation prediction calculation are mainly within the band from VLF to EHF. The main propagation model and according spectrum are listed in Table 1. In application the model is modified from ITU’s statistics model[12] according to the actual media situation of China after localization and engineering.

Table 1 Spectrum and its corresponding propagation model

| Spectrum | frequency range | propagation model |
|----------|----------------|-------------------|
| VLF      | 9kHz -30kHz    | Waveguide mode, ground wave, sky wave |
| LF       | 30kHz -300kHz  | Ground wave, sky wave |
| MF       | 300kHz -3000kHz| Space wave, diffraction, troposcatter, line of sight, etc |
| HF       | 3MHz-30MHz     | Line-of-sight |
| VHF      | 30MHz-300MHz   |                                 |
| UHF      | 300MHz-3000MHz |                                 |
| SHF      | 3GHz-30GHz     |                                 |

Take Line-of-sight propagation for example, the main effects considered includes multipath effect, focusing effect, atmospheric absorption effect. The field strength is calculated as follows:

$$E = 74.7 + P_i + G_t + G_r - 20 \log d - E_i(p) - A_v \text{ (dBμV/m)}$$

(3)

In which $E_i(p) = 2.6 \left[1 - e^{-0.02p}\right] \log \left(\frac{p}{50}\right)$, $A_v = \left[\gamma_v + \gamma_a(p)\right] d$ and $P_i$ --Transmission power (dBW), $G_t$ --The transmitting antenna gain (dB), $G_r$ --The receiving antenna gain(dB), $d$--The length of the propagation(dB), $\gamma_v$ --Dry air attenuation, $\gamma_a(p)$ --Water vapor attenuation ratio, $\rho$ --vapor density(g/m3).

The field strength of ground wave propagation is calculated as follows:

$$E = 109.54 + P_i - 20 \log W(\sigma, \varepsilon, d, f) - 20 \log d$$

(4)

$W$ denotes the ground wave attenuation, and is a complex function of transmitting frequency, transmission medium dielectric, conductivity, atmospheric dielectric[13].

3.2. data fusion based on D-S evidence theory

As shown in Figure 1, firstly the analysis region is gridded, and then the correlation between the spectrum monitoring points and the evaluation point are analysed based on the spectrum monitoring data and the wave propagation prediction model. According to the correlation information, a mass distribution table is constituted. lastly the field intensity of the prediction points is comprehensive evaluated by rules of evidence synthesis, the area electromagnetic situation is finally generated.
3.2.1 Information generated for the predicted point
Firstly, the designated area is divided into multiple grid points, and the field intensity of each grid point is predicted, then the regional situation is forecasted using the interpolation algorithm. The latitude and longitude of the divided grid points are as follows:

\[ \text{Plat} = \{\text{plat}_1, \text{plat}_2, \ldots, \text{plat}_m\} \]  
\[ \text{Plon} = \{\text{plon}_1, \text{plon}_2, \ldots, \text{plon}_m\} \]  

3.2.2 Perceptive resource information sorting
The latitude and longitude information of perception points are:

\[ \text{Lat} = \{\text{lat}_1, \text{lat}_2, \ldots, \text{lat}_n\} \]  
\[ \text{Lon} = \{\text{lon}_1, \text{lon}_2, \ldots, \text{lon}_n\} \]  

The sensation information of sensing point is \( R = \{e, k, q, u\} \) in which \( e \) is the measurement field intensity, \( k \) is the type of work for perception devices, 0 represents only having the field strength, 1 represents having both field results and direction; \( q \) is the direction finding precision, \( u \) is the threshold level, only when \( k \) is 1, \( q \) and \( u \) have value.

3.2.3 Calculation of field intensity difference
After getting the field strength of sensing points represented as \( E_s \), according to the characteristics of radio waves propagation, the maximum field strength changes between the perception point and prediction point can be calculated, the concrete calculation process is as follows.

**Step1** assumes the characteristic parameters of two endpoints of the communication link is: short vertical whip antenna, the antenna gain is 0, the antenna frame 0 meters high, transmission power is 1000 w, antenna elevation angle is defined as 0.1 for the ground wave, and its appropriate value is calculated according to the path length for sky wave, polarization mode is horizontal polarization, modulation mode is amplitude modulation.

**Step2** field intensity calculation for positive (increase) ground wave: suppose the prediction point is the launch source, the equivalent radiation power of antenna mouth is 30 DBW, according to the terrain parameters combination of ground wave propagation model, the field strength propagating to the perception source is calculated as \( E_{on} \), then the field intensity difference is \( \Delta E_{on} = 30 - E_{on} \); The maximum field strength of the forecast point is \( E_{sg,\text{max}} = E_s + \Delta E_{on} \).

**Step3** field intensity calculation for reverse (reduce) ground wave: assuming that perception point is launch source, the equivalent radiation power of antenna mouth is 30 DBW, the field intensity spread to the predict point is \( E_{on} \), then the field intensity difference is \( \Delta E_{on} = 30 - E_{on} \). The minimum field strength of the forecast point is \( E_{sg,\text{min}} = E_s - \Delta E_{on} \).
Step4 field strength calculation for sky wave: suppose the prediction point is the launch source, the equivalent radiation power of antenna mouth is 30 DBW, the field intensity spread to the perception source is $E_{ob}$, then the field intensity difference is $\Delta E_{ob} = 30 - E_{ob}$. The maximum field strength of the forecast point is $E_{ss_{\text{max}}} = E_{s} + \Delta E_{ob}$. As the sky wave has nothing to do with the terrain, the field strength of sky wave is only need to compute once, The minimum field strength of the forecast point is $E_{ss_{\text{min}}} = E_{s} - \Delta E_{ob}$.

3.2.4 Expert knowledge digitization
In this step, the mass distribution table is developed by considering the expert knowledge about environmental impact in the process of wave propagation, integrated with a variety of situations. We believe every perception equipment contributes to the prediction of the field strength of the designated point, so we make mass distribution for each sensation. According to the expert knowledge, the following are considered:

Working frequency, in accordance with the frequency and the expert knowledge, the transmission possibility of ground wave is $w_{fg}$ and the transmission possibility of sky wave is $w_{fs}$;

Distance between two points: calculate the distance from the prediction point to the perception point $d$, according to the expert knowledge, the transmission possibility of ground wave is $w_{dg}$ and the transmission possibility of sky wave is $w_{ds}$.

Terrain: according to the terrain height difference between two points $h$, as well as the path difference series in height between the grid point, $H = \{h_1, h_2, \ldots, h_k\}$, the transmission possibility of ground wave is $w_{hg}$ and the transmission possibility of sky wave is $w_{hs}$.

Then, The transmission possibility of sky wave and ground wave are

$$w_{s} = \frac{w_{fs} \cdot w_{ds} \cdot w_{hs}}{w_{fs} \cdot w_{ds} \cdot w_{hs} + w_{gs} \cdot w_{gs} \cdot w_{gs}}$$  \hspace{1cm} (9)$$

$$w_{g} = \frac{w_{gs} \cdot w_{gs} \cdot w_{gs}}{w_{fs} \cdot w_{ds} \cdot w_{hs} + w_{gs} \cdot w_{gs} \cdot w_{gs}}$$  \hspace{1cm} (10)$$

3.2.5 interval division of predicted field intensity
On the basis of field intensity information perceived from n sensors, the range can be divided as follows:

When there is only one monitoring results, i.e., $E_{s} = \{E_{s}\}$, predicted point field $E_{a}$ belongs to one of the following

- case 1 $E_{a} \leq E_{s}$;
- case 2 $E_{a} > E_{s}$

When there are two monitoring results, sort them and get $E_{s} = \{e_{s1}, e_{s2}\}$, then

- case 1 $E_{a} \leq e_{s1}$;
- case 2 $E_{a} > e_{s1}$ & $E_{a} \leq e_{s2}$;
- case 3 $E_{a} > e_{s2}$

When there are three monitoring results, sort them and get $E_{s} = \{e_{s1}, e_{s2}, e_{s3}\}$, then

- case 1 $E_{a} \leq e_{s1}$;
- case 2 $E_{a} > e_{s1}$ & $E_{a} \leq e_{s2}$;
- case 3 $E_{a} > e_{s2}$ & $E_{a} \leq e_{s3}$;
- case 4 $E_{a} > e_{s3}$.
If there are more than three monitoring results, and so on. as excessive divided interval increases the calculation load, generally five intervals are preferred (i.e., determining four judgment points) and can basically meet the calculation requirements.

3.2.6 Mass Distribution Table Construction
Map the calculation results of propagation model to various circumstances to the interval, and then the corresponding probability results will also be got,

\[
\min \leq m(x) \leq \max \qquad \text{if } x \in [\min, \max]
\]

Constitute the mass distribution table.

| Interval | h1 | h2 | h3 | h4 | h5 |
|----------|----|----|----|----|----|
| m1       | m1(A1) | m1(A2) | m1(A3) | m1(A4) | m1(A5) |
| m2       | m2(A1) | m2(A2) | m2(A3) | m2(A4) | m2(A5) |
| ...      | ...   | ...   | ...   | ...   | ...   |
| mn       | mn(A1) | mn(A2) | mn(A3) | mn(A4) | mn(A5) |

Normalize the constant N, and get

\[
K = \sum_{A_i \cap A_j \cap A_k = \emptyset} m_1(A_1)m_2(A_2) \cdots m_n(A_n)
\]

If K=0, the BPA (basic probability assignment) of some mass functions needs appropriate adjustments, find the column in the mass distribution table with the largest arithmetic mean of BPA and the value of BPA is 0, then change the BPA values of the column with the largest arithmetic mean to be MinMass instead, and accordingly find the biggest BPA, and reduce its value MinMass.

3.2.7 Field Intensity Synthesis
According to the Dempster synthesis rules, the synthetic formula for \( n \) mass functions \( m_1, m_2, \ldots, m_n \) is

\[
(m_1 \oplus m_2 \oplus \cdots \oplus m_n)(A) = \frac{1}{K} \sum_{A_i \cap A_j \cap A_k = A} m_1(A_1)m_2(A_2) \cdots m_n(A_n)
\]

And in which \( m(h_i) = \frac{1}{K} \times m_1(A_1) \times m_2(A_2) \times \cdots \times m_n(A_n) \), \( i = 1, 2, \ldots, 5 \).

Comparing these results, the biggest result means the largest probability that falls within the range, and defined it as \( h_i \). Finally, fuse the multiple waves forecast results in the maximum reliability interval, and get the electromagnetic environment characteristics of the fuzzy spectrum monitoring area. According to the above calculated probability and the field strength, it is concluded that the field strength of the predicted points after fusion is the mean of overlap range of all equipment, it is

\[
E_a = \text{mean} \left( \bigcap_{\text{max}, i} E \left( m_{\text{max}, i} \right) \right)
\]

In which \( E \left( m_{\text{max}, i} \right) = h_i \bigcap \left[ (E_{\text{max}, i} \cdot w_g + E_{s\text{max}, i} \cdot w_s), (E_{s\text{max}, i} \cdot w_g + E_{s\text{max}, i} \cdot w_s) \right] \)
4. Calculation examples

4.1. example of time domain fusion
For a single monitoring station, we get about 20 monitoring data as a small time fragment, after normalizing and then the Bootstrap method is used to get the estimate the field intensity and its variance of the electromagnetic field, about 1000 times Monte Carlo Simulation is executed. For test, we simulate 500 fragments, the field intensity and its variance are shown in Figure 3. we can see that a large amount of spectral sensing data in a short period of time has a strong fluctuation. This method can eliminate the vagueness and uncertainty of a mass of sensing data in a short period of time.

![Figure 3 simulation of Time domain fusion](image)

4.2. example of electromagnetic situation visualization
We use the method above to build an electromagnetic situation awareness and real-time display system based on the geographic information systems of China. Figure 4 gives a calculation example, in this example, four monitoring stations were deployed in Hubei province of China, electromagnetic monitoring data is virtual generated using background simulation data. Then the electromagnetic situation is inverse constructed by the application of sensory data and propagation theory. the field intensity distribution of frequency 9050 MHz is shown in Figure 4, and other frequencies are similar. The distribution of radiation sources is also shown in the figure for comparison. By contrast, the inversion electromagnetic situation is basically consistent with the generation situation of radiation source.

![Figure 4 example of multi-source monitoring data fusion](image)

5. Conclusion
In complex battlefield environment, refactoring the space electromagnetic distribution based on electromagnetic spectrum sensing data is the foundation for the following analysis of area spectrum occupy, complexity analysis, equipment threat analysis. It is of great significance to grasp the battlefield. The certainty and reliability of the evaluation conclusion can be improved by comprehensive utilization the complementary or redundancy of multi-sensor information. The
The developed method is suitable for fuzzy estimation on condition of enough monitoring station but single monitoring function. If the monitoring station is few in number but with direction positioning function, the D-S evidence theory can be directly used for attribute identification of emitters, and then the space electromagnetic situation can be reconstructed.

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