An adaptive multi-sensor resource allocation algorithm based on efficiency function

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Abstract. In this paper, combined with the Kalman filtering algorithm, the linear weighted sum of the normalized prediction information increment DI and the norm of target filter error covariance matrix \( ||P|| \) is used to represent the pairing function of the target-sensor combination and the assignment and automatic updating of the pairing function between sensor and target are realized. Based on the analytic hierarchy process (AHP), an adaptive sensor resource allocation algorithm is proposed. The simulation results show that the algorithm can effectively integrate various evaluation factors and is compatible with different types of targets. The algorithm has simple structure and good versatility. The limited sensor resources can be dynamically adjusted according to the priority of targets, making the sensor allocation strategy more reasonable and effective.

1. Introduction

With the rapid development of sensor networks and the aggravation of the complex situation of sea, land, and air combat, in order to obtain the best combat effect, cooperative operations among platforms and information fusion among sensors are indispensable. As an important part of information fusion technology, the research of multi-sensor management method is very necessary. Sensor management refers to the use of multiple sensors to collect information about the target and environment, and decompose the task of each sensor [1], making full use of the resources of the whole system [2].

The purpose of sensor management is to allocate sensor resources reasonably using certain optimal criteria [3]. In order to solve the problem that the target-sensor (combined) matching function is difficult to quantify in the previous effectiveness function method, this paper comprehensively considers the impact of target threat evaluation and the sensor-target pairing function, and defines the sensor effectiveness function. A sensor-target pairing function calculation method based on the normalized information increment and the target filter error covariance matrix norm is proposed. This algorithm can realize the automatic update of the sensor-target pairing function and make the sensor allocation strategy more reasonable.

2. Multi-sensor resource allocation scheme

Let the threat degree of target \( j \) be \( t(j=1,2,...,n) \) and the effectiveness function of sensor \( s(i=1,2,...,m) \) to target \( o_j \) is \( E_{ij} \). The analysis shows that there are two main factors affecting the sensor's comprehensive effectiveness against the target. One is the threat level of the target. The higher the
threat level is, the higher the sensor’s effectiveness will be. The second is the sensor-target pairing function.

The effectiveness function is defined as

$$\begin{align*}
E_{ij}(s_1, s_2, \ldots, s_m; o_1, o_2, \ldots, o_n) = q_j(o_1, o_2, \ldots, o_n) \times p_{ij}(s_1, s_2, \ldots, s_m) 
\end{align*}$$

(1)

Where $q_j(o_1, o_2, \ldots, o_n)$ is the ranking function of target threat degree, representing the influence of priority on comprehensive effectiveness function. $p_{ij}(s_1, s_2, \ldots, s_m; o_1, o_2, \ldots, o_n)$ is a sensor-target pairing function, which represents the sensor’s ability to process the target. The stronger the sensor’s ability to process a specific attribute target, the higher its effectiveness value to that target.

Let $X$ be the sensor allocation matrix, where the element $x_{ij}$ in the sensor allocation matrix can only be taken as 0 or 1, when $x_{ij} = 0$, it means that sensor $i$ is not allocated to target $j$, and when $x_{ij} = 1$, it means that sensor $i$ is allocated to target $j$. According to the above assumption, the purpose of sensor allocation is to maximize the integrated performance value after allocation, that is, to find the sensor allocation matrix $X = [x_{ij}]_{m \times n+1}$, $i \in [1, m']$, $j \in [1, n+1]$ that maximizes $G = \sum_{i=1}^{m'} \sum_{j=1}^{n+1} (x_{ij}E_{ij})$, where $m' = 2m-1$, including any combination of sensors. The collection of $M(i=1, 2, \ldots, m)$ represents all sensor combination serial Numbers using sensor $S_i$. In addition, the number of targets is one more than the actual number of targets, and the maximum value of $j$ is $n+1$. Here, a virtual target $o_{n+1}$ is defined, because when the sensor capacity is excessive, the sensor is allowed to be idle, and the sensor matched with $o_{n+1}$ is the idle sensor.

In addition, the sensor allocation matrix $X = (x_{ij})_{m' \times n}$ should meet the following constraints

Constraint 1: Constraint on sensor tracking capability

$$\begin{align*}
\sum_{i \in M_j} \sum_{j=1}^{n+1} x_{ij} \leq c_i, x_{i,n+1} = 0 & \quad i \in [1, m'] \\
\sum_{i \in M_j} \sum_{j=1}^{n} x_{ij} = 0, x_{i,n+1} = 1 & \quad j \in [1, n+1]
\end{align*}$$

(2)

Where $c_i$ is the maximum number of targets tracked by the sensor.

Constraint 2: The coverage constraint of the sensor to the target

$$\begin{align*}
\sum_{j=1}^{n} x_{ij} \geq 1, j \in [1, n] \\
\sum_{i=1}^{m'} x_{ij} \geq 0, j = n + 1
\end{align*}$$

(3)

The second inequality indicates that the sensor is allowed to be idle, and the sensor covering the $n + 1$ target is the idle sensor [4].

3. Target threat assessment

Target threat assessments obtained by the weighted summation of the enemy’s combat capabilities and combat objectives. In this paper, combined with prior knowledge, the threat degree algorithm based on the AHP model is used to evaluate the threat degree of the target.

Analytic hierarchy Process (AHP) was proposed by operations research scientist T.L. Smarty in the last century [5], and has been widely used in solving decision-making problems with multiple influencing factors [6-9]. The analytic Hierarchy Process first uses the Numbers 1-9 and their reciprocal as scales to construct the judgment matrix [10], and the larger the number is, the more important the former is than the latter [11].
The eigenvector $\lambda_i$ of the judgment matrix is calculated and normalized. Then the average random consistency index $RI$ was obtained by looking up the table, and the consistency index $CI$ was calculated according to (4):

$$CI = \frac{\lambda_{max} - n}{n - 1}$$ (4)

Finally, the consistency ratio $CR$ is calculated by formula (5). When CR is less than 0.10, the constructed matrix meets the requirement of consistency[12], and the normalized eigenvector $\lambda_i$ is the weight of each factor.

$$CR = \frac{CI}{RI}$$ (5)

According to the above discussion, the steps of threat assessment are as follows:

- The distance of the target distance platform, the flight speed of the target, the azimuth Angle of the target relative to the observation platform, the type of the target and the manoeuvrability of the target are taken as the influencing factors.
- According to expert experience and prior knowledge, an acceptable criterion layer judgment matrix is constructed, and its maximum eigenvalue and corresponding eigenvector are calculated. After normalization, the resulting vector is the weight of each impact factor $\lambda_i$.
- Construct a reasonable function to get the quantized value $T_i$ of each factor, and finally calculate the threat degree of the target by pressing the following formula:

$$t_j = \sum_{i=1}^{5} \lambda_i T_i$$ (6)

4. Target-sensor pairing function

The form of the pairing function $p_{ij}$ is difficult to express with a specific expression. The method used in reference[13] is to assign a fixed value to the pairing function according to the parameter table, but this method can not automatically update the value of sensor (combination) - target pairing function, and is not suitable for fast and real-time changing airspace environment. In this section, the normalized prediction information increment $\Delta I$ and the linear weighted sum of the norm of the target filtering error covariance matrix $||P||$ were used to define the pairing function.

$$p_{ij}(s_1, s_2, ..., s_s; a_1, a_2, ..., a_s) = \alpha \Delta I + \beta ||P||$$ (7)

Where $\alpha$ and $\beta$ are weight factors, and $\alpha + \beta = 1$. Here, according to the importance degree, $\alpha$ and $\beta$ can be taken as 0.7 and 0.3 respectively. $||P||$ represents the norm of the matrix $P$. The predicted information increment $\Delta I$ represents the difference of the information entropy before and after the sensor measurement. The larger the difference, the more information is obtained[14]; the smaller the norm value of the target filter error covariance matrix, the more accurate the trajectory of the measured target will be, and the demand on the sensor will decrease accordingly, so the value of the pairing function becomes smaller.

At time $k$, the calculation formula for the pairing function of sensor combination $s_i$ and target $o_j$ is[15]

$$p_{ij}(k) = \alpha \Delta I + \beta ||P|| = \frac{\alpha}{2} \log(\frac{||P_{ij}||}{||P_{<ij}||}) + b ||P_i||$$ (8)
5. Simulation analysis

Suppose that during airspace combat, the number of radars (RD) on our platform is 3, labeled RD1, RD2, and RD3 respectively. The radar can accurately detect the movement situation of the target in motion, and obtain the precise position, speed, and azimuth of the target information. Currently, 4 enemy aircraft have flown into the surveillance area of these 3 radars. The efficiency-based multi-sensor resource allocation algorithm assigns these four enemy aircraft to three radar sensors reasonably to obtain the most reasonable multi-sensor resource allocation solution.

According to the steps given in Section 2, the threat coefficients of the five influencing factors, including the distance between the target and our platform, the target's own moving speed, the target's azimuth, type and mobility, were calculated

\[ \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5 \]

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Suppose that at a certain time, the information values of each factor of the four targets detected by the sensors on our platform are shown in Table 1.

| enemy airplane 1 | enemy airplane 2 | enemy airplane 3 | enemy airplane 4 |
|------------------|------------------|------------------|------------------|
| distance (km)    | 80               | 93               | 96               | 180               |
| velocity (m/s)   | 5                | 12               | 21               | 26                |
| azimuth (°)      | 30               | -45              | 65               | 105               |
| target type      | fighter plane    | attack plane     | helicopter       | early warning aircraft |
| maneuverability  | strong           | average          | poor             | poor              |

According to the attribute value of each factor in the above table, the threat index of each target can be obtained

\[ (t_1, t_2, t_3, t_4) = (0.997, 0.738, 0.573, 0.1) \]

In order to simplify the model, it is stipulated that three radar sensors can observe the status information of the target in different directions. RD1 can only observe the coordinates in the x direction, RD2 can only observe the coordinates in the y direction, and RD3 can observe the coordinates in both directions. The capability matrix is shown in Table 2.

| direction and ability of observation | x direction | observed noise variance | y direction | observed noise variance | maximum number of observations |
|-------------------------------------|-------------|-------------------------|-------------|-------------------------|-------------------------------|
| RD1                                 |             | 0.12                    |             |                         | 1                             |
| RD2                                 |             |                         | 0.46        |                         | 2                             |
| RD3                                 | 0.23        |                         | 0.36        |                         | 3                             |

The current state covariance matrix for the four targets is as follows

\[ P_1 = \begin{bmatrix} 0.25 & 0.50 \\ 0 & 0.30 \end{bmatrix}, P_2 = \begin{bmatrix} 0.35 & 0 \\ 0 & 0.30 \end{bmatrix}, P_3 = \begin{bmatrix} 0.45 & 0 \\ 0 & 0.45 \end{bmatrix} \]

The covariance matrix of the external jamming noise (maneuvering noise) of the target is
respectively

\[
Q_1 = \begin{bmatrix}
0.35 & 0 \\
0 & 0.45
\end{bmatrix},
Q_2 = \begin{bmatrix}
0.12 & 0 \\
0 & 0.10
\end{bmatrix},
Q_3 = \begin{bmatrix}
0.20 & 0 \\
0 & 0.15
\end{bmatrix},
P = \begin{bmatrix}
0.70 & 0 \\
0 & 0.85
\end{bmatrix}
\] (12)

Take the 2-norm of the matrix and get the sensor-target pairing function matrix through formula (8), as shown in Table 3.

| Sensor | \(T_1\) | \(T_2\) | \(T_3\) | \(T_4\) |
|--------|--------|--------|--------|--------|
| \(S_1\) | 1.9446 | 1.7428 | 2.0135 | 2.5402 |
| \(S_2\) | 1.1352 | 0.6364 | 0.6360 | 1.2741 |
| \(S_3\) | 2.4751 | 1.7754 | 2.0010 | 3.1358 |
| \(S_4\) | 3.0802 | 2.3767 | 2.6504 | 3.8165 |
| \(S_5\) | 3.4935 | 2.7732 | 3.0312 | 4.2537 |
| \(S_6\) | 2.9482 | 2.1367 | 2.3594 | 3.6272 |
| \(S_7\) | 3.9655 | 3.1040 | 3.3918 | 4.7473 |

Where \(S_1, S_2\) and \(S_3\) respectively represent the basic sensor \(RD_1, RD_2\) and \(RD_3\); \(S_4\) represents the combination of sensor \(RD_1\) and \(RD_2\); \(S_5\) represents the combination of sensor \(RD_2\) and \(RD_3\); \(S_6\) represents the combination of \(RD_1\) and \(RD_3\); and \(S_7\) represents the combination of three sensors \(RD_1, RD_2\) and \(RD_3\).

The target threat index has been calculated as \((t_1, t_2, t_3, t_4)=(0.997, 0.738, 0.573, 0.1)\). According to formula (1), \(S_i\) of the sensor (and its sensor combination) and the monitoring efficiency function value of the target \(T_j\) can be calculated. At the same time, the optimal allocation results can be obtained by integer programming.

| Sensor | \(T_1\) | \(T_2\) | \(T_3\) | \(T_4\) |
|--------|--------|--------|--------|--------|
| \(S_1\) | 0 | 0 | 0 | 0 |
| \(S_2\) | 0 | 0 | 0 | 0 |
| \(S_3\) | 0 | 1 | 1 | 0 |
| \(S_4\) | 0 | 0 | 0 | 1 |
| \(S_5\) | 1 | 0 | 0 | 0 |
| \(S_6\) | 0 | 0 | 0 | 0 |
| \(S_7\) | 0 | 0 | 0 | 0 |

According to the distribution results, \(RD_1\) only distributes one target, which is enemy aircraft 4. \(RD_2\) assigns two targets, enemy 1 and 4; \(RD_3\) allocates three targets, namely enemy aircraft 1, 2, and 3. It can be seen that the result conforms to the constraint of observation ability of each sensor, and enemy aircraft with large covariance, such as \(T_1\) and \(T_4\), allocate sensor combination, namely pseudo sensor. In this way, more information increment can be obtained by information fusion through data observed by multiple sensors. For targets \(T_2\) and \(T_3\) with small covariance, only one sensor is needed to obtain information, thus saving sensor resources.

6. Conclusion
In this paper, the AHP three-level hierarchical model of target threat assessment is established, and the target threat assessment algorithm based on AHP is proposed. At the same time, the sensor target pairing function calculation method based on the normalized information increment and the norm of the target filtering error covariance matrix is proposed, and the effectiveness function is expressed by
the combination of the two. Through the establishment of multi-sensor multi-objective resource scheduling model based on efficiency function and the simulation experiment, the results show that the model realizes the effective allocation of sensor resources.

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