Weight Adjusting Algorithm Based on Sensor-space-time Quantum for Air-Information Fusion Precision Evaluation

Wu Xiao-chao, Cheng Ying, Cui Long-fei and Tang Yun-ge

Electronic Equipment Test Centre of China, Luoyang Henan 471003, China

*Corresponding author: wuxiaochao@126.com

Abstract. The precision index in the performance test of air-information fusion system is one of the important indexes, which benchmark to be determined in complex environment is difficult. This paper proposes a space-time weight adjusting algorithm for the air-information fusion system to solve this problem, as follows: The first is to build the weight priority by the magnitude of radar detection precision; the second is to find the sets of the radars’ time domain that play a dominant role during fusing; the third is to calculate the time cumulate value of radar precision; the fourth is to use the time cumulate value of radar precision and fusion track to allocate all the radar precision weights, and calculate the reference precision by weighting the radar detection data precision; the last is to evaluate the precision index according to fuzzy evaluation method. This algorithm applies to the precision evaluation of the air-information fusion system under the static simulation or dynamic flight conditions with good adaptability and credibility. The simulation shows its value.

1. Induction

As one of the core components of command and control system for air defense, the air-information fusion system is the main information source for its battlefield situation judgment and operations decision, which plays an important part in the battlefield awareness, command decision and artillery strike of command and control system. So the performance and effectiveness of the air-information fusion system are strongly associated with the viability of air defense system. The precision index is one of very important indexes to get the error distribution difference between the tracking position and the real one, which can be used to reflect the ability of tracking and guiding of the air-information fusion system, and verify its fusion performance. According to the theory of information fusion, an excellent algorithm can improve the precision of tracking object information. However, it is difficult to acquire this result for the complicated battlefield environment, such as electromagnetic interference, air disturbance, mountain blockage, radar detection characteristics, etc., which can lead to sensor data uncertainty and discontinuity resulting in the precision of the air-information fusion system reduced, and the process of precision evaluation is become harder. This is a problem to be resolved urgently that confirms the precision reference for evaluating.

This paper proposes a weight adjusting algorithm based on sensor-space-time quantum to acquire the reference precision for air fusion precision evaluation. After obtaining the precision weight value of radars by the sensor-space-time quantum from the data of radar, fusion and real track in a single test, the reference precision can be figured out with the current radars’ detecting precision. Subsequently, fuzzy evaluation method is used to assess the fusion precision. At last, an example shows that this algorithm is practical.
2. Main Factors Affecting Fusion Precision

In practice, the actual value of fusion precision of air-information fusion system is often worse than the theoretical one, which reasons are as follows:

1) Data exception caused by fusion algorithm: If a fusion algorithm, generally involving temporal-spatial matching, track correlating, combined filtering, detection and tracking, is designed so worse, it would lead the fusion result to big error. For example, if the target movement model cannot adapt well to target maneuvers, the fusion precision would be declined for the worse deviation by predicting and tracking as the target maneuvers changing. This problem can be distinguished on the situation picture that belongs to the track association mistakes or position deviation.

2) Information delay received by fusion system: The information that the fusion system receives from sensors is transmitted by wired or wireless network, thus the network latency can cause the fusion information interrupted partially or completely so that the fusion result maybe appear discontinuity or low precision.

3) Discontinuity of sensor’s target detection: There are many factors that can cause the discontinuity of sensor’s target detection, such as the terrain defilade (lead to the radar blind space) causes track data interrupted, the radar characteristics (involving detection probability, upper space of silence, detection range, etc.) result in the detection data missed, and the networks of different radars (the disposal principle of radars is complementary in terms of airspace, function and advantage. For example, the radar network models include the combinations of high-low precision, long-short range, high-low altitude, and even two-three coordinate) make the detection data instable. Therefore, the reasons of discontinuity of sensor’s target detection have the characteristics of diversity and complexity. The instable data results in the instable fusion result which precision at different times is rather changeable.

Based on the above analysis, during the test and evaluation of fusion precision, it is necessary not only to be familiar with the design and application of the air-information system, but also to analyze objectively the precision problems in the test to judge that the reason for the unsatisfactory fusion precision is the internal design factor of the fusion system or the external intelligence data factor according to the located result from the data distribution, data continuity and data anomaly characteristics.

3. Fusion Precision Evaluation Problems

Fusion precision evaluation is a process of quantitatively evaluating the dispersion degree of error of the fusion track relative to the true value of the track. Precision evaluation is the most controversial item in multiple index evolution of the fusion system performance. The main reason is that precision evolution benchmark is hard to determine. At present, there are three precision evaluation benchmark methods, namely the best detection precision value, the worst detection precision value and the average detection precision value, but these three methods have their shortcomings as the follows:

1) Best detection precision value: This method is only suitable for the evaluation process that uses pure simulation means to verify fusion algorithm, where the simulation data is an ideal radar data, namely uniform noise distribution, without losing points, and consistent-overlap detection range. It is mainly used for laboratory to test fusion algorithm performance, but, in a complex test environment close to actual combat, fusion precision cannot be exceeded the highest detection precision value of participate radar. Therefore, this method makes most of fusion system precision not up to the standard, and loss its evaluation significance.

2) Worst detection precision value: If the worst radar precision value is used as the benchmark, it is possible that the fusion system with poor performance will pass the test and examination, and even one track being simply mixed by the flight tracks can also pass the evaluation. That method loses the significance of air-information fusion. Therefore, this method is only applied to the basic test in the case of fusion system’s design and production.

3) Average detection precision value: It is the most common method to use the average value of radar detection precision as the benchmark, which is to average the detection precision of all radars involved in the experiment. This method solves the above problems well, and can reflect the performance of the
fusion system to some extent, but its defect is also obvious. The defect is that it is difficult to reflect the main effect of the data volume and the duration volume of radar detection. Because the time and duration of air targets entering into the airspace of radar detection and the space position of the track detected by radar are different, the amount of data detected by each radar are different. There is no doubt that the more data volume and the more duration volume the radar data have, the more it can affect the fusion result, even the fusion precision. But the Average method cannot describe this kind of situation.

Therefore, in order to scientifically and objectively verify the quality of the fusion precision of air-information fusion system, it is necessary to explore a new fusion precision evaluation method to solve the above problems.

4. Fusion Precision Evaluation Method of Space-time Weight

The fuzzy evaluation method is selected to evaluate the air-information fusion, and the fuzzy membership function is selected as the satisfaction index function according to the "satisfactory principle", which is designed as follows:

\[ f_{s} = \exp(-0.1054\times \sigma_{i}/\sigma_{u}) \]  

(1)

where \( \sigma_{i} \) is the radar position precision to be evaluated, such as longitude and latitude position, or azimuth and pitch angle, and \( \sigma_{u} \) is the radar weight precision (namely the reference precision taken as the benchmark), which formula is given by:

\[ \sigma_{w} = \sum w_{i} \sigma_{i} \]  

(1)

where \( \sigma_{i} \) is the detection precision of all current radar track data, \( w_{i} \) is the radar precision weight, and \( \sum w_{i} = 1 \).

In this paper, the evaluation method of space-time weight is proposed to solve the problem that the fusion precision evaluation is inaccurate for the uncertainty of the space and time of multi-sensor track detection information, which is a method to design the \( w_{i} \). Its principle is to calculate the fusion effect proportion of space-time domain of each radar detection data based on sorting every radar precision values, and ultimately get the reference precision \( \sigma_{w} \). The Figure 1 is the main steps as follows:

- Arrange the radar array. If we have \( N \) radars to fuse the air-information, the radars are sorted according to the magnitude of every radar detection precision \( \sigma_{i} \), which is acquired by counting the radar detection data, and get the radar array \( R_{i} \in \{R_{1}, R_{2}, \cdots, R_{N}\} \).

![Figure 1. Flowchart of air-information fusion reference precision](image)

- Associate the radar track with the true track. In the simulation test, the true track is the actual flight path in the scenario. In the dynamic flight test, the true track is the high-precision measurement data for aerial target trajectory, such as GPS navigation equipment and high-precision radar, etc. By using the spatial distance method, the minimum spatial distance between radar track and truth track is taken as the matching principle. If the spatial distance between the \( j \)th track in \( R_{i} \) radar and each truth track is the set as:
where \( k \) is the number of true track, and \( d_k \) is the spatial distance between the \( j \)th track in \( R_i \) radar and \( k \)th truth track. We can choose the minimum in \( D_j \), so the true track corresponding to the minimum is the track related to the \( j \)th radar track. For instance, if \( d_k \) is the minimum, the \( k \)th truth track is corresponding to the \( j \)th radar track. In this way, we can find the correspondences, in turn, between all the tracks in \( R_i \) radar and truth tracks, and find the correspondences between the tracks in all the radars and truth tracks as well. It is possible that a truth track can correspond to several tracks in one radar, so the time domain set of \( R_i \) radar corresponding to the \( j \)th true track is shown as follows:

\[
D_j = \{d_1, d_2, \ldots, d_k\}
\]  

(2)

where \( k \) is the number of true track, and \( d_k \) is the spatial distance between the \( j \)th track in \( R_i \) radar and \( k \)th truth track. We can choose the minimum in \( D_j \), so the true track corresponding to the minimum is the track related to the \( j \)th radar track. For instance, if \( d_k \) is the minimum, the \( k \)th truth track is corresponding to the \( j \)th radar track. In this way, we can find the correspondences, in turn, between all the tracks in \( R_i \) radar and truth tracks, and find the correspondences between the tracks in all the radars and truth tracks as well. It is possible that a truth track can correspond to several tracks in one radar, so the time domain set of \( R_i \) radar corresponding to the \( j \)th true track is shown as follows:

\[
F_j' = \{[t_{i1}', t_{i2}'], [t_{i1}', t_{i2}'], \ldots, [t_{i1}', t_{i2}']\}
\]  

(3)

where \([t_{i1}', t_{i2}']\) is the interval of the \( n \)th detection track in \( R_i \) radar, \( t_{in}' \) is the starting time of the \( n \)th detection track in \( R_i \) radar, and \( t_{i2}' \) is the ending time of the \( n \)th detection track in \( R_i \) radar. If the number of true tracks is \( K \), the time domain set of \( R_i \) radar is shown as follows:

\[
F_j' = \{F_{j1}, F_{j2}, \ldots, F_{jk}\}
\]  

(4)

- Count the fusion time domain set and its time cumulate value. The method to match the fusion track to the truth track is the same as the second step above. And we can reckon the fusion time domain set of \( m \) fusion tracks corresponding to the \( j \)th true track as follows:

\[
F_j = \{[t_{11}, t_{12}], [t_{11}, t_{22}], \ldots, [t_{mn}, t_{mn}]\}
\]  

(5)

Then the total fusion track time domain set is:

\[
F_s = \{F_{j1}, F_{j2}, \ldots, F_{jk}\}
\]  

(6)

If the number of fusion tracks is \( M \), the time cumulate value of fusion track is:

\[
T_s = \sum_{j=1}^{M} T_j
\]  

(7)

where \( T_j = \sum_{m=1}^{L_j} (t_{mn} - t_{in}) \) is the fusion time duration of \( j \)th true track, and \( L_j \) is the number of fusion track corresponding to the \( j \)th true track, also the number of time domain in the set \( F_j \). Thus, \( T_s \) is the summation of all intervals in the time domain set \( F_s \).

- Reckon each radar time cumulate value \( T_i \) according to the sequence of \( R_i \). The calculation process of time cumulate of each radar is shown in the Figure 2:
Array $R_i$ is ready.

Reckon the time cumulate $T$ of $R_i$

$\vdots$

Calculate the remaining fusion time domain $F_i = F_i \cap (I - F_i')$

$\vdots$

Calculate the intersection of $F_i'$ and $R_i$ in the time domain $F_i'' = F_i' \cap F_i$

Use $F_i''$ to compute the time cumulate $T$ of $R_i$

If $i = i + 1$, finish

$\vdots$

Figure 2. Flowchart of the radar time cumulate

where $\tilde{F}_i = F_i \cap (I - F_i')$ is the remaining fusion time domain to separate the processed radar time domain from the fusion time domain, and $I$ is the universal set of fusion time domain. $\tilde{F}_i' = F_i' \cap F_i'$ is extract the remaining time domain from the $R_i$ radar that participates in the fusion process. The time cumulate value of $R_i$ calculated by using $\tilde{F}_i'$ is:

$$T_i = \sum_{j=1}^{n_i} T_{ij}$$

where $n_i'$ is the track number of $R_i$, and $T_{ij}'$ is the time duration of $R_i$ tracks, namely the difference between the ending time and the starting time of the track time interval, whose computing method is the same as the formula (8).

- Here, we can get the radar precision weight:

$$w_i = T_i' / T_s$$

If the calculation error results in $\sum w_i \neq 1$, then all $w_i$ need to be normalized again.

- Finally, the reference precision $\sigma_w$ can be obtained according to the formula (2).

It can be seen from the above that the weight adjusting algorithm based on sensor-space-time quantum for air fusion precision evaluation is a method to determine the reference precision according to the spatial and temporal distribution of radar detection track and fusion track. With different test data, the precision weight will also change accordingly, so as to adapt to requirements of fusion evaluation for different tests in complex environments. Thus this method can reflect the situation of the air-information fusion system under many environmental conditions.
5. Simulations and Illustrations

In this paper, we propose three important contents to implement the fusion precision evaluation which include the radar time domain set \( F_i \), the radar time cumulate value \( T_i \) and the radar precision weight \( w_i \). To understand more about the relationship between these three contents, it is assumed that there are three radars arranged as \((R_1, R_2, R_3)\) from high to low precision. If these radars find a target at the same time, three possible distributions of the radar time domain are shown in Figure 3.

\[ a) \quad F_i^1 < F_i^2 < F_i^3 \]

\[ b) \quad F_i^2 < F_i^3 < F_i^1 \]

\[ c) \quad F_i^2 < F_i^3 < F_i^1 \]

Figure 3. Diagrams of three possible distributions of the radar time domain

In the figure, the radar time domain is composed of short lines of different lengths. Each short line represents a radar track time interval. In the case of a), all three radars can be obtain respective the radar time cumulate, so that a precision weight value can be calculated. In the case of b), the time domain of \( R_2 \) radar is merged by the \( R_1 \) radar, so that the precision weight value of \( R_2 \) radar is 0. In the case of c), the time domains of \( R_2 \) radar and \( R_3 \) radar are all merged by the \( R_1 \) radar, so that the precision weight values of \( R_2 \) radar and \( R_3 \) radar are 0, and the precision weight values of \( R_1 \) radar is 1. From the above three examples, we illustrate the theory that the allocation priority of radar precision weight is determined by the magnitude of radar precision, and the time domain of high precision will merge the low precision’s. If the highest precision radar has the biggest time domain and contains the other radar’s time domain, this highest precision should be taken as the fusion precision evaluation benchmark. Thus, this method can keep the consistent in the air-information fusion evaluation principle and connotation, which meets the fusion demand of practical application, and reflects its adaptability and effectiveness.
Figure 4. Radar detection information and fusion information

Figure 4 shows the practical radar detection track and fusion track for a plane, where the plane has two runway curves, and there are five different precision and detection range of radars (these radars are sorted by the precision as \( R_1, R_2, R_3, R_4, R_5 \)). The track space position and data amount obtained by each radar are different, among which radar \( R_1 \), radar \( R_2 \) and radar \( R_5 \) are relatively low precision but large search range, and the search range of radar \( R_5 \) is the largest, so the data is relatively complete; radar \( R_2 \) and radar \( R_4 \) are of high precision but small search range, so the data of these two radars are fragmentary. The air-information fusion system produces the fusion track based on radar detection data. The lower left part of the track in the figure is mainly based on the radar \( R_5 \) data, while other radar data are basically absent. It can be seen that the error distribution of fusion air-information changes with the change of current radar information.

Taking the flight track recorded by the high-precision measurement equipment as track truth value, the detection precision of each radar track was calculated, and the fusion precision was evaluated as shown in Table 1.

Table 1. Data record table for evaluating the fusion precision of space-time weights

|            | Latitude precision B (°) | Longitude precision L (°) | High precision H (m) |
|------------|--------------------------|---------------------------|----------------------|
| Radar R1   | 0.002736                 | 0.002653                  | 212.56               |
| Radar R2   | 0.002428                 | 0.003651                  | 232.17               |
| Radar R3   | 0.004890                 | 0.002703                  | 612.55               |
| Radar R4   | 0.005386                 | 0.003579                  | 557.30               |
| Radar R5   | 0.008869                 | 0.011212                  | 996.25               |
| Reference precision | 0.005717             | 0.005755                  | 629.37               |
| Fusion precision  | 0.003352             | 0.05422                   | 436.01               |
| Satisfaction evaluation of individual indicators | 0.940               | 0.905                     | 0.930                |
| Comprehensive satisfaction evaluation           |                          |                           | 0.925                |
Note

The weight of each radar precision is respectively: 0.32, 0.23, 0.21, 0.14, 0.1.
The weight of comprehensive satisfaction is the average weight.

If the comprehensive satisfaction evaluation value greater than 0.9 is taken as the qualified standard, the evaluation result of this data is qualified. It can be seen from the data in table that the reference precision and fusion precision are related to the radar precision and amount of air-information involved in fusion. The evaluation process and result of this method can reflect the influence of radar detecting air-information on fusion system, moreover, and the fusion system’s ability to adapt to the complex air-information, which can use to verify the performance of air-information fusion system very well.

From the above, the key to acquire these weights is to determine the sum of durations based on the priority of radar precision that the radars work in the air-information fusion, and calculate the weight assignment of each radar in precision based on the total fusion time. This method has the following advantages:

- The weight of radar precision will vary with the space-time domain of track data in each test, reflecting the influence of each radar detection track on fusion precision. Therefore, this method can adapt to the evaluation and verification process of air-information fusion in complex environment;
- The weight assignment of each radar is related to the magnitude of radar precision and the proportion of radar time domain. By automatically assigning precision weight, it can well reflect the theory that the fusion algorithm can improve the precision of target tracking. For instance, when the track time domain of the highest precision radar in the fusion system is consistent with the fusion time domain, the calculation result of precision weight takes this radar precision as the reference precision which meets the requirement of fusion enhancing precision;
- The radar precision weight can adapt to fusion precision of various test methods. No matter simulation test or dynamic flight test, only the objective test data is needed as the evaluation basis to reduce the impact of subjective factors on the evaluation process, which can scientifically verify the performance of fusion system.

6. Conclusion
As a major source of intelligence in air defense operation, the air-information fusion system is an important component of the air defense combat command system, where the performance of air-information fusion system directly affects the winning ability of the troop in modern high-tech war. The fusion precision is an important index to reflect the performance of the air-information fusion system, and it is also a controversial index in the evaluation results. The method to acquire the reference precision for fusion precision evaluation is performed according to the following steps: construct the priority of radar precision, analyze radar detection time domain, compute the time cumulative value of each radar in fusion time domain, adaptively assign the radar precision weight based on the time cumulative values, and calculate the reference precision to resolve the problem of precision evaluation of air-information fusion system in complex environment. This method can well verify the precision performance of the air-information fusion system and provide a basis for improving the operational efficiency of the air-information fusion system.

References
[1] Yang Liping, Wang Yinglong. Research on Application of Data Fusion to C3I System of Air Defense. Fire Control and Command Control. 2008,33(12):73-76
[2] Dong Qiang. Information Systems in Command Post. Beijing: National Defense Industry Press, 2012
[3] Han Chongzhao, Zhu Hongyan, Duan Zhansheng. Multi-source Information Fusion. Beijing: Tsinghua University Press, 2010
[4] Huang Peikang. Radar Target Characteristics. Beijing: Electronic Industry Press, 2005
[5] Wang Xiaoxuan. *Evaluation Method for Track Quality of Target Fusion*. Command Information System and Technology, 2012, 3(2): 17-22.

[6] Ma Yalong, Shao Qiufeng, Sun Ming. *Evaluation Theories and Methods and Their Military Applications*. Beijing: National Defense Industry Press, 2013

[7] Wu Xiaochao, Li Dong, Zhang Xing, Huang Zhenyu, Liu Bo. *Performance Evaluation Method Based on Satisfactory Degree for Air-Information Fusion System*. Journal of System Simulation, 2017, 29(10): 2415-2422

[8] Zhao Zonggui, Xiong Zhaohua, Wang Ke, Xu Yang. *Conceptions, Methods and Applications on Information Fusion*. Beijing: National Defense Industry Press, 2010