Beyond-Visual-Range Tactical Game Strategy for Multiple UAVs

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Abstract—**Beyond-visual-range (BVR) air-to-air unmanned aerial vehicles (UAVs) combat has complex and varied characteristics. It always performs in a multiple UAVs cooperative way. This paper proposes a BVR air-to-air combat tactical strategy for multiple UAVs to achieve effective confrontations. The strategy is implemented by incorporating several one-versus-one air-to-air combat cases. For each one-versus-one case, a decision action space and a situation assessment function are developed. Then a minmax method based decision algorithm is designed to obtain the optimal tactic. Afterwards, to realize the optimal tactic, flight controllers for each UAV are designed. The superiority of the proposed BVR air-to-air combat tactical action decision strategy is validated by simulations in three representative scenarios.**

Keywords—Multiple UCAVs combat, action decision, minmax algorithm, situation assessment function, flight control system

I. INTRODUCTION

With the development of navigation in recent years, the unmanned aerial vehicles (UAVs) are not only used in aerial photography or exploration, but also increasingly applied to the modern air combat [1]. Therefore, a reliable unmanned combat aerial vehicles (UCAVs) system is required. Moreover, UCAVs mission features multi-target and multi-mission, which makes it difficult to be accomplished by single UAV [2]. According to this reason, the US Air Force Research Laboratory put forward "Loyal Wingman" system. It plans to assign some drones to the front-line combat units [3].

The process of multiple UCAVs air combat can be divided into groups of confrontations. Therefore, this paper focuses on the two-versus-one air-to-air combat system which is extended from one-versus-one air-to-air combat system. The UCAVs system mainly consists of situation assessment, task allocation, tactics decision, and execution mechanism. Some researches focus on establishing a new non-parameter model for situation assessmen [4]. Task allocation algorithm determines the goal of each UAV. The authors in [5] proposed a tactic algorithm which divides the combat into group-to-group combats. The tactic combined grouping and sorting strategies which are formulated as matrix games. The flight envelope and maximum maneuvering point of a fighter jet model were analyzed to achieve cooperative maneuvers role assignment in [6].

The core of the UCAVs system is the decision algorithm. Various studies on BVR air-to-air combat tactical action decision algorithm have been performed, mainly including five common methods, i.e., matrix game, influence diagram game, differential game, rule-based game, and fuzzy logic. The authors in [7] proposed a game-matrix approach to find an intelligent maneuvering decision. The authors in [8]-[9] designed a multi-stage influence diagram game method, which yielded the optimal control sequences with respect to their preference models. In [10]-[11], the optimal combat maneuvers can be founded by building scoring function matrix and analyzing enemy combat maneuver based on differential game. The authors in [12]-[13] proposed an air-to-air combat simulation method based on rule. The decision-making results obtained by this method are close to the actual flight actions of pilots. In addition, fuzzy logic based artificial intelligence methods were applied to solve complex problems [14]-[15]. At present, overloads are usually regarded as the outputs of the decision algorithms in most existing literature. However, most of pilots consider the desired state variables as the fighting decision results in practice, which is more intuitive. Hence, a novel decision action space related to state variables is proposed in this paper. In this sense, the designed decision algorithm outputs the desired state variables, including the desired altitude, flight path azimuth angle, and velocity. Then the desired state variables can be followed by designing a control system. Moreover, multiple UAVs combat system is studied based on the one-versus-one air-to-air combat system in this paper.

This paper consists of five sections. Following the first Introduction section, the second section gives the UAV kinematics model. Then the air-to-air combat tactical action decision strategy for multiple UAVs is designed. It includes developing a decision action space and situation assessment function, designing the coordination and decision algorithm, and designing fight controller of multiple UAVs combat system. The fourth part contains simulations in three representative scenarios. Conclusion is followed at last.

II. UCAVs SIMULATION MODELS

A. 6DOF Model for UAV

In this section, a brief description of the model which is used in this paper is given. A model is adopted which has 6DOF for simulation in this paper. The coordinates used are

shown in Fig. 1. Kinematics and overload models are included. They are derived from the assumption where each UAV is a mass point, regardless of sideslip. Each UAV of both sides has the same model. The kinematics model is described as

$$\dot{x} = V \cos \gamma \sin \varphi$$
$$\dot{y} = V \cos \gamma \cos \varphi \qquad (1)$$
$$\dot{z} = V \sin \gamma$$

where x, y, z denote positions in X direction, Y direction, and the altitude, respectively. V, γ, φ are the velocity, flight path angle, and flight path azimuth angle. The overload model is described as

$$\dot{V} = g(n_x - \sin \gamma)$$
$$\dot{\gamma} = g(n_z \cos \phi - \cos \gamma) / V \qquad (2)$$
$$\dot{\varphi} = g n_z \sin \phi / (V \cos \gamma)$$

where n_x, n_z and ϕ are the control variables, denoting overloads in X direction and Z direction, and the bank angle. Considering the maneuverability of UAV, γ is limited to $\left[-35^\circ, 35^\circ \right]$. Meanwhile, in order to avoid generating singularities, the range of γ is defined as $\left(-90^\circ, 90^\circ \right)$.
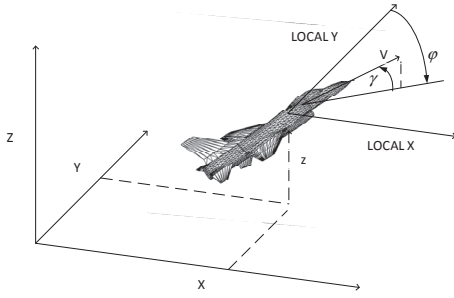

Fig. 1. Model of UAV.

B. Victory conditions

In this paper, the combat is finished when the BLUE enters into a specific zone. We call this zone as non-escape zone, which is shown in Fig 2. The non-escape zone is a space where the distance between the two UAVs is the optimal attack distance and the target is in the optimal attack angle of the RED UAV.
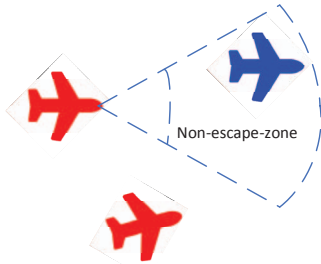

Fig. 2. Non-escape zone.

In this paper, the target is shoot down once it enters non-escape zone of UAV.

III. BVR AIR-TO-AIR COMBAT TACTICAL DECISION STRATEGY

The BVR air-to-air combat tactical action decision strategy is comprised of four portions, including the tactical action space, situation assessment function, minmax decision algorithm, and control system. The overall decision structure is shown in Fig. 3.
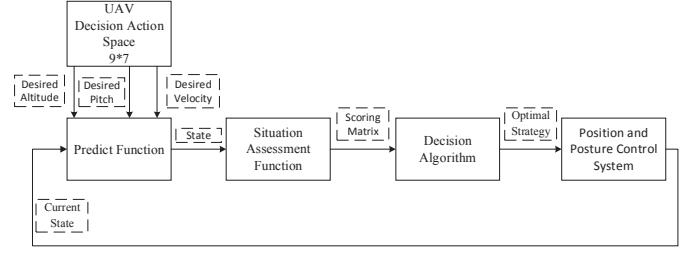

Fig. 3. Decision structure.

Actions are selected in turn in the tactical action space by each UAV. Different states are got by prediction model. The score matrix can be acquired by situation assessment system. The optimal strategy can be generated by decision algorithm. The actions are completed by the control system.

A. Decision action space

In practical UAV combat, each UAV focuses on winning advantages in terms of energy and heading angle. The energy advantage is related to altitude and velocity. The heading angle advantage comes from flight path azimuth angle. As the output of decision algorithm, a decision action space is defined as $\Lambda = (\Delta h, \Delta \varphi)$, where Δh is the altitude variation and $\Delta \varphi$ denotes the azimuth angle change. The altitude variation is limited within [-250m, 250m] and discretized into 9 choices, i.e. $\Delta h = \left\{ -250, -150, -100, -50, 0, 50, 100, 150, 250 \right\}$ m. The flight path azimuth angle variation is limited within [-10°, 10°], and discretized into 7 choices, i.e. $\Delta \varphi = \left\{ -10^\circ, -5^\circ, -2.5^\circ, 0^\circ, 2.5^\circ, 5^\circ, 10^\circ \right\}$. Therefore, for each UAV, the size of the decision action space is 63.

B. Situation assessment function

In BVR air-to-air combat, the situation assessment should consider the airborne sensor performance, the attack system performance and the position geometry relationship of both sides simultaneously. The position geometric relationship between the two sides is shown in Fig. 4. Here, D represents the distance between the two sides, α is the target aspect angle, and β is the target bearing angle.
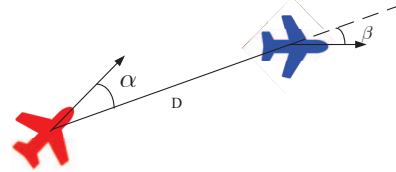

Fig. 4. Geometric relationship between the two sides.

An integrated function is defined for situation assessment, which are divided into two components: a dynamic performance advantage function and a static one. Moreover, the dynamic performance advantage function consists of a vision capability dominance function and an energy dominance function. The static performance advantage function is related to maneuver ability parameters of UAV.

- Vision capability dominance function

Vision information is perceived by fire control radar, so it is related to the distance D, aspect angle α and bearing angle β of UAV. The score of BVR air combat is affected by distance[16]. Therefore, the distance dominance function is constructed as

$$T_D = \begin{cases} 0 & D \geq D_{R\max} \\ 0.5e^{\frac{D-D_{M\max}}{D_{R\max}-D_{M\max}}} & D_{M\max} \leq D < D_{R\max} \\ 2^{-\frac{D-D_{MK\max}}{D_{M\max}-D_{MK\max}}} & D_{MK\max} \leq D < D_{M\max} \\ 2^{-\frac{D-D_{MK\min}}{10-D_{MK\min}}} & 10 \leq D < D_{MK\min} \\ 1 & D_{MK\min} \leq D < D_{MK\max} \end{cases} \quad (3)$$

where $D_{R\max}$ is maximum detection range of fire control radar. $D_{M\max}$ is maximum range of the missile. $D_{MK\max}$ is maximum inescapable range of the target. $D_{MK\min}$ is minimum inescapable range of the target.

The score of BVR air combat is affected by aspect angle as well. The aspect angle dominance function is defined as

$$T_\alpha = \begin{cases} 0 & \alpha > \alpha_{R\max} \\ 0.3(1-\frac{|\alpha|-\alpha_{M\max}}{\alpha_{R\max}-\alpha_{M\max}}) & \alpha_{M\max} \leq \alpha < \alpha_{R\max} \\ 0.8-\frac{|\alpha|-\alpha_{M\max}}{2(\alpha_{R\max}-\alpha_{M\max})}) & \alpha_{M\max} \leq \alpha < \alpha_{MK\max} \\ 1-\frac{|\alpha|}{5\alpha_{MK\max}} & 0 \leq \alpha < \alpha_{MK\max} \end{cases} \quad (4)$$

where $\alpha_{R\max}$ is the maximum search angle of fire control radar. $\alpha_{M\max}$ is maximum off-axis launch angle of missile. $\alpha_{MK\max}$ is missile strike zone boundary.

According to [13], the scoring function of bearing angle score is obtained as

$$T_\beta = \begin{cases} \dfrac{|\beta|}{50} & \beta < 50° \\ 1-\dfrac{|\beta|-50}{130} & 50° \leq \beta \leq 180° \end{cases} \quad (5)$$

Since the aspect angle and bearing angle influence each other, the angle dominance function is calculated as

$$T_A = T_\alpha^{q_1} T_\beta^{q_2} \quad (6)$$

where $q_1 \in [0,1]$, $q_2 \in [0,1]$, and $q_1 + q_2 = 1$.

Based on the distance dominance function T_D and the angle dominance function T_A, the vision capability dominance function is computed as

$$T_{horizon} = T_D^{h_1} T_A^{h_2} \quad (7)$$

where $h_1 \in [0,1]$, $h_2 \in [0,1]$, and $h_1 + h_2 = 1$.

- Energy dominance function

Recall that the velocity is set as a constant in this paper, hence the energy dominance function is related to the height difference between the two sides. But considering the radar detection limitation, we define a radian R outside of which the energy dominance function becomes meaningless. The energy dominance function is calculated as

$$\Delta z = z_1 - z_2 \quad (8)$$

$$T_E = \begin{cases} 0.5-0.5(\dfrac{\Delta z}{R})^2 & \Delta z \leq 0 \\ 1-0.5(\dfrac{|R-\Delta z|}{R})^{0.5} & \Delta z > 0 \end{cases} \quad (9)$$

where z_1 is the altitude of the UAV running the tactical decision algorithm (the RED or the BLUE), z_1 is the target, and Δz is the altitude difference.

- Static performance dominance function

Six indexes related to operations are selected to evaluate static performance, including maneuverability B, firepower A_1, target detection capability A_2, operability k_1, survivability k_2, range and electronic countermeasures k_3 [17]. Static performance dominance function is calculated as

$$T_{static} = (\ln(B) + \ln(A_1+1) + \ln(A_2))k_1 k_2 k_3 \quad (10)$$

- Total score function

Finally, the situation assessment function is integrated as.

$$T = \omega_1 T_{horizon} + \omega_2 T_E + \omega_3 T_{static} \quad (11)$$

Where $\omega_1 \in [0,1]$, $\omega_2 \in [0,1]$, $\omega_3 \in [0,1]$ are the weights with $\omega_1 + \omega_2 + \omega_3 = 1$.

C. MinMax Decision Algorithm

The scoring matrix is the basis for selecting the optimal action strategy. The scoring matrix is established by situation assessment function. Therefore, as a two-person matrix game, the size of scoring matrix is 63*63 in this paper, as shown in TABLE I.

In the score matrix, first the minimum value of each row is selected and then the maximum value among them is selected. The optimal strategy is generated. UAV can maintained advantages or reverse disadvantages by the optimal action strategy. By doing this, the strategy selected by this method is the most guaranteed minimum benefit of the game, and the worst outcome can be avoided regardless of the strategy selected by target. Although minimax decision algorithm may be conservative sometimes, the strategy generated by this method achieves a high success rate for the whole game process. Solving the optimal strategy algorithm obtains

$$\nu = \max_{0 < i \leq 63} \min_{0 < j \leq 63} T_{ij} \quad (12)$$

where ν is the result of the minmax decision algorithm which is an element of the decision action space Λ.

TABLE I.   SCORING MATRIX

		BLUE Action					
		1	2	3	...	j	63
RED Action	1	$T_{1,1}$	$T_{1,2}$	$T_{1,3}$			$T_{1,63}$
	2	$T_{2,1}$	$T_{2,2}$	$T_{2,3}$			$T_{2,63}$
	3	$T_{3,1}$	$T_{3,2}$	$T_{3,3}$			$T_{3,63}$
	...	...			...		
	i	...				$T_{i,j}$	
	63	$T_{63,1}$	$T_{63,2}$	$T_{63,3}$	...		$T_{63,63}$

In the two-versus-one experiment, task assignment and attack target selection are carried out. According to the current state, each aircraft is scored against the other by using the above situation assessment function, and the score matrix is obtained as

$$Score\_matrix = \begin{bmatrix} S_{11'} & S_{21'} \\ S_{1'1} & S_{1'2} \end{bmatrix} \qquad (13)$$

For two UAVs, the UAV with lower score is responsible for feint, which is aimed at pinning down the enemy and employing minmax decision algorithm. The one with the higher score is served as main attacker and employed the one-sided minmax decision algorithm.

D. Control System Design

The output of the above decision system is the desired flight path azimuth angle and altitude. These two variables, together with the predefined constant velocity, constitute the reference commands for the control system to follow. According to (2), the control variables of the control system is transformed as

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & \sin\phi \\ 0 & 0 & \cos\phi \end{bmatrix} \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} \qquad (14)$$

- Velocity controller

Define the actual velocity and desired velocity of UAV as V and V_C, hence the velocity error is expressed as $e_V = V - V_C$. Then, the controller of the velocity model is designed as

$$u_1 = \sin\gamma + (\dot{V}_C - k_V e_V)/g \qquad (15)$$

Therefore, the error dynamics of the velocity is expressed as

$$\dot{e}_V = -k_V e_V \qquad (16)$$

where k_V is the controller gain. According to Lyapunov stability theory, the system (16) is asymptotically stable with $k_V > 0$.

- Flight path azimuth angle controller

Define the actual flight path azimuth angle and expected Flight path azimuth angle of UAV as φ and φ_C, hence the Flight path azimuth angle error is expressed as $e_\varphi = \varphi - \varphi_C$.

Similarly to the design of the velocity controller, the controller of the flight path azimuth angle model is designed as

$$u_2 = V\cos\gamma(\dot{\varphi}_C - k_\varphi e_\varphi)/g \qquad (17)$$

where $k_\varphi > 0$ is the controller gain.

- Altitude controller

The altitude model is a second-order system. In this paper, a double loop control method is used to design the altitude controller, which is similar to the backstepping control method. The outer loop is the altitude control system and the inner loop is the flight path angle control system.

For the outer loop control system, define the actual altitude and expected altitude of UAV as z and z_C. Therefore, the altitude error is expressed as $e_z = z - z_C$. Then, the controller of the altitude model is designed as

$$\gamma_C = (\dot{z}_C - k_z e_z)/V \qquad (18)$$

where $k_z > 0$ is the controller gain.

For the inner loop control system, define the actual flight path angle and expected flight path angle of UAV as γ and γ_C. Therefore, the Flight path angle error is expressed as $e_\gamma = \gamma - \gamma_C$. Then, the controller of the flight path angle model is designed as

$$u_3 = \cos\gamma + V(\dot{\gamma}_C - k_\gamma e_\gamma)/g \qquad (19)$$

where $k_\gamma > 0$ is the controller gain.

IV. SIMULATION

To verify the effectiveness of the proposed algorithm in this paper, three representative scenarios are set in this section. They are Minmax-Versus-Line, Minmax-Versus-Minmax of one-versus-one air-to-air combat and two-versus-one air-to-air combat respectively. In this paper, all UAVs adopt the same model and the same parameters.

A. MinMax-Versus-Line/Snake combat

In this scenario, we design two fight actions for the BLUE, including a line and a snake maneuver. The RED adopts minmax decision algorithm while the BLUE adopt the above two maneuvers. The initial conditions are shown in TABLE II.

TABLE II. MINMAX-VERSUS-LINE/SNAKE MANEUVER INITIAL CONDITIONS

	Initial Conditions		
	Position(m)	*Heading(deg)*	*Velocity(m/s)*
RED	[0, 0, 10000]	90	300
BLUE	[80000, -50000, 10000]	-90	300

The experimental results with the BLUE using the line maneuver are shown in Fig. 5. Fig. 5.1 is the *xoz* plane of trajectory. It is shown that when the two UAVs are in the attackable zone, the RED climbs 500m immediately to occupy an advantage in altitude. Fig. 5.2 is the *xoy* plane of trajectory. As shown in Fig. 5.2, the RED changes the heading to make sure the BLUE is in the range of radar's angle detection. After about 90 seconds, the BLUE is in the non-escape zone of the RED. Hence, the RED wins.
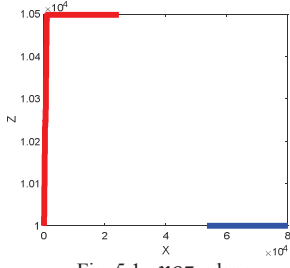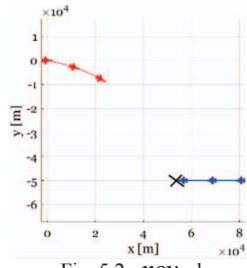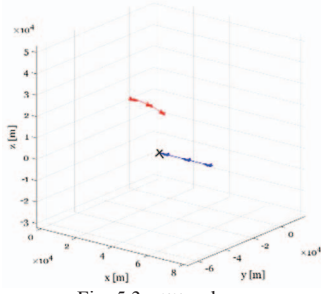
Fig. 5.1. *xoz* plane.

Fig. 5.2. *xoy* plane.

Fig. 5.3. *xyz* plane.

Fig. 5. Experimental trajectories.

In addition, we have conducted another simulation. The results show that when the BLUE adopts snake maneuver, the RED can win after about 150 seconds.

To prove the validity of minmax decision algorithm, we have conducted Monte-Carlo experiment for 300 runs. The initial conditions of position are generated by random functions. The result shows that the RED wins 245 runs and draws 55 times. The draw runs are due to time limit of simulation, but situation shows that the RED is superior to BLUE. Statistical diagram is shown as TABLE III.

TABLE III.   MONTE-CARLO EXPERIMENT

	Monte Carlo experiment			
	WIN	*DRAW*	*FAIL*	*WIN RATE*
RED	245	55	0	81.7%
BLUE	0	55	245	0%

B. MinMax-Versus- MinMax combat

In this scenario, it is assumed that the two UAVs adopt the same decision algorithm, the minmax decision algorithm. The initial conditions are shown in TABLE IV.

TABLE IV.   MINMAX-VERSUS-MINMAX INITIAL CONDITIONS

	Initial Conditions		
	Position(m)	*Heading(deg)*	*Velocity(m/s)*
RED	[0, 0, 10000]	90	300
BLUE	[60000, 50000, 10000]	-90	300

The experimental results are shown in Fig. 6. It shows that when the two UAVs are in the attackable zone, the strategy is the same. Therefore, the trajectories are symmetrical in Fig. 6.3. Each plane tries to gain a greater advantage in energy, therefore z is keeping increasing in Fig 6.1. In addition, minmax tactics is conservative, hence the two UAVs both try to avoid being in non-escape zones. Fig. 6.2 shows symmetrical and circle trajectories in *xoy* plane. The result of the UCAVs is a draw.

C. Two- Versus-One Combat

In this scenario, we have conducted a Two-Versus-One UCAVs simulation. The RED has two UAVs, while the BLUE only has one UAV. The two sides adopt the same decision algorithm, the minmax decision algorithm. The initial conditions are shown in TABLE V.
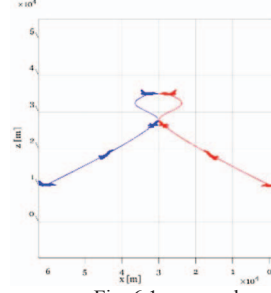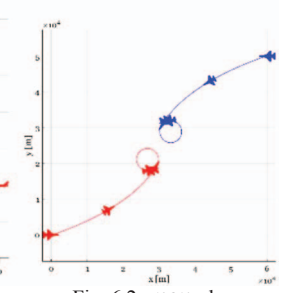

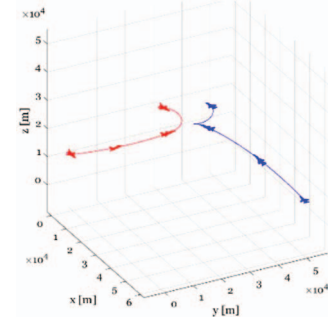Fig. 6.1. *xoz* plane.

Fig. 6.2. *xoy* plane.

Fig. 6.3. *xyz* plane.

Fig. 6. Experimental trajectories: MinMax-Versus- MinMax combat.

TABLE V.   MINMAX-VERSUS-MINMAX INITIAL CONDITIONS

	Initial Conditions		
	Position(m)	*Heading(deg)*	*Velocity(m/s)*
RED#1	[0, 0, 10000]	90	300
RED#2	[0, -1000, 10000]	90	300
BLUE	[80000, 0, 10000]	-90	300

In this scenario, we calculate current situation firstly. Then the two UAVs of RED are divided into the main attack one and feign attack one by (13). In this scenario, RED#1 is the main attacker and RED#2 is the feign attacker. RED#2 attracts the BLUE and both of the two UAVs use minmax decision algorithm. The RED#1 fights with the BLUE based on single minmax decision algorithm. As shown in Fig. 7.2, the trajectory of RED#2 and the BLUE is symmetrical. After 40 seconds, RED#1 destroys the BLUE successfully，as shown in Fig. 7.3. This result shows that the time to complete the task can be reduced greatly.
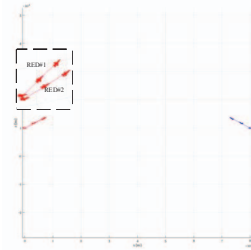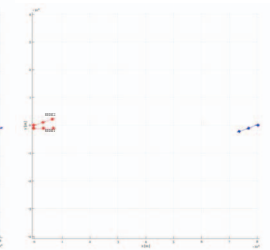

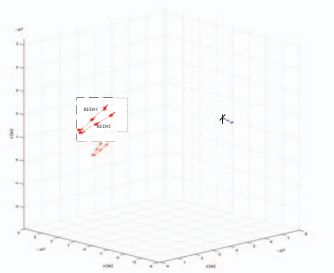Fig. 7.1 *xoz* plane.

Fig. 7.2 *xoy* plane.

Fig. 7.3 *xyz* plane.

Fig. 7. Experimental trajectories: Two- Versus-One combat

V.   CONCLUSION

In this paper, based on 6DOF model, a decision action space is developed that is close to actual UCAVs decision. Using situation assessment function and minmax decision algorithm, the optimal strategy solution of UCAVs is achieved. Then, through the control system, UAV can achieve the strategy. Finally, the effectiveness of this combat system is verified by simulations in three representative scenarios. The decision of single UCAV and the cooperation of multiple UCAVs can be realized by using the proposed combat system.

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