Hybrid Game Theory and D-S Evidence Approach to Multiple UCAVs Cooperative Air Combat Decision

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Abstract. Mission decision-making is one of the most important techniques for cooperative combat of multiple unmanned combat aerial vehicles (UCAVs), while game theory is an efficient method in solving mission decision-making. In this paper, the game theory is applied to the air combat decision of multiple UCAVs. Then a weapon model for UCAVs' air-to-air missiles is proposed to obtain the basic probability value of the D-S evidence theory. In order to obtain the Nash equilibrium point, the bimatrix problem is transferred into an optimization problem. In this way, the function "linprog" in MATLAB can be used to obtain the optimal solution, which can greatly simplify the steps of solving the bimatrix problem. Finally, the optimal strategy is obtained by optimizing calculation. Series of experimental results demonstrate the feasibility and effectiveness of the proposed approach in solving the multiple UCAVs cooperative air combat decision problem.

Keywords: UCAVs, Game Theory, Mission Decision-making, D-S Evidence Theory.

1 Introduction

Following with the development of unmanned combat aerial vehicles' (UCAV) technology, cooperative unmanned aerial vehicles control will receive a great attention in the future. For many military missions, it is unthinkable to be taken on a single UCAV. And more instances show that it is more complicated and expensive to exploit a single UCAV than to create a multiple UCAVs' system. Wang, H.L. analyzed a maneuvering-decision method for air-to-air combat [1], Yang, Y.C. proposed quantitative air combat decision approach in [2], and Wang, Y.N presented an intelligent differential game on air combat decision [3]. Yao, Z.X. also presented the game theory model to solve this problem, and tests prove that it can conduct the mission decision-making effectively [4], But these approaches to establish the basic probability value and solve the bimatrix are very complicated.

To overcome the above-mentioned shortcomings, we present a weapon model of UCAVs' air-to-air missiles to obtain the basic probability value. In order to solve the bimatrix, we transfer it into an optimization problem first, and then the function "linprog" in MATLAB is used to solve the optimization problem. Furthermore, we apply the method on the issue of multiple UCAVs air combat, and design corresponding

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strategy sets. Finally, series of experimental results are given to demonstrate the feasibility and effectiveness of the proposed approach in solving the multiple UCAVs cooperative air combat decision problems.

2 Introduction to Related Theories

2.1 D-S Evidence Theory

D-S evidence theory is proposed by Dempster in 1976, then his student Shafer develops and organizes it into a comprehensive mathematical theory. Through synthesizing several evidences, D-S evidence theory can improve the dependable degree of the proposition, now the theory has specifically applied on some areas, such as multiple sensors network, medical diagnosis and so on. In D-S evidence theory, the combinatorial formula is very important [5]. If θ is the discriminating frame, 2^{θ} is the aggregate composed by all its subsets, m_1, m_2 are the basic probability values of the independent authentic function of 2^{θ}, A_i and B_j are the focus respectively, then the D-S combinatorial formula is:

$$m(c)=\begin{cases}0 & ,C=\phi \\ \dfrac{\sum\limits_{A_i\cap B_j=C} m_a(A_i)m_b(B_j)}{1-K_1} & ,\forall C\subset\theta, C\neq\phi\end{cases} \quad (1)$$

Where Φ is the empty aggregate, $C = A_i \cap B_j \neq \Phi$ is the focus to be fused.

$$K_1=\sum_{A_i\cap B_j=\Phi} m_1(A_i)\, m_2(B_j)<1 \quad (2)$$

2.2 Game Theory

Game theory, defined mathematically by Nash J.F [11], has found its first applications in economics, especially to solve the problems concerning the decisions that have some effects on different and often competitive fields.

In a model of game theory, three elements must exist. They are players, strategy set, and criterion. Each player has its own strategy set and its own criterion. When a game begins, each player searches its own best strategy in its search space to improve its own criterion with all the rest criteria fixed by others players. So there exists the exchange of strategies among the players. The frequency of exchangeδ is called the Nash frequency, generallyδ=1, which means the exchange of best strategies happens at the end of each generation. When no player can further improve its criterion, it means that the system has reached a state of equilibrium called Nash equilibrium[6].

We take a two-player game to present the process of Nash equilibrium.

Let A be the search space for the first player, B the search space for the second player, a strategy pair $(x^*, y^*) \in A\cdot B$ is said to be a Nash equilibrium iff:

$$\begin{aligned} f_A(x^*,y^*) &= \inf_{x\in A} f_A(x,y^*) \\ f_B(x^*,y^*) &= \inf_{x\in B} f_B(x,y^*) \end{aligned} \quad (3)$$

Where f_A is the gain for the first player, f_B is the gain for the second player.

3 Mission Decision-Making Method

3.1 A Mission Scenario

The red UCAV formation attacks the blue ground target, its main task is to attack the blue airport (G_1). The formation includes an unmanned fighter-bomber (R_1) and m-1 UCAVs ($R_2, R_3, \ldots, R_m$). The unmanned fighter-bomber's mission is to bomb the blue airport and the other UCAVs are to help it complete the bombing mission. m-1 UCAVs are exactly the same, i.e. they have the same flight performance and weapon performance. Each UCAV carries several air-to-air missiles and they are their main tools for fighting. Air-to-air missile's shooting average is determined by q situation factors (such as distance, angle and speed and so on) in a battlefield situation. The unmanned fighter-bomber's maneuverability is lower. Except for air-to-air missiles it carries air-to-surface missiles to bomb the blue airport yet. (In the following paper , we don't distinguish the unmanned fighter-bomber and the m-1 UCAVs and all are named as UCAVs).

The blue k UCAVs ($B_1, B_2, \ldots, B_k$) composed an attack formation. Their mission is to prevent the fighter-bomber from bombing the airport and annihilate them. The UCAVs in the formation are also exactly the same, i.e. each UCAV carries air-to-air missiles and they are their main tools for fighting. Air-to-air missile's shooting average is determined by q situation factors (such as distance, angle and speed and so on) in a battlefield situation.

The blue strategy set $S_1 = (\alpha_1, \alpha_2, \cdots, \alpha_w)$ includes w strategies. The aggregate composed by the blue k UCAVs is defined as WU. The aggregate composed by all subsets of the WU is 2^{WU}, so in the blue strategy set, the strategy α_i:

$$\alpha_i = ((T_{i1}, R_1), (T_{i2}, R_2), \cdots\cdots, (T_{il}, R_l))$$

$$T_{ib} = 2^{WU},\ b = 1,2,\cdots k; \bigcup_{k=1}^{l} T_{ik} = WU; T_{ig} \cap T_{ih} = \phi, \forall g,h, g = 1,2,\cdots l, h = 1,2,\cdots l, g \neq h.$$

denotes the blue puts the UCAVs in aggregate T_{i1} attack the target R_1 cooperatively, puts the UCAVs in aggregate T_{i2} attack the target R_2 cooperatively and so on.

The red strategy set $S_2 = (\beta_1, \beta_2, \cdots\cdots, \beta_d)$ includes d strategies. The aggregate composed by the red m UCAVs is defined as DU. The aggregate composed by all subsets of the DU is 2^{DU}, so in the red strategy set, the strategy β_i:

$$\beta_i = ((T_{i1}, B_1), (T_{i2}, B_2), \cdots\cdots, (T_{ik}, B_k))$$

$$T_{ib} = 2^{DU},\ b = 1,2,\cdots k; \bigcup_{p=1}^{k} T_{ip} = DU; T_{ig} \cap T_{ih} = \phi, \forall g,h, g = 1,2,\cdots k, h = 1,2,\cdots k, g \neq h.$$

denotes the red puts the UCAVs in aggregate T_{i1} attack the target B_1 cooperatively, puts the UCAVs in aggregate T_{i2} attack the target B_2 cooperatively and so on.

Therefore the model of game theory in this paper is: $G = \langle N, S_1, S_2, u_1, u_2 \rangle$, $N = \{1, 2\}$, 1 denotes the blue formation (including k UCAVs), 2 denotes the red formation (including an unmanned fighter-bomber and m-1 UCAVs). S_1 is the blue strategy set, S_2 is the red strategy set. u_1 is the blue payoff function, u_2 is the red payoff function.

3.2 Evidence Syntheses

D-S evidence theory uses the synthesis of multiple evidence to make decision. It has a great deal of flexibility in dealing with the unknown and uncertainty. In this paper, the high-level evidence is obtained through the synthesis of low-level evidence until the effectiveness (income) and the invalidity (price) of some attack (or defense) strategy are obtained.

The D-S basal combinatorial formula of the mission decision-making method is below:

$$m1^{\alpha_i}{}_{nt} = m1^{\alpha_i}{}_{1nt} \oplus m1^{\alpha_i}{}_{2nt} \oplus \cdots \oplus m1^{\alpha_i}{}_{qnt} \tag{4}$$
$$Where\ ,\ q = 1,2,\cdots,q; n = 1,2,\cdots,n; t = 1,2,\cdots,t;$$

denotes the basic probability value when the n-th UCAV in blue formation attacks the t-th UCAV in red formation considering q momentum factors (in this paper q=3, i.e. the distance between two UCAVs, the speed of the UCAVs and the angles between the UCAVs).

The basic probability value when the blue p UCAVs attack the red t-th UCAV cooperatively can be expressed as follows:

$$m1^{\alpha_i}{}_{t} = m1^{\alpha_i}{}_{1t} \oplus m1^{\alpha_i}{}_{2t} \oplus \cdots \oplus m1^{\alpha_i}{}_{pt} \tag{5}$$
$$Where\ ,\ p = 1\ 2,\cdots,p; \quad t = 1,2,\cdots,t;$$

The basic probability value when the blue selects the strategy α_i can be expressed as follows:

$$m1^{\alpha_i} = m1^{\alpha_i}{}_{1} \oplus m1^{\alpha_i}{}_{2} \oplus \cdots \oplus m1^{\alpha_i}{}_{h} \tag{6}$$

The basic probability value when the blue p-th UCAV attacks the red t_1-th, t_2-th… t_q-th UCAV at the same time can be expressed as follows:

$$m1^{\alpha i}{}_{p:(t_1,t_2\cdots t_q)} = (m1^{\alpha i}{}_{pt_1} + m1^{\alpha i}{}_{pt_2} + \cdots + m1^{\alpha i}{}_{pt_q}) / q \tag{7}$$

By the same token, we can synthesis the red every evidence $m2^{\beta i}{}_{nt}$, $m2^{\beta i}{}_{t}$, $m2^{\beta i}$, $m2^{\beta i}{}_{p:(t_1,t_2\cdots t_q)}$. The formula below:

$$u_1(\alpha_i, \beta_j) = \frac{m1^{\alpha_i}(a) \bullet m2^{\beta_j}(b)}{m1^{\alpha_i}(b) \bullet m2^{\beta_j}(a)} \tag{8}$$

is defined as the blue payoff function when the blue selects the strategy α_i and the red selects the strategy β_j.

$$u_2(\alpha_i, \beta_j) = \frac{m1^{\alpha_i}(b) \bullet m2^{\beta_j}(a)}{m1^{\alpha_i}(a) \bullet m2^{\beta_j}(b)} \tag{9}$$

is defined as the red payoff function when the blue selects the strategy α_i and the red selects the strategy β_j .

All of the above evidence has both the effectiveness and invalidity. The letters "a", "b" are used to characterize the both separately: $m1^{\alpha_i}(a)$ and $m1^{\alpha_i}(b)$ are defined as the effectiveness and the invalidity of attack when the blue selects the strategy α_i. $m2^{\beta_j}(a)$ and $m2^{\beta_j}(b)$ are defined as the effectiveness and the invalidity of attack when the red selects the strategy β_j . Therefore, the blue payoff matrix $A=(a_{ij})_{k\times l}$ and the red payoff matrix $B=(b_{ij})_{k\times l}$ can be obtained.

3.3 The Acquisition of the Basic Probability Value

In order to get the $m1^{\alpha i}{}_{1nt}$, $m1^{\alpha i}{}_{2nt}$,…, $m1^{\alpha i}{}_{qnt}$, A database is established, the database can be obtained from a large number of air-to-air missile tests. Considering calculating easily, the database is put into an abstract linear.

Table 1. Distance definition in weapon model of UCAVs' air-air missiles

DISTANCE(D) /km	<=1	2	3	4	5	6	7	8	>=9
Attack effectiveness $m^{\alpha_i(\beta_j)}{}_{1pt}(a)$	0.9500	0.8438	0.7375	0.6312	0.5250	0.4187	0.3125	0.2062	0.1000
Attack invalidity $m^{\alpha_i(\beta_j)}{}_{1pt}(b)$	0.0300	0.1162	0.2025	0.2888	0.3750	0.5012	0.6275	0.7538	0.8800
Attack uncertainty $m^{\alpha_i(\beta_j)}{}_{1pt}(\theta)$	0.0200	0.0400	0.0600	0.0800	0.1000	0.0800	0.0600	0.0400	0.0200

Table 2. Speed definition in weapon model of UCAVs' air-air missiles

SPEED(V) /m/s	<200	300	400	500	600	700	800	900	>=1000
Attack effectiveness $m^{\alpha_i(\beta_j)}{}_{2pt}(a)$	0.8900	0.7900	0.6900	0.5900	0.4900	0.3900	0.2900	0.1900	0.0900
Attack invalidity $m^{\alpha_i(\beta_j)}{}_{2pt}(b)$	0.0800	0.1575	0.2350	0.3125	0.3900	0.5125	0.6350	0.7575	0.8800
Attack uncertainty $m^{\alpha_i(\beta_j)}{}_{2pt}(\theta)$	0.0300	0.0525	0.0750	0.0975	0.1200	0.0975	0.0750	0.0525	0.0300

Table 3. Angle definition in weapon model of UCAVs' air-air missiles

ANGLE (S_{ij}) / °	180	160	140	120	100	80	60	40	20	0
Attack effectiveness $m^{\alpha_i(\beta_j)}{}_{3pt}(a)$	0.9900	0.9356	0.8811	0.8267	0.7722	0.7178	0.6633	0.6089	0.5544	0.5000
Attack invalidity $m^{\alpha_i(\beta_j)}{}_{3pt}(b)$	0.0100	0.0478	0.0856	0.1233	0.1611	0.1989	0.2367	0.2744	0.3122	0.3500
Attack uncertainty $m^{\alpha_i(\beta_j)}{}_{3pt}(\theta)$	0	0.0167	0.0333	0.0500	0.0667	0.0833	0.1000	0.1167	0.1333	0.1500

Table 3. *(Continued)*

ANGLE (S_{ij}) / °	-20	-40	-60	-80	-100	-120	-140	-160	-180	
Attack effectiveness $m^{\alpha_i(\beta_j)}{}_{3pt}(a)$	0.4456	0.3911	0.3367	0.2822	0.2278	0.1733	0.1189	0.0644	0.0100	
Attack invalidity $m^{\alpha_i(\beta_j)}{}_{3pt}(b)$	0.4211	0.4922	0.5633	0.6344	0.7056	0.7767	0.8478	0.9189	0.9900	
Attack uncertainty $m^{\alpha_i(\beta_j)}{}_{3pt}(\theta)$	0.1333	0.1167	0.1000	0.0833	0.0667	0.0500	0.0333	0.0167	0	

DISTANCE (D) is defined as the real length between the centers of two UCAVs. SPEED (V) is defined as the speed of the other side when one side calculates its basic probability value. ANGLE(S_{ij}) is defined as $S_{ij}=\alpha_j-\alpha_i$ which denotes the angle when one side calculates its basic probability value.

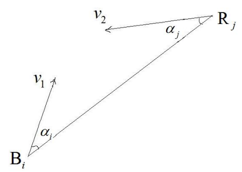

Fig. 1. The relation of angle between two UCAV ($S_{ij}=\alpha_j-\alpha_i$)

For example, when the blue i-th UCAV calculates its own basic probability value against the red j-th UCAV, the α_i in Fig.1 stands for the angle composed of the blue i-th UCAV's velocity vector and its line of sight towards the red. The α_j stands for the angle between the red j-th UCAV's velocity vector and line of sight towards the blue.

In addition, the basic probability value is defined when the uninhabited fighter-bomber bombs the airport as:

$$m2^{\beta_j}{}_{R_1G_1}(a)=0.7345\ ,\qquad m2^{\beta_j}{}_{R_1G_1}(b)=0.2277\ ,\qquad m2^{\beta_j}{}_{R_1G_1}(\theta)=0.0378$$

By searching the database, the basic probability values can be obtained. If the number is not the existing numbers, it can be sought through the linear relationship. For example, if the distance between two UCAVs is d km, its corresponding basic probability values are:

$$\begin{aligned} m^{\alpha_i(\beta_j)}{}_{1pt}(a) &= \frac{0.8438-0.2062}{8-2}\bullet(8-d)+0.2062 \\ m^{\alpha_i(\beta_j)}{}_{1pt}(b) &= 0.1-0.02\times\left|5-d\right| \\ m^{\alpha_i(\beta_j)}{}_{1pt}(\theta) &= 1-m^{\alpha_i(\beta_j)}{}_{1pt}(a)-m^{\alpha_i(\beta_j)}{}_{1pt}(b) \end{aligned} \tag{10}$$

In the similar way, the basic probability values based on speed and angle can be obtained: ($m^{\alpha_i(\beta_j)}{}_{2pt}(a)$, $m^{\alpha_i(\beta_j)}{}_{2pt}(b)$, $m^{\alpha_i(\beta_j)}{}_{2pt}(\theta)$, $m^{\alpha_i(\beta_j)}{}_{3pt}(a)$, $m^{\alpha_i(\beta_j)}{}_{3pt}(b)$, $m^{\alpha_i(\beta_j)}{}_{3pt}(\theta)$).

3.4 Solving the Bimatrix

The bimatrix problem can be transferred into an optimization problem [7], and the bimatrix are as follows:

$$A=\begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ c_{m1} & c_{m2} & \cdots & c_{mn} \end{bmatrix} \qquad B=\begin{bmatrix} c'_{11} & c'_{12} & \cdots & c'_{1n} \\ c'_{21} & c'_{22} & \cdots & c'_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ c'_{m1} & c'_{m2} & \cdots & c'_{mn} \end{bmatrix}$$

$$\begin{aligned} &\min v \\ &A_i \cdot y \le v, \quad i=1,2,\cdots,n \\ &y_1 + y_1 + \cdots + y_m = 1, \\ &y_j > 0, \quad j=1,2,\cdots,n \end{aligned} \quad (11) \qquad \begin{aligned} &\min w \\ &x^T \cdot B_j \le w, \quad j=1,2,\cdots,m \\ &x_1 + x_1 + \cdots + x_m = 1, \\ &x_i > 0, \quad i=1,2,\cdots,m \end{aligned} \quad (12)$$

the formula (11) can be transferred into (11) ' and the formula (12) to (12) ':

$$\begin{aligned} &\min v \\ &A_i \cdot y - v \le 0, \quad i=1,2,\cdots,n \\ &y_1 + y_1 + \cdots + y_m = 1, \\ &y_j, v > 0, \quad j=1,2,\cdots,n \end{aligned} \quad (11)' \qquad \begin{aligned} &\min w \\ &x^T \cdot B_j - w \le 0, \quad j=1,2,\cdots,m \\ &x_1 + x_1 + \cdots + x_m = 1, \\ &x_i, w > 0, \quad i=1,2,\cdots,m \end{aligned} \quad (12)$$

In MATLAB, "linprog" is an efficient function to solve the above optimization problem. In this way, the Nash equilibrium point can be obtained.

If there is no optimal value, the mixed strategies needs to be solved. Assume (x^*, y^*) is the Nash equilibrium point. If $x = \max(x^*_1, x^*_2, \cdots, x^*_m) = x^*_i \quad i=1,2,\cdots,m$,

$$y = \max(y^*_1, y^*_2, \cdots, y^*_n) = y^*_j \quad j=1,2,\cdots,n \ .$$

Where $x^* = (x^*_1, x^*_2, \cdots, x^*_m)$; $y^* = (y^*_1, y^*_2, \cdots, y^*_n)$; α_i (Its probability is x^*_i) is the strategy the blue should select. β_j (Its probability is y^*_j) is the strategy the red should select.

4 Simulation Experiments

In order to investigate the feasibility and effectiveness of the proposed hybrid game theory and D-S evidence approach, a series of experiments are conducted in this section.

4.1 Mission Scenario

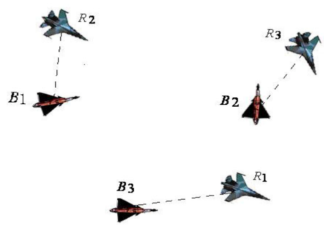

Fig. 2. Multiple UCAVs battlefield situation (R_1, R_2, R_3 belongs to the red, and B_1, B_2, B_3 belon gs to the blue)

Table 4. The relations of distance, angle and speed between UCAVs

	B_1-R_1	B_1-R_2	B_1-R_3	B_2-R_1	B_2-R_2	B_2-R_3	B_3-R_1	B_3-R_2	B_3-R_3
Distance (km)	8	4	10	4	11	5	5	7	7
Speed (m/s)	720	660	800	720	660	800	720	660	800
Angle (°)	90	-10	-10	-90	-80	60	90	-12	0
	R_1-B_1	R_1-B_2	R_1-B_3	R_2-B_1	R_2-B_2	R_2-B_3	R_3-B_1	R_3-B_2	R_3-B_3
Distance(km)	8	4	5	4	11	7	10	5	7
Speed (m/s)	360	660	800	360	660	800	360	660	800
Angle (°)	-90	90	90	10	80	12	10	-60	0

The blue strategy set:

$$\alpha_1=((B_1,R_1),(B_2,R_2),(B_3,R_3))$$
$$\alpha_2=((B_1,R_1),(B_2,R_3),(B_3,R_2))$$
$$\alpha_3=((B_1,R_2),(B_2,R_3),(B_3,R_1))$$
$$\alpha_4=((B_1,R_2),(B_2,R_1),(B_3,R_3))$$
$$\alpha_5=((B_1,R_3),(B_2,R_1),(B_3,R_2))$$
$$\alpha_6=((B_1,R_3),(B_2,R_2),(B_3,R_1))$$
$$\alpha_7=(((B_1,B_2),R_1),(B_3,(R_2,R_3)))$$
$$\alpha_8=(((B_1,B_3),R_1),(B_2,(R_2,R_3)))$$
$$\alpha_9=(((B_2,B_3),R_1),(B_1,(R_2,R_3)))$$

The red strategy set:

$$\beta_1=((R_1,B_1),(R_2,B_2),(R_3,B_3))$$
$$\beta_2=((R_1,B_1),(R_2,B_3),(R_3,B_2))$$
$$\beta_3=((R_1,B_2),(R_2,B_3),(R_3,B_1))$$
$$\beta_4=((R_1,B_2),(R_2,B_1),(R_3,B_3))$$
$$\beta_5=((R_1,B_3),(R_2,B_1),(R_3,B_2))$$
$$\beta_6=((R_1,B_3),(R_2,B_2),(R_3,B_1))$$
$$\beta_7=((R_1,G_1),(R_2,(B_1,B_2)),(R_3,B_3))$$
$$\beta_8=((R_1,G_1),(R_2,(B_1,B_3)),(R_3,B_2))$$
$$\beta_9=((R_1,G_1),(R_2,(B_2,B_3)),(R_3,B_1))$$
$$\beta_{10}=((R_1,G_1),(R_3,(B_1,B_2)),(R_2,B_3))$$
$$\beta_{11}=((R_1,G_1),(R_3,(B_1,B_3)),(R_2,B_2))$$
$$\beta_{12}=((R_1,G_1),(R_3,(B_2,B_3)),(R_2,B_1))$$

4.2 Simulation Results

The blue payoff matrix:

	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8	β_9	β_{10}	β_{11}	β_{12}
α_1	0.2603	0.1924	0.0039	0.0004	0.0005	0.0068	0.0035	0.0017	0.0047	0.0079	0.0060	0.0004
α_2	10.196	7.5372	0.1510	0.0140	0.0182	0.2653	0.1385	0.0666	0.1839	0.3095	0.2359	0.0142
α_3	395.08	292.04	5.8491	0.5426	0.7049	10.278	5.3656	2.5788	7.1263	11.993	9.1415	0.5510
α_4	9.5824	7.0832	0.1419	0.0132	0.0171	0.2493	0.1301	0.0625	0.1728	0.2909	0.2217	0.0134
α_5	0.6498	0.4803	0.0096	0.0009	0.0012	0.0169	0.0088	0.0042	0.0117	0.0197	0.0150	0.0009
α_6	0.6841	0.5057	0.0101	0.0009	0.0012	0.0178	0.0093	0.0045	0.0123	0.0208	0.0158	0.0010
α_7	2.7147	2.0067	0.0402	0.0037	0.0048	0.0706	0.0369	0.0177	0.0490	0.0824	0.0628	0.0038
α_8	30.400	22.471	0.4501	0.0418	0.0542	0.7909	0.4129	0.1984	0.5483	0.9229	0.7034	0.0424
α_9	8.6004	6.3573	0.1273	0.0118	0.0153	0.2237	0.1168	0.0561	0.1551	0.2611	0.1990	0.0120

The red payoff matrix:

	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8	β_9	β_{10}	β_{11}	β_{12}
α_1	3.8411	5.1963	259.45	2796.5	2152.9	147.65	282.82	588.46	212.95	126.53	166.00	2753.9
α_2	0.0981	0.1327	6.6243	71.402	54.970	3.7698	7.2212	15.025	5.4371	3.2306	4.2385	70.314
α_3	0.0025	0.0034	0.1710	1.8428	1.4187	0.0973	0.1864	0.3878	0.1403	0.0834	0.1094	1.8147
α_4	0.1044	0.1412	7.0489	75.978	58.494	4.0114	7.6840	15.988	5.7856	3.4377	4.5101	74.821
α_5	1.5389	2.0818	103.94	1120.4	862.56	59.153	113.31	235.76	85.314	50.692	66.507	1103.3
α_6	1.4618	1.9776	98.741	1064.3	819.39	56.192	107.64	223.96	81.045	48.155	63.178	1048.1
α_7	0.3684	0.4983	24.881	268.19	206.47	14.159	27.123	56.434	20.422	12.134	15.920	264.10
α_8	0.0329	0.0445	2.2219	23.949	18.438	1.2644	2.4221	5.0395	1.8237	1.0836	1.4216	23.584
α_9	0.1163	0.1573	7.8537	84.653	65.173	4.4694	8.5614	17.813	6.4462	3.8302	5.0251	83.364

By calculating, the conclusion can be obtained :

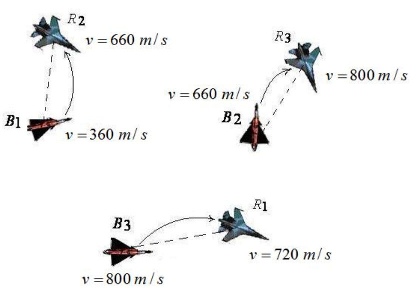

Fig. 3. The blue target allocation (B_1 against R_2, B_2 against R_3, B_3 against R_1)

The blue should select the strategy $\alpha_3 = ((B_1, R_2), (B_2, R_3), (B_3, R_1))$ and the value of its payment is 0.5426. The red should select the strategy $\beta_4 = ((R_2, B_1), (R_1, B_2), (R_3, B_3))$ and the value of its payment is 1.843. The blue and red target allocation results can be shown with Fig 3 and Fig 4. It is obvious that the target allocation is reasonable. In reality, they are corresponding with the actual situation. The simulation results demonstrate the proposed approach to multiple UCAVs cooperative air combat decision is feasible and effective.

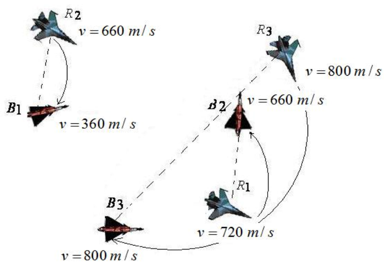

Fig. 4. The red target allocation (B_1 against R_2, B_2 against R_1, B_3 against R_3)

5 Conclusions

This paper has proposed hybrid game theory and D-S evidence approach to multiple UCAVs cooperative air combat decision. Series of experimental results demonstrate the feasibility and effectiveness of the proposed approach in solving the multiple UCAVs cooperative air combat decision problems. Our future work will focus on applying the proposed hybrid method to real multiple UCAVs cooperative air combat in more complicated combating environments.

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