Study on the BVR Cooperative Air Combat Based on BP Neural Network

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Abstract. Aimed at multi-target assignment in the multi-fighter's cooperative combat, the paper compares and evaluates several typical 3-g fighters' air combat performance in the BVR combat using on the constructed BP neural network; based on which the assignment model of cooperative priority and how to calculate the cooperative priority. The simulation proves the validity of the model.

Keywords: Air Combat, BP Neural Network, Cooperative Target Assignment

1. Introduction

With the development of Aviation Science and technology and the demand of military combat, cooperative multi-target attack is the main form and development trend of air combat in the future [1]. Cooperative air combat refers to the mode of air combat in which two or more fighters cooperate and cooperate with each other to carry out combat tasks. It is one of the main development directions of multi-aircraft air combat in modern high-tech air combat [2]. It is a brand-new air combat style which appears with the development of fighter, airborne weapon and air combat C3I system, it is the concrete reflection of modern land, sea, air, sky and electricity integrated operation mode in multi-aircraft air combat. Cooperative Air Combat Analysis is an effective method to evaluate the operational effectiveness of both sides of air combat dynamically [3]. It develops from Matrix game, differential game and optimization method to intelligent method. In the research of Cooperative Air Combat, the theory and method of intelligent control, such as expert system and artificial neural network, are highly valued for their ability to control complex objects [4]. The problem of how to make multiple planners produce cooperative planning in the changing situation of multi-aircraft air combat is studied. In this paper, some important concepts such as Event, Goal and Plan are presented. The original shape-based Plan manager can accomplish Conflict Resolution, Goal management and Scheduling [5]. AN ACM Intelligent Tutoring System (ITS) is established, and the experience is that many aspects of air combat are better modeled using Qualitative Physics. The decision-making process of air combat needs the coordination of neural network (NN) and rule-based system, ES (expert system) should do Reasoning and Planning, NN should do Recognition and Adaptation, a hybrid architecture of NN/rule-based air combat planning is proposed [6]. The application of artificial neural network (Ann) in ACM field is studied. The established NN model integrates the knowledge of air-to-air combat maneuver, maneuver composition, maneuver planning and Situation Assessment,
and carries out the training and validity test of NN model [7]. A computer Logic (CLWS) for Air-to-air Warfare Simulation is designed by using artificial intelligence technology. clws is a knowledge-based Tactical Decision Generator (TDG), lisp is a blackboard based system written in Lisp that is tested against a traditional TDG that is designed differently. This work directly introduces human knowledge into air combat decision-making, and points out a new way for the realization of intelligent fire control. However, the existing literature for multi-aircraft cooperative multi-target attack research is less, the overall allocation of the target algorithm remains to be studied. The most significant difference between multi-aircraft air combat and one-to-one air combat is the target allocation for each friendly aircraft according to our resources, that is, cooperative target allocation. In the past, the method of Air Combat Situation Assessment was used to assign cooperative targets. In this paper, the performance of several typical 3rd generation fighters in beyond visual range air combat is evaluated by using the constructed BP neural network model, and a collaborative priority assignment model is established.

2. Evaluation of Aircraft Static Air Combat Capability Index based on BP Artificial Neural Network

2.1 Construction of BP Network Model

The Static Air Combat Capability Index of aircraft is a comprehensive evaluation problem of multi-performance indexes, which can be described by four-tuple \((C, X, P, Y)\). In order to reflect the index system of the performance of weapon equipment, \(C\) is the attribute value of the equipment under the index system, \(X\) analyze the preference structure of the performance index system, \(P\) is the concept of weight can be used to describe \(Y\) is compare the performance of the equipment.

![Figure 1. Neural Network Structure Diagram of weapon system effectiveness comparison](image)

A neural network for comparison of equipment performance is shown in figure 1. Among them, \(X_1, X_2, ..., X_n\) is the attribute value of the equipment under the performance index system, \(O_{11}, O_{21}, ..., O_{m1}\) is the node of the input layer, \(O_{12}, O_{22}, ..., O_{m2}\) is the node of the middle layer and the node of the output layer, which correspond to the judgment result of the equipment under comparison. For the comparison of the performance of weapons and equipment, the training samples are taken as the comparison benchmark, and through the self-learning of these training samples, by adjusting the weights and feedback parameters of the intermediate nodes in the network, the output of the network is consistent with the results of the actual test samples.

2.2 Evaluation of beyond Visual Range Air Combat Capability Index

The main factors considered in over-the-horizon air combat are range capability, maneuverability index, radar detection range, radar detection probability, number of simultaneous tracking targets, number of simultaneous attacking targets, air-to-air missile range, kill probability, Mount Number, self-guided attack, aircraft maneuverability, ECM capability, RCS (radar reflection area).
Table 1. Main performance indicators affecting over-the-horizon attacks

| Indicators                        | Model | F-15  | F-16  | F/A-18 | F22  |
|----------------------------------|-------|-------|-------|--------|------|
| Range Capability                 |       | 1.09  | 1.05  | 1.27   | 1.04 |
| Maneuverability Index            |       | 3.26  | 3.28  | 3.25   | 3.24 |
| Radar Detection Range (km)       |       | 185   | 296   | 256    | 130  |
| Probability of discovery         |       | 0.85  | 0.85  | 0.85   | 0.90 |
| Tracking the target at the same time |   | 1     | 10    | 10     | 1    |
| Attack the target at the same time |     | 1     | 1     | 1      | 1    |
| Missile Range (km)              | AIM-120| 60    | 60    | 60     | 45   |
| Kill probability                 |       | 0.75  | 0.75  | 0.75   | 0.75 |
| Mount Quantity                   |       | 4     | 2     | 2      | 2    |
| Aircraft Dependence              |       | 0     | 0     | 0      | 0    |
| Aircraft handling performance    |       | 0.90  | 0.90  | 0.90   | 0.95 |
| ECM capability                   |       | 1.10  | 1.10  | 1.10   | 1.10 |
| RCS(m2)                          |       | 9.85  | 4.93  | 5.63   | 5.84 |
| Missile Range (km)              | AIM-9L | 14    | 14    | 14     | 12   |
| Kill probability                 |       | 0.78  | 0.78  | 0.78   | 0.75 |
| Mount Quantity                   |       | 4     | 2     | 2      | 2    |
| Aircraft Dependence              |       | 0     | 0     | 0      | 1    |
| Aircraft handling performance    |       | 0.90  | 0.90  | 0.90   | 0.95 |

The performance indicators shown in Table 1, the air combat range capability, maneuverability index, radar detection range, radar detection probability, number of targets tracked at the same time, number of targets attacked at the same time, air-to-air missile range, kill probability, number of payload, self-guided attack, aircraft maneuverability and electronic countermeasures capability are considered as the bigger the better; The RCS (radar reflection area) index is considered to be the smaller the better.

SELF-DIRECTED AGGRESSION: launch regardless, have a certain degree of dependence, dependence was quantified as 1,0.5,0.

In beyond visual range air combat, the range capability, maneuverability index and maneuverability of aircraft have less influence on the result of air combat than other indexes, so the weight of them should be adjusted properly in the training process of artificial neural network. The specific modified value is subject to the error reaching the allowable range. The performance index of each aircraft in Table 1 is normalized, and the index Matrix is as follows:

\[
X_i = \begin{bmatrix}
0.8583 & 0.9820 & 0.6250 & 0.9444 & 0.1000 & 0.2500 & 0.5455 & 0.9375 & 0.6667 & 1.0000 & 0.9474 & 1.0000 & 0.8188 \\
0.8268 & 0.9880 & 1.0000 & 0.9444 & 1.0000 & 0.2500 & 0.5455 & 0.9375 & 0.3333 & 1.0000 & 0.9474 & 1.0000 & 0.4098 \\
1.0000 & 0.9790 & 0.8649 & 0.9444 & 1.0000 & 0.2500 & 0.5455 & 0.9375 & 0.3333 & 1.0000 & 0.9474 & 1.0000 & 0.4680 \\
0.8189 & 0.9760 & 0.4392 & 1.0000 & 0.1000 & 0.2500 & 0.4091 & 0.9375 & 0.3333 & 1.0000 & 0.9474 & 1.0000 & 0.4855 
\end{bmatrix}
\]

According to this index Matrix, the training samples of the over-the-horizon air combat effectiveness comparison are set up as follows:

\[
X_g = (1,1,1,1) \\
X_{g^-} = (0.9626, 0.9891, 0.9004, 0.9931) \\
X_{m^+} = (0.9252, 0.9782, 0.8007, 0.9681) \\
X_{m} = (0.8878, 0.9673, 0.7011, 0.9792) \\
X_{m^-} = (0.8130, 0.9453, 0.5018, 0.9653)
\]
$X_{bm} = (0.7756, 0.9346, 0.4021, 0.9583)$
$X_{b-} = (0.7382, 0.9237, 0.3024, 0.9514)$
$X_{b} = (0.7008, 0.9127, 0.2027, 0.9444)$

The corresponding assessment scores of the training and test samples were:

$Y = (1, 0.2, 0.4, 0.8)$

Using BP Algorithm, $X_g, X_{g-}, X_m, X_{m-}, X_{bm}, X_{b-}, X_b$ is taken as 8 training samples and test samples, the input layer node is 13, the middle layer is 40 neurons, the output layer node is 1, the network is trained 15000 times, the minimum error is 0.000000005. Taking the normalized performance vectors as the inputs of the neural network, the over-the-horizon air combat effectiveness of each fighter is as follows:

Table 2. Third-generation Jet Fighter Bvr Air Combat Capability Indices

|       | F-15 | F-16 | F/A-18 | F22 |
|-------|------|------|--------|-----|
| Value | 0.8983 | 0.9127 | 0.8864 | 0.8251 |

This model mainly starts from the specific performance indexes that affect the capability index of Beyond Visual Range (Bvr) air combat, and through constructing BP neural network model, comprehensively weighs the influence degree of each performance index on air combat, the total index of the over-the-horizon attack capability of each aircraft type is obtained.

3. Target Assignment and Attack Sequencing of Multi-Aircraft Cooperative Multi-Target Attack

The target assignment principle of multi-target cooperative attack is not only to improve the kill probability, but also to avoid repeated attack and omission. The target priority is divided into autonomous priority and cooperative priority, and the attack priority is calculated based on the target priority [8].

3.1 Computation of Autonomous Priority

The autonomous priority is calculated according to the priority group rule based on the information obtained by the sensor carried by the fighter under the condition of no friendly aircraft information support. It is a prerequisite for the computation of collaborative priority. Factors to be considered in autonomous priority: target identification, combat mission of fighter aircraft, pre-empted weapons, vulnerability of enemy aircraft, results of lethality assessment, relative geometric conditions, pilot control, etc. There are a lot of literatures about the calculation method of autonomous priority, which are not repeated in this paper.

3.2 Computation of Collaborative Priority

The cooperative priority is to describe the pairing requirements of each cooperative fighter to the target. (1) according to the relative geometric conditions, four red aircraft attack 12 blue aircraft in coordination, each blue aircraft ($B_i$, where $i = 1, 2, ..., 12$) can correctly identify friend or foe, and its relative red aircraft ($R_j$, where $j = 1, 2, 3, 4$) situation is given by the Matrix $a = [\varphi_y, v_i, D_y, q_y, v_y]$. $D_y$ is the target line, that is, the connection from the blue machine ($B_i$) to the red machine ($R_j$); $\varphi_y$ is the Position Angle, that is, $D_y$ is the angle of deviation from the Velocity Direction; for the Target Entry Angle, that is, the angle of deviation from the velocity direction of the target line extension. Red $i$ to blue $j$ situation assessment value is:

$$p_{ij} = p_{jia}p_{i\theta}$$  \hspace{1cm} (1)

$$p_{jia} = (p_{i\theta} + p_{j\theta})/2$$  \hspace{1cm} (2)
\[ p_{ij\theta} = 1 - 2|\Phi_{ij}|/\pi \]  

(3)

\[ p_{ijq} = 1 - 2|q_{ij}|/\pi \]  

(4)

\[ p_{ijD} = \begin{cases} 
1 & D_j \leq D_{\text{max}} \\
1.8 - 0.00001D_j & D_j > D_{\text{max}} 
\end{cases} \]  

(5)

\[ p_{ijr} = p_{ijD} p_{ij\Delta D} \]  

(6)

\[ D_{ij} = v_{2j} \cos q_{ij} - v_{1i} \cos \phi_{ij} \]  

(7)

\[ p_{ij\Delta D} = \begin{cases} 
1 & D_j \leq 55 \\
1 - 0.0091(D_j + 55) & -55 \leq D_j \leq 0 \\
0.95 - 0.00176D_j & 0 \leq D_j \leq 85 \\
0.8 & D_j > 85 
\end{cases} \]  

(8)

In formula (1) to formula (8), \( p_{ij\alpha} \), \( p_{ij\theta} \) and \( p_{ijq} \) are the corresponding angular situation assessment factors, \( p_{ijD} \) and \( p_{ij\Delta D} \) are the distance and distance change assessment factors, \( p_{ijr} \) is the total situation assessment value, and its range is \([-1,1]\]. Consider the position angle of red machine \( i \): When \(|\Phi_{ij}| = 0\), Blue Machine \( j \) in red machine \( i \) is in front, the position of red machine \( i \) most favorable, so \( p_{ij\phi} = 1 \). When \(|\Phi_{ij}| = \pi\), red \( i \) in front of Blue \( j \), the position of red \( I \) most adverse, so \( p_{ij\phi} = -1 \). Blue Machine Entry Angle \( q_{ij} \) can be considered similarly. In equation (5), \( D_{\text{max}} \) is the maximum effective range of the air-to-air missile carried by the red aircraft. When \( D_j \leq D_{\text{max}} \), the missile can be launched; when \( p_{ijD} = 1 \), \( D_j > D_{\text{max}} \), \( p_{ijD} \) gradually decreases; when \( D_j \) reaches the maximum operational range, \( p_{ijD} = 0 \). Formula (7) calculates the difference in the projection of the speed of the two machines in the direction of the marking line. A negative value indicates that the blue machine is close to the red machine, while a positive value is the opposite\[9\].

By calculating the Air Combat Situation Index of each red aircraft relative to the blue aircraft, the air combat situation matrix \( P = \{p_{ijr}\} \) can be generated, where \( p_{ijr} \) is the air combat situation index of the first red aircraft relative to the \( J \) blue aircraft.

(2) to determine the threat index of air combat Angle Threat Index \( T_{\alpha} \):  
\[ T_{\alpha} = \{\Phi_{ij}\} + \{q_{ij}\}\times 360^\circ\]  

(9)

Range Threat Index \( T_{\alpha} \):

\[ T_{\alpha} = \begin{cases} 
0.5 \times \frac{r - r_{\text{min}}}{r_{\text{max}} - r_{\text{min}}} & r_{\text{min}} \leq r < r_{\text{min}} \\
0.5 \times \frac{r - r_{\text{max}}}{r_{\text{max}} - r_{\text{min}}} & r_{\text{max}} < r \leq r_{\text{max}} \\
1.0 & \text{max}(r_{\text{min}}, r_{\text{max}}) < r < r_{\text{max}} \\
0.8 & \text{max}(r_{\text{max}}, r_{\text{max}}) \leq r_{\text{max}} \leq r_{\text{max}} 
\end{cases} \]  

(10)

Speed Threat Index \( T_{\alpha} \):

\[ T_{\alpha} = \begin{cases} 
0.1 & v_{\alpha} < 0.6v_{\alpha} \\
-0.5 + v_{\alpha} / v_{\alpha} & 0.6v_{\alpha} \leq v_{\alpha} \leq 1.5v_{\alpha} \\
1.0 & v_{\alpha} > 1.5v_{\alpha} 
\end{cases} \]  

(11)
\( v_R \) is the velocity vector of our aircraft, \( v_i \) is the velocity vector of the target aircraft, \( \Phi_i \) is the forward angle of the target aircraft, \( q_B \) is the angle between the target aircraft heading and the target line (the right deviation is positive). \( r_i \) is the target distance. In the formula, \( rm \) is the maximum range of the missile of our aircraft, \( rmt_i \) is the attack range of the missile carried by the enemy aircraft, \( rr \) is the maximum tracking range of our aircraft radar. Therefore, the angle threat factor and the distance threat factor should be treated as a multiplicative relation. Then the total air combat threat index is:

\[
T = a_1 \cdot T_r \cdot T_a + a_2 \cdot T_v
\]

Among them, \( a_1, a_2 \) is the weight Coefficient \((0 \leq a_1, a_2 \leq 1)\), if the two parts before and after the same treatment, cannot consider the weight value \((a_1 = a_2 = 1)\).

(3) Air-to-air Capability Index

An operational aircraft or on-board weapon system is a long process from development to commissioning and the modification and upgrading of existing aircraft and on-board weapon systems during a given period of time in a campaign, the level of weapons and equipment of both sides can be regarded as "static", and it is feasible to use the static air combat capability index to evaluate their air combat capability.

(4) Threat assessment

Carried out to calculate the threat index of each blue aircraft relative to the red aircraft, and the total threat index was obtained by integrating the air combat capability of enemy aircraft and the impact of the air combat threat:

\[
W_i = b_1 \cdot C_i + b_2 \cdot T_i (i = 1, 2, ..., n)
\]

Among them, \( W_i \) is the first enemy aircraft to our aircraft threat index, \( b_1, b_2 \) is the weighting factor \((0 \leq b_1, b_2 \leq 1)\). Comprehensive Threat Index, all the blue machine to all the red machine threat ranking vector \( t \) (threat index from small to large).

(5) determine the blue machine corresponding to the first element in the vector \( t \) (Minimum Threat Index)(set as blue machine \( j \));

(6) find the largest element in the \( J \) column of the Matrix \( P \), set as \( p_{ij} \);

(7) assign Blue Machine \( J \) to red machine \( I \) attack (good attack or bad attack);

(8) delete column \( J \) in \( P \) and the element corresponding to the blue aircraft \( J \) in Vector \( t \);

(9) If the number of blue aircraft assigned to a red aircraft is equal to the number of multiple target attack capabilities of the aircraft or the number of missiles mounted, the red aircraft withdraws from target assignment, delete Line \( I \) in Matrix \( P \);

(10) Repeat steps 5-9 until all elements of Matrix \( P \) are deleted, that is, the target assignment process is completed.

Due to the antagonism, initiative, uncertainty and uncertainty of Cooperative Air Combat, so the traditional modeling methods, such as Matrix game, differential game and optimal direction vector, cannot meet the requirements of modern cooperative air combat. As a result, the application of AI technology in cooperative air combat, such as air combat expert system, artificial neural network Ann and Fuzzy Air Combat System, etc.. Here we use neural networks to make air combat decisions [10].

4. Simulation Example

The simulation takes 4:12 multi-aircraft air combat as the research object. In this paper, we consider our aircraft as four fighters of the same type with multi-target attack capability, which are recorded as red aircraft A, B, C and D respectively. The maximum radar tracking distance \( rr = 100km \), each carries
four medium range air-to-air missile of the same type, capable of hitting four air targets at the same
time, with a maximum range of 60 km; 12 enemy aircraft of both types, designated blue 1-12, are
within the range of our fire control radar. My machine speed is VR = 240m/s. Red Machine Training
and testing a good neural network for coordination, coordination is embodied in the specific target
distribution, blue machine fight on their own. The simulation results show that our situation
dominance matrix is:

\[
a = \begin{bmatrix}
0.56 & 0.30 & 0.16 & 0.53 & 0.28 & 0.39 & 0.10 & 0.90 & 0.75 & 0.09 & 0.59 & 0.37 \\
0.44 & 0.83 & 0.01 & 0.06 & 0.36 & 0.60 & 0.02 & 0.06 & 0.57 & 0.18 & 0.09 & 0.30 \\
0.19 & 0.54 & 0.57 & 0.01 & 0.48 & 0.86 & 0.12 & 0.13 & 0.42 & 0.25 & 0.89 & 0.39 \\
0.25 & 0.33 & 0.63 & 0.48 & 0.02 & 0.36 & 0.32 & 0.95 & 0.20 & 0.92 & 0.32 & 0.50
\end{bmatrix}
\]

Taking the computed situation Matrix \(a\) as the input of the neural network, the program is run to
obtain the cooperative target assignment scheme as shown in Table 3.

| Our | Target1 | Target2 | Target3 |
|-----|---------|---------|---------|
| 1   | 2       | 6       | 12      |
| 2   | 1       | 10      | 11      |
| 3   | 5       | 8       | 9       |
| 4   | 3       | 4       | 7       |

5. Conclusion
Cooperative tactical decision-making of multi-aircraft air combat is based on multi-sensor data fusion,
multi-aircraft communication, information resource sharing and target recognition technology, the key
to realize cooperative air combat is to complete the air combat situation assessment, threat assessment
and sequencing, target assignment and firepower assignment. In this paper, the threat index method is
introduced as the calculation method of cooperative priority and the teacher value of BP network
training, the simulation results show that the method is feasible and effective.

Reference
[1] Liwei L, Rongshuang F. Simulated annealing algorithm in solving frequency assignment
problem//Advanced Computer Theory and Engineering (ICACTE), 2010 3rd International
Conference on. IEEE, 2010, 1: V1-361-V1-364.
[2] Castelino D J, Hurley S, Stephens N M. A tabu search algorithm for frequency assignment.
Annals of Operations Research, 1996, 63(2): 301-319.
[3] Alabau M, Idoumghar L, Schott R. New hybrid genetic algorithms for the frequency assignment
problem. Broadcasting, IEEE Transactions on, 2002, 48(1): 27-34.
[4] Peter Panec. The Management of Planning in Tactical Air Combat. AIAA-91-3840-CP, New
York: AIAA,1991
[5] Robert J. Bechtel. Air Combat Maneuvering Expert System Trainer. AD A246 459, 1992, 1
[6] Roger W. Schvaneveldt, Alen E. Benson, Timothy E. Goldsmith. Neural Network Models of
Air Combat Maneuvering. AD A 254 653, 1992, 1
[7] John W. McManus, Kenneth H. Goodrich. Artificial Intelligence (AI) Based Tactical Guidance
for Fighter Aircraft. A-IAA-90-3435-CP,1990
[8] Harold E. Bullock. ACE: The Airborne Combat Expert System. AD A-170 416,1986,3
[9] Rodrick William Lekey. ACMS:A Prototype Expert Database for Air Combat Maneuvering.
AD-A225 774,1990,3
[10] LIU Wei dong, JIANG Qing shan, LI Yong.Fire distribution of the network centric
ship-to-air missile based on earlier damage[J],Ship Science And Technology, 2011,33
(2) :98-101