Efficiency Analysis of Typical Application based on Manned/Unmanned Aerial Vehicle Cooperative Combat

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Abstract— **Manned/Unmanned Aerial Vehicle cooperative combat is an inevitable trend in the future, and the determination of its efficiency has always been the focus of the research. This paper analyzes the system composition of Manned/Unmanned Aerial Vehicle cooperative combat, then establish integrated index model of collaborative system. Based on this, this paper put forward the task-oriented cooperative combat effectiveness evaluation method, and carry out the simulation under the typical combat application for qualitative validation. The conclusion is the theoretical calculation results are consistent with cooperative combat efficiency simulation results, and the efficiency evaluation model can provide a reference for the selection of the optimal formation combination mode in actual combat.**

Keywords—Cooperative Combat; Efficiency Analysis; Integrated Index Model; Manned/Unmanned Aerial Vehicle

I. INTRODUCTION

Since the 1970s, The use of Unmanned Aerial Vehicle (UAV) has attracted much attention, because of its low cost, no life risk, strong maneuverability, flexible operation, suitable for a variety of environments and other advantages [1]. However, only UAV is often difficult to complete some complex and multi-demand tasks at present [2], which can only play a role of assistant. Restricted by various constraints, there is still a large gap combat ability between the UAV's and Manned Aerial Vehicle's (MAV). Such as UAV needs strong dependence on satellites, unstable to make communicate with remote command or control center, hard to detect to dynamic changes in the battlefield, and other outstanding problems. Therefore, the close cooperation between people and weapons will affect the situation of the battlefield directly in the future war, and way of cooperation is changing constantly. The potential capabilities of MAV/UAV will be applied in the short-term battlefield space-time, and it will be a normal state in the future.

Scholars from all over the world have done a lot of researches on the cooperative operation of MAV / UAV[3][4]. But there are also great challenges, such as the interdisciplinary problems, the complexity of the cooperative model of MAV/UAV, large-scale optimization algorithm and random events[5]. The effectiveness evaluation of MAV/UAV cooperative operations is an important issue in the field of cooperative operations, Liu Y F[6] analysis the efficiency about a task assignment model of MAV/UAV formation based on multi-agent system(MAS) theory. To assessment the cooperative effect of MAV/UAV team, Xiaoguang[7] built a analysis model of cooperative effect based on fuzzy cognitive map(FCM). Sun Xiao-wen[8]discussed the efficiency analysis of MAV/UAV cooperative detection. Zhang Guochun[9] discussed the system effectiveness analysis in anti-jamming simulation based on the principle of system effectiveness measurement and analysis. Comparing the various concepts of effectiveness, Cheng Kai[10] analyzes the basic concepts of operational effectiveness, defines the action effectiveness and explains its connotation and all the evaluation methods have been classified by traditional and newly developed methods, then analyzes both strengths and weaknesses of these methods.

Although previous scholars have done a lot of in-depth discussion, but most of them only stay at the conceptual level[11][12][13]. An outline of this paper about the study of the MAV/UAV cooperative combat efficiency is as followed. In Section II, The composition of cooperative combat system and two typical cooperative combat missions are described. In Section III, we established the evaluation model of MAV/UAV cooperative combat efficiency under typical missions (Reconnaissance and Attack). We used the analytic hierarchy process to aggregate the function parameter of a single aircraft into a quantitative expression of the efficiency of MAV/UAV cooperative combat. In Section IV, We select the current typical MAV/UAV cooperative combat equipment in the United States, and set them as the combination mode under the mission mode of Section II. So we could get the theoretical results of cooperative combat efficiency, and deduce the same situation in the reliable simulation system to make a comparative analysis to verify the correctness of the evaluation model in Section III. Finally, concluding remarks are stated in Section V.

II. COOPERATIVE COMBAT PATTERN

The MAV/UAV cooperative combat system is composed of four main subsystems: Ground Command Center(GCC),

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MAV, UAV and Communication Link System(CLS). GCC, MAV and UAV shared information, situation, command through CLS to achieve cooperative combat; MAV/UAV formation are Controlled by GCC; MAV can command UAV. In the future actual battlefield, the MAV is mainly responsible for the decision-making level control, such as collaborative decision task assignment. While the UAV is mainly responsible for the task level, such as reconnaissance, surveillance, detection and attack.

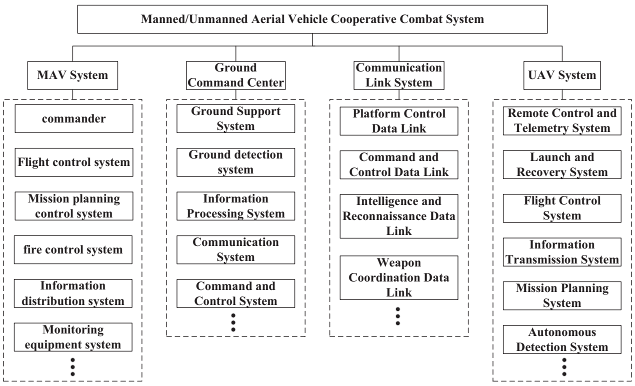

Fig. 1. The structure diagram of the MAV/UAV Cooperative Combat System

A. *Cooperative Reconnaissance Mission*

Compared with UAVs cooperation, the main advantages of MAV/UAV hybrid formation cooperative reconnaissance are as follows: In the process of reconnaissance mission, the initial position of the target is unknown, and many threat factors are in the reconnaissance area. When the mission area is too large and too many targets are needed to be reconnoitred, multiple UAVs may not be able to complete the mission within the specified time due to the restriction of flight speed. In the special reconnaissance situation, multiple UAVs need to avoid the threat and are easy to lose the target., even to break down or be shot down by the enemy. Due to the limitation of carrying weight and type, the detection range of UAV's sensors is limited, which may not meet the reconnaissance requirements of each target. Different performance targets need different performance sensors to detect. But when MAV joins the UAVs formation, it can adjust the decision-making temporarily, allocate the reconnaissance task area and the target of sensor matching reasonably. MAV/UAV can meet the requirements of reconnaissance mission perfectly. The schematic is illustrated in Fig. 2.

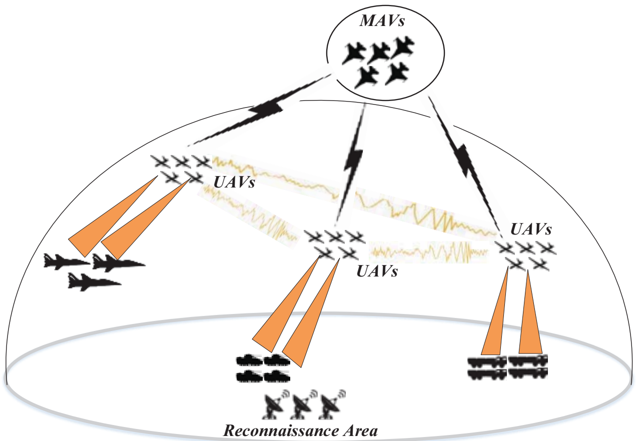

Fig. 2. The mission of MAV/UAV cooperative reconnaissance

B. *Cooperative Attack Mission*

1) *Attack Mission on Air Targets*

Typical application scenario of air attack mission is one MAV and two UAVs formations attack the air target. MAV behind UAVs is responsible for tracking and detecting enemy targets, also send the target information to the UAV constantly. The UAV's radar only receives signals and does not transmit electromagnetic waves so that they can approach to target quietly and quickly. When the target enters the fire attack range of the UAV, UAV received the weapon launch command and then take over the guidance to complete the attack mission on the enemy aircraft. The schematic is illustrated in Fig. 3.

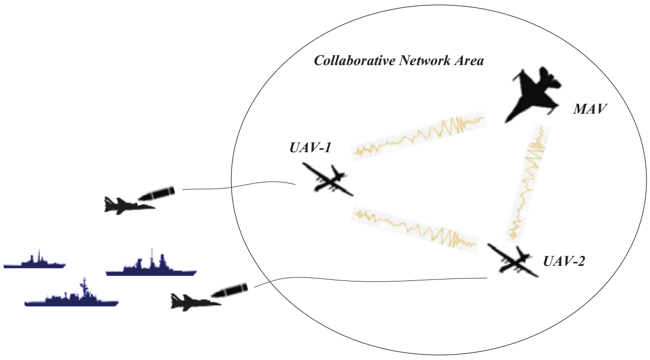

Fig. 3. The mission of MAV/UAV cooperative attack on air targets

2) *Attack Mission on Ground Targets*

Typical application scenario of ground attack mission is MAV control multiple UAVs formation to attack ground targets together. Each UAV carries a variety of sensors and different types of ground attack weapons, such as air-to-ground missiles, bombs, machine guns, etc., thus reducing the load of each UAV. All kinds of aircrafts cooperate closely and follow the instructions of MAV to attack the ground targets. The schematic is illustrated in Fig. 4.

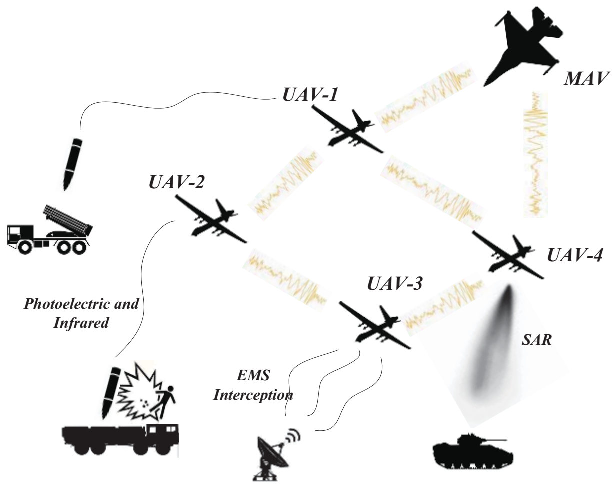

Fig. 4. The mission of MAV/UAV cooperative attack on ground targets

III. Efficiency Evaluation

As described in Section II, there are typical MAV/UAV cooperative combat modes, and evaluating its efficiency has great significance for the development of future weapons equipment, which is the basis and starting point of aviation equipment development and mass production[14][15].

Analytic Hierarchy Process(AHP) is used to evaluate efficiency[16], thus the comprehensive index model of MAV/UAV cooperative combat is established described in Fig. 5. The first layer is the value of overall efficiency. The second and third layer are the subsystem capability layers, which are the capability index of each subsystem of the system. The fourth layer is the index quantification layer, which obtained through a large number of statistics and expert knowledge.

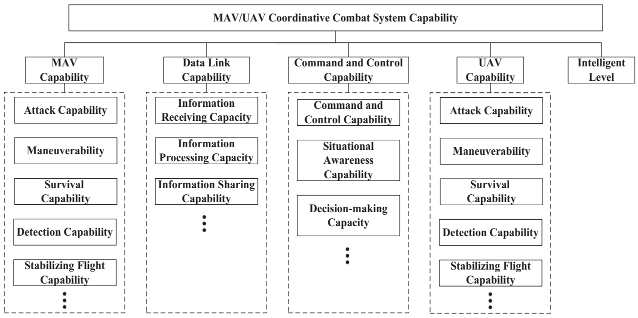

Fig. 5. The capability hierarchy of MAV/UAV cooperative combat

A. Mathematical Model of MAV/UAV Efficiency

According to the characteristics of MAV/UAV cooperative combat pattern described in Section II, There's tight coupling relationship between command/control capability, UAV intelligence level and data link capability. Single aircraft combat capability is independent, therefore mathematical model of MAV/UAV efficiency can be expressed as:

$$S = 0.9\overline{D_c} \cdot \overline{A_D} \cdot \overline{I_{UAV_i}} \sum_{i=1}^{n} C_{UAV_i} n^{\mu} + 0.1 \sum_{k=1}^{m} C_{MAV_k} m^{\mu}$$

In formula, D_c is the data link capability, A_D is the command and decision-making capability of MAV, I_{UAV_i} is the intelligent level of the UAV, C_{UAV_i} and C_{MAV_k} represent single efficiency of the number i UAV and the number k UAV, n and m are the number of UAVs and MAVs. In the typical mission described above, the main task of MAV is to assist and command, and UAV is the main unit of action, so its efficacy weight is 0.9 and 0.1(Ideal Conditions). According to the experience of experts, cooperative combat will reduce the advantage of single aircraft capability. μ represents the influence of the total number of aircrafts on the single aircraft efficiency. After statistical arrangement, the relationship between μ and the total number of aircrafts is shown in Tab.3-1.

Tab.3-1 The influence of the total number of aircrafts

total number of aircrafts	2	3	4
μ	1	0.9	0.8

The "—" above the sub-item capacity index is the standardized value. Considering the physical significance of various performance parameters, we used the normalization method of nonlinear differentiable function to make the value of each index between zero and one.

$$f(x) = \frac{1}{1 + \alpha \cdot e^{-\beta x}} \quad \alpha > 0,\ \beta > 0$$

The α and β are the parameters of regulating curve, which can make the data consistent relatively and have a small difference between themself.

B. Algorithm of Subsystem Capability

The factors involved in the calculation of the capacity of each subsystem are determined by a large number of data research and the results of experts discussed. Limited by the length of the article, only the calculation of factors considered and the selection methods of important weights will be described in detail.

1) Data link capability(D_c)

The Data Link Capability includes Information Receiving Capacity, Information Processing Capacity and Information Sharing Capability. The calculation method of each capacity is shown in the Tab.3-2.

TAB.3-2 THE CALCULATION OF DATA LINK CAPABILITY

Capability Name	Calculation Formula
Data Link Capability(D_c)	$DC = 0.2 \times M_R + 0.2 \times M_D + 0.6 \times M_S$
Information Receiving Capacity(M_R)	$M_R = D_E = (D_{\max} - D_L) \cdot (t_c - t_p)$
Information Processing Capacity(M_D)	$M_D = \frac{\sum_{i=1}^{n} q_i}{n}$
Information Sharing Capability(M_S)	$M_S = \frac{1}{n_r} \cdot \frac{\sum_{y=1}^{n_r} (M_r)_y}{\sum_{x=1}^{n_s} (M_s)_x}$

2) Command and control capability(A_D)

The Command and Control Capability includes Situational Awareness Capability and Decision-making Capacity. The calculation method of each capacity is shown in the Tab.3-3.

TAB.3-3 THE CALCULATION OF COMMAND AND CONTROL CAPABILITY

Capability Name	Calculation Formula
Command and Control Capability(A_D)	$A_D = 0.4 \times S_N + 0.6 \times S_L$
Situational Awareness Capability(S_N)	$S_N = \frac{U}{U_0} \times \sum_{i=1}^{n} (1 - E_i) q_i$
Decision-making Capacity(S_L)	$S_L = \frac{t_{\max}}{\sum_{j=1}^{m} \alpha_j t_j}$

3) Intelligence level of UAV(I_{UAV_i})

The value of UAV intelligence level is based on 10 levels of autonomous control defined by relevant research units in the United States.

TAB.3-4 THE VALUE OF UAV INTELLIGENCE LEVEL

Level	Capability Name	I_{UAV_i}
10	Fully Autonomous Swarm	1.0
9	Group Strategic Goals	0.9
8	Distributed Control	0.8
7	Group Tactical Goals	0.7
6	Group Tactical Re-plan	0.6
5	Group Coordination	0.5
4	Onboard Route Re-plan	0.4
3	Adapt to Failure and Flight Conditions	0.3
2	Real Time Health/Diagnosis	0.2
1	Remotely Guide	0.1

4) Self-capability of aerial vehicle(C)

Self-capability of aerial vehicle includes Attack Capability, Maneuverability, Survival Capability, Detection Capability and Stabilizing Flight Capability. The calculation method of each capacity is shown in the Tab.3-5.

TAB.3-5 THE CALCULATION OF AERIAL VEHICLE SELF-CAPABILITY

Capability Name	Calculation Formula
Self-capability of aerial vehicle(C)	$C = \omega_1 \cdot \overline{C_A} + \omega_2 \cdot \overline{C_M} + \omega_3 \cdot \overline{C_s} + \omega_4 \cdot \overline{C_D} + \omega_5 \cdot \overline{C_R}$
Attack Capability(C_A)	$C_A = Det \cdot \sum_{i=1}^{k} W_i \cdot L_i \cdot Cc \cdot \sqrt{n_i}$
Maneuverability (C_t)	$C_M = 0.35\overline{SEP} + 0.25\overline{N}_{\max} + 0.25\overline{\omega}_{\max} + 0.15\overline{T}_{\max}$
Survival Capability(C_s)	$C_s = \left(\frac{10}{l} \times \frac{15}{w} \times \frac{5}{RCS}\right)^{0.0625}$
Detection Capability(C_D)	$C_D = 0.5 \times \frac{2\pi r_{\max}^3 \theta_A}{3} + 0.5 \times \frac{2^k \beta n_\beta n_\varepsilon T_d}{(\frac{d}{2}) R_0^3 \theta_\infty}$
Stabilizing Flight Capability(C_R)	$C_R = \frac{R}{1270} \times \frac{H}{18000} \times \sqrt{\frac{V_{max}}{1.95} \times \frac{V_s}{0.8}}$

For the determination of the weights in the above table, the expert scoring method is used to build the judgment matrix, and the relative weights are calculated under a single criterion. Finally, through the consistency test, the capability weight coefficients of the aircraft under different mission conditions are obtained shown in the Tab.3-6.

TAB.3-6 THE CAPABILITY WEIGHT UNDER DIFFERENT MISSION CONDITIONS

Weights	Value	
	Reconnaissance	Attack Mission
ω_1	0.1117	0.4105
ω_2	0.4163	0.1036
ω_3	0.2387	0.2368
ω_4	0.1557	0.1725
ω_5	0.0776	0.0766

IV. SIMULATION TEST AND RESULTS

In this section, we designed two kinds of mission scenarios, and compared the simulation results with the theoretical calculation results.

A. Battlefield Scenario Description

In this paper, MAV/UAV cooperative reconnaissance and attack missions are described based on the basic data of typical UAV RQ/MQ-1A(U_A), UAV MQ-9(U_B)and MAV F-16(M) in the US. The specific battlefield constituent objects and normalized theoretical efficiency value of aircraft are shown in Tab.4-1.

TAB.4-1 THE SCENARIO DESCRIPTION OF MISSIONS

Mission	Combat Objects	
	Blue	Red
Reconnaissance	Airport-A	Airport-S
	Airport-B	/
	Radar Station-A	Radar Station-S
	RQ/MQ-1A(U_A)	Air Defense System
	MQ-9 (U_B)	/
	F-16 (M)	/
	Command Center	Command Center
Attack	Airport-A	Airport-S
	Airport-B	Airport-K
	Radar Station-A	Radar Station-S
	/	Air Defense System
	RQ/MQ-1A(U_A)	J-11B
	MQ-9 (U_B)	/
	F-16 (M)	/
	Command Center	Command Center

Specially, The weapon loading types of F-16(M) are 2×AIM-9 and 2×L-C; The weapon loading types of RQ/MQ-1A(U_A) are 2×AGM-114; The weapon loading types of MQ-9 (U_B) are 2×AIM-9 and 4×AGM-114.

The lots details are also considered in the scenario, such as the selection of radar for different mission, the strategies for action, command control relationship, and hit probability of random factors, etc.

B. Simulation Process

The simulation program is written in the XSim Studio military simulation environment which lies in Intel(R) Core (TM) i7-9700k, 32G RAM and 64-bit Windows 10 operating system. The simulation operation process is shown in the Fig. 6.

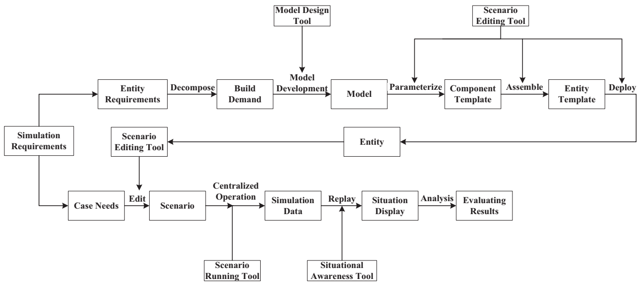

Fig. 6. The simulation operation process

According to the needs of different mission scenarios, the model is redeveloped by parameterizing and assembling. In this way, the mission scenario is initialized and deployed shown in Fig.7 and Fig.8. Each combat object is given different military symbol according to its type, and the yellow arrow with direction indicates the control relationship between superior and subordinate. The area covered by the red or blue line indicates the range that each system can detect or attack.

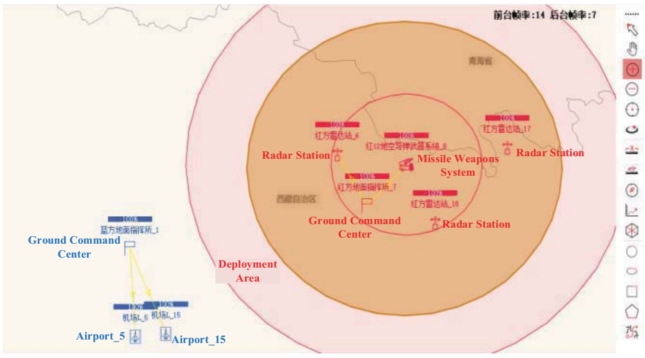

Fig. 7. The scenario initialization of reconnaissance mission

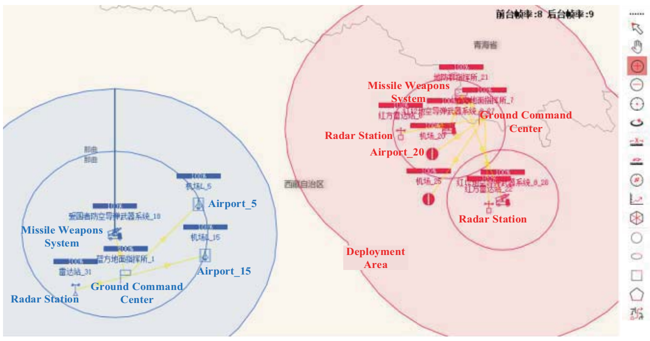

Fig. 8. The scenario initialization of attack mission

The most important step in the simulation process is to assemble the behavior capability to each combat object. For the blue army, the aerial reconnaissance mission model is assembled on the aircraft. After assembling this behavior capability, the UAV and MAV can conduct reconnaissance on the designated area or target, and calculate the airspace route independently. At the same time, it can also set the takeoff and landing airport of the aircraft, the maneuver mode in the mission airspace, and the rules to avoid threats. For the red army, The base scheduling task model is assembled on the airport, and it can command the J-11B to intercept the target from the airport. After sensing the air target, J-11B will carry out the battle with the target based on the setting of attack priority.

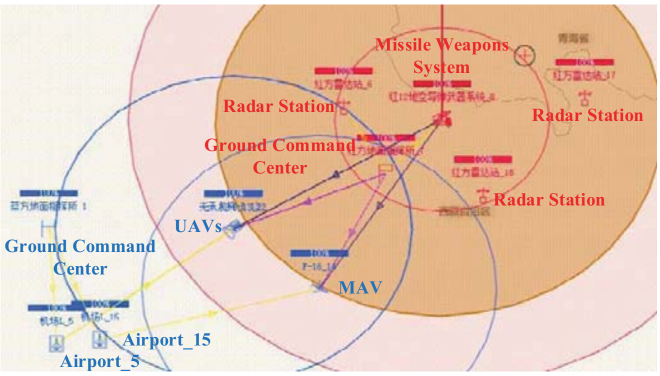

Fig. 9. The simulation process of reconnaissance mission

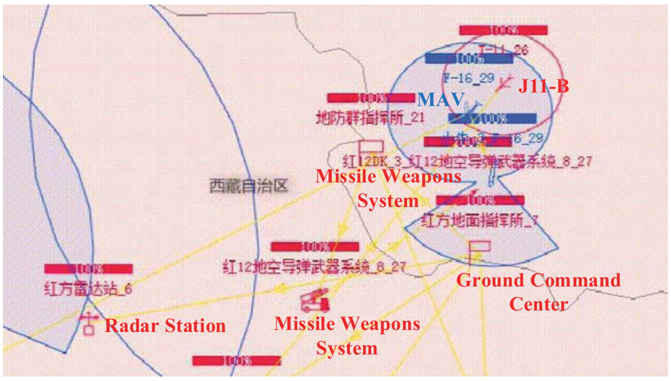

Fig. 10. The simulation process of reconnaissance mission

Fig.9 shows that MAV command UAVs enter the reconnaissance and detection mission area first, then MAV is located in the safe area outside the red army defense area. According to the situation of detection and battle damage, MAV decide to enter the red army area to replace the UAVs and continue the reconnaissance mission, so as to obtain the maximum deployment information.

Fig.10 shows that MAV/UAV carry out air to air combat with J-11B. In the meantime, the UAVs attack the ground airport, radar station and air defense system. Eventually, they return to the airport with some damage.

C. Simulation Results

Before the large-scale simulation, using theoretical calculation method to evaluate the capability indexes of three kinds of aircrafts based on real survey data shown in Tab.4-2.

TAB.4-2 THE THEORETICAL CALCULATION OF AIRCRAFTS CAPABILITY

Mission	Self-capability of aerial vehicle(C)		
	F-16 (M)	RQ/MQ-1A(U_A)	MQ-9 (U_B)
Reconnaissance	0.8117	0.3048	0.2288
Attack	0.7965	0.2325	0.2682

Under the same combat rules and battlefield conditions, 100 times Monte-Carlo random simulation experiments were carried out for five combination modes with a total number of 3 aircraft respectively, aiming at two combat tasks. The statistics obtained limited are shown in Tab.4-3.

TAB.4-3 THE STATISTICS OF SIMULATION DATA

Mode	Mission Index Value				
	Reconnaissance		Attack		
	Detection Area	Survival Number	Weapon Launche	Weapon hits	Survival Number
$1\times(M)$ $2\times(U_B)$	1349.64	4.06	2.72	1.82	5.18
$1\times(M)$ $2\times(U_A)$	2201.31	3.86	2.98	1.22	5.66
$1\times(M)$ $1\times(U_A)$ $1\times(U_B)$	1761.47	4.72	2.66	1.34	5.22
$3\times(U_B)$	226.35	3.52	0.12	0.3	5.08
$3\times(U_A)$	538.14	3.01	0.02	0.2	5.08

AE Studio software is a mature professional efficiency evaluation application platform has multi-function evaluation tools and supports secondary expansion development. With comprehensive efficiency evaluation method, AE Studio software can be used as an evaluation standard in the industry.

According to the statistical data results, We get the evaluation result of AE normalization, and compared with the theoretical calculation of the overall efficiency to realize its accuracy of analysis efficiency. The comparison between theoretical calculation and simulation results is shown in Tab.4-4.

Tab.4-4 THE EFFICIENCY EVALUATION VALUE COMPARISON BETWEEN THEORY AND SIMULATION

#	Mode	Efficiency Evaluation Value			
		Reconnaissance		Attack	
		Theory	Simulation	Theory	Simulation
①	$1\times(M)$ $2\times(U_B)$	0.6900	0.581	0.7948	0.784
②	$1\times(M)$ $2\times(U_A)$	0.8922	0.875	0.6999	0.412
③	$1\times(M)$ $1\times(U_A)$ $1\times(U_B)$	0.7911	0.833	0.7473	0.585
④	$3\times(U_B)$	0.3563	0.076	0.4111	0.377
⑤	$3\times(U_A)$	0.4613	0.118	0.3615	0.344

From the comparison results in the table, the efficiency ranking of reconnaissance mission is ②③①⑤④, and the highest efficiency evaluation value is 0.8922 and 0.875; The efficiency ranking of attack mission is ①③②④⑤, and the highest efficiency evaluation value is 0.7948 and 0.784. The final processing results of the simulation real data are consistent with the theoretical evaluation results, and the ranking of the attack and reconnaissance efficiency of the modes are also consistent.

Therefore, the theoretical evaluation model is quite accurate and reliable, which can provide support for the selection of attack and reconnaissance combination mode. And we can see from the statistical calculation results that the efficiency value of MAV/UAV cooperative combat mode in two missions is close to twice more than its of UAVs. Even, it has a great influence on improving the efficiency of aircraft formation combat mission once MAV join in UAVs formation combat.

V. Conclusion

Based on the research of the key technologies of MAV/UAV cooperative combat, this paper introduces MAV/UAV cooperative advantages and analysis of its cooperative mode further. Through the construction of an efficiency evaluation index system of MAV/UAV cooperative combat system, a comprehensive index evaluation model is established. For two different combat missions, the weight of single aircraft efficiency index of MAV/UAV is determined by AHP, then 100 times simulation were carried out under the same conditions. Finally, AE Studio software is used to evaluate the combat efficiency, which is compared with the conclusion of theoretical model analysis to verify the practicability of the evaluation model.

Through comparison, it can be shown that the combat efficiency of MAV/UAV cooperation is much higher than that of UAVs cooperation. The commander of MAV can adjust decision based on the battlefield situation. However, MAV/UAV cooperative combat is one of the main ways of future air combat, which involved many complex problems. In this paper, only limited factors are considered, Many the practical factors such as aircraft availability, reliability and cost-effectiveness ratio are neglected to add to the efficiency evaluation to improve the evaluation method. In order to make the evaluation result more authoritative, further discussion and analysis is very important so that the real experiment is needed and the data in practice is added to provide support for the model in future research.

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