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Combat Effectiveness Evaluation of UAV Intelligent Swarm Based on AHP-Fuzzy Comprehensive Evaluation

Yuan Li

Army University of Engineering, Shijiazhuang 050003, China

Abstract: In order to evaluate the combat effectiveness of UAV intelligent swarm, this paper puts forward the establishment of UAV intelligent swarm combat effectiveness evaluation index system based on availability, credibility and combat ability, analyzes the factors affecting the combat effectiveness of UAV intelligent swarm, establishes the effectiveness evaluation model, determines the weight of each factor by AHP, and evaluates the effectiveness index by fuzzy evaluation matrix. Using this method to evaluate the combat effectiveness of UAV intelligent swarm, the evaluation result is objective and reasonable, which provides theoretical reference for the optimal design and use of UAV intelligent swarm system.

Keywords: Efficiency evaluation, UAV intelligent swarm, AHP, fuzzy comprehensive evaluation.

1. Introduction

As a new type of combat force, the drone intelligent swarm has obvious advantages, with various capabilities such as distributed perception, target recognition, autonomous decision-making, collaborative planning and attack, and is expected to bring a new style of combat. Due to the fact that its related research is still in its early stages and lacks effective technical validation and simulation evaluation methods, it is difficult to provide support for further equipment model development. Therefore, a combined evaluation method based on AHP and fuzzy comprehensive evaluation is proposed to conduct research on the combat effectiveness evaluation of unmanned aerial vehicle intelligent swarms.

2. Evaluation Index System for Combat Effectiveness of Unmanned Aerial Vehicle Intelligent Swarm

The evaluation of the combat effectiveness of unmanned aerial vehicle intelligent swarm mainly starts from the system mission tasks and the characteristics of support use [1-3]. From the perspectives of availability, credibility, and combat capability, taking the unmanned aerial vehicle intelligent swarm combat system as the object, an evaluation index system for the combat effectiveness of unmanned aerial vehicle intelligent swarm is established.

2.1. Battlefield Mobility Capability

The battlefield mobility reflects the ability of the unmanned aerial vehicle intelligent swarm system to overcome various natural and man-made obstacles, quickly transfer positions, march quickly, and switch between marching and combat to ensure the rapid and accurate completion of tasks on the battlefield. Including maximum flight range, maximum flight speed, acceleration, maneuvering positioning accuracy, steering capability, emergency response capability, etc.

2.2. Reconnaissance and Surveillance Capability

The reconnaissance and surveillance capability reflects the ability of the unmanned aerial vehicle intelligent swarm system to detect the battlefield situation within the enemy's control range, which can be considered from the aspects of intelligence reconnaissance, battlefield link monitoring, etc. Including cruise time, target detection probability, tracking and positioning error, reconnaissance altitude, and reconnaissance distance.

2.3. Command and Control Capability

The command and control capability reflects the level of informatization of the unmanned aerial vehicle intelligent swarm system, reflecting the ability to plan, make decisions, and regulate unmanned aerial vehicles based on the battlefield situation. It can be considered from the aspects of network communication, task planning, collaborative control, including maximum communication distance, packet loss rate, transmission delay, response planning time, individual control accuracy, swarm control accuracy, etc.

2.4. Overall Protection Capability

The overall protection capability refers to the ability to comprehensively adopt various protective measures and measures to resist enemy strikes and destruction, which can be considered from the aspects of anti reconnaissance and surveillance, anti precision strike, interference and anti-interference. Including stealth efficiency, interference efficiency, protection and disposal time, anti-interference efficiency, anti damage efficiency, etc.

2.5. Firepower Strike Capability

Firepower strike capability refers to the ability to accurately strike enemy targets, which can be considered from aspects such as target coverage and comprehensive damage. Including maximum projection distance, breakthrough probability, strike accuracy, kill radius, coordinated strike time, etc.

3. Analytic Hierarchy Process[4]

3.1. Determine the weight of indicators

3.1.1. Establish a judgment matrix

By experts judging the importance of each element in the indicator system and representing it numerically, a 1-9 scale method is used here [5]. For N indicator elements, a judgment matrix Q can be formed:

$$Q=\begin{pmatrix} q_{11} & \cdots & q_{1n} \\ \vdots & \vdots & \vdots \\ q_{m1} & \cdots & q_{mn} \end{pmatrix} \tag{1}$$

3.1.2. Hierarchical Single Sorting

Hierarchical single sorting is the process of calculating the eigenvalues and eigenvectors of a judgment matrix, where the maximum eigenvalue λ max corresponds to each component of the eigenvector M as the weight of each element. Here, the root square method is used to solve λ max and M, and finally normalized to obtain the following formula:

$$QM=\begin{pmatrix} q_{11} & \cdots & q_{1n} \\ \vdots & \vdots & \vdots \\ q_{m1} & \cdots & q_{mn} \end{pmatrix}\begin{pmatrix} m_1 \\ m_2 \\ \vdots \\ m_n \end{pmatrix}=\lambda\begin{pmatrix} m_1 \\ m_2 \\ \vdots \\ m_n \end{pmatrix} \tag{2}$$

$$\overline{m_i}=\sqrt[n]{\prod_{j=1}^{n} q_{ij}} \tag{3}$$

$$m_i=\frac{\overline{m_i}}{\sum_{i=1}^{n}\overline{m_i}} \tag{4}$$

3.1.3. Consistency check [6]

Define the random consistency metric CR:

$$CR=CI/RI \tag{5}$$

Define consistency indicator CI:

$$CI=\lambda_{\max}-n/n-1 \tag{6}$$

$$\lambda_{\max}=\frac{1}{n}\sum_{i=1}^{n}\ \sum_{i=1}^{n} a_{ij}m_j \Big/ m_j \tag{7}$$

Define RI as the average random consistency index, with values shown in Table 1 [7]

Table 1. Average Random Consistency Index RI Values

Order (n)	**1**	**2**	**3**
RI	0	0	0.52
Order (n)	**4**	**5**	**6**
RI	0.89	1.12	1.26
Order (n)	**7**	**8**	**9**
RI	1.36	1.41	1.46
Order (n)	**10**	**11**	**12**
RI	1.49	1.52	1.54

Only when CR<0.1, it indicates that the consistency of the comparison matrix has passed the test. Otherwise, it is necessary to adjust the interrelationships between the elements of the judgment matrix until the consistency requirement is met.

4. Fuzzy Comprehensive Evaluation Method [8-11]

Fuzzy comprehensive evaluation is an evaluation method based on fuzzy mathematics that makes an overall assessment of things or objects that are constrained by multiple factors. The basic idea is to use membership degree instead of belonging or not belonging. To conduct fuzzy comprehensive evaluation, the following general steps need to be completed.

4.1. Determine evaluation factors and evaluation levels

Assuming $U=\{u_1,u_2,\ldots,u_n\}$ is the n evaluation indicators of the evaluated object, where n is the number of evaluation indicators. According to the attributes of the evaluation indicators, they can be divided into primary evaluation indicators and their corresponding secondary and tertiary evaluation indicators, and so on.

Assuming $V=\{v_1,v_2,\ldots,v_m\}$ is a set of evaluation levels, m is the number of levels. The purpose of the evaluation set is to clarify the effectiveness of the rating objectives in the minds of users and experts. Therefore, the following evaluation sets can be established:

V={Excellent, Good, Qualified, Poor}.

4.2. Constructing a single factor fuzzy evaluation matrix

Starting from a single factor evaluation, determine the membership degree of the evaluated object, and then obtain a single factor fuzzy evaluation matrix:

$$K=\begin{bmatrix} k_{11} & k_{12} & \ldots & k_{1n} \\ k_{21} & k_{22} & \ldots & k_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ k_{m1} & k_{m1} & \ldots & k_{mn} \end{bmatrix} \tag{8}$$

4.3. Comprehensive evaluation of multiple factor indicators

The fuzzy comprehensive evaluation model can be obtained as follows:

$$A=\eta\circ K=(\eta_1,\eta_2,\ldots\eta_m)\begin{bmatrix} k_{11} & k_{12} & \ldots & k_{1n} \\ k_{21} & k_{22} & \ldots & k_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ k_{m1} & k_{m1} & \ldots & k_{mn} \end{bmatrix}=(a_1,a_2,\ldots a_n) \tag{9}$$

Among them, η is the weight vector.

4.4. Analysis of Fuzzy Comprehensive Evaluation Results

(1) The principle of maximum membership can be adopted to compare the sizes of $(a_1,a_2,\ldots a_n)$, and the largest comparison size is the quantitative evaluation result of the combat effectiveness of the unmanned aerial vehicle intelligent swarm system, while the corresponding evaluation set is the qualitative evaluation result.

(2) Using the weighted average principle, it is expressed as:

$$a_j = \sum_{i=1}^{n} b_i k_{ij} \tag{10}$$

Among them , $b_i \, (i = 1, 2, \ldots, n)$ are the weights of each factor.

5. UAV Intelligent Swarm Combat Effectiveness Evaluation System

Adopting a comprehensive approach of AHP and fuzzy theory for combat effectiveness evaluation, combining qualitative and quantitative methods, using AHP to provide weight coefficients, and using fuzzy theory for final evaluation.

5.1. Determination of Weight Coefficient

Hire more than 10 experts to engage in professional work such as equipment demonstration, experimental appraisal, scientific research and teaching, and command training. Evaluate and score the five primary indicators of overall mobility, battlefield protection, firepower strike, command and control, and reconnaissance and surveillance capabilities, as well as their corresponding secondary indicators, using the Analytic Hierarchy Process importance comparison method. The final scoring result will be based on the opinions of the majority of experts, in order to determine the weights of each indicator.

5.1.1. Weight of primary indicators

The importance rating of primary indicators by experts is shown in Table 2.

Table 2. Weight Judgment Table for Primary Indicators

Capability indicators	mobility	monitor	command	protection	strike
mobility	1	1/3	1/3	1	5
monitor	3	1	1	3	1/3
command	3	1	1	3	1/3
protection	1	1/3	1/3	1	1/5
strike	5	3	3	5	1

The element relationships between the indicators filled in by experts are abstracted and organized into a judgment matrix. The judgment matrix for a certain indicator is as follows:

$$P = \begin{bmatrix} 1 & 1/3 & 1/3 & 1 & 1/5 \\ 3 & 1 & 1 & 3 & 1/3 \\ 3 & 1 & 1 & 3 & 1/3 \\ 1 & 1/3 & 1/3 & 1 & 1/5 \\ 5 & 3 & 3 & 5 & 1 \end{bmatrix}$$

Using the root mean method to calculate the eigenvector Mi of the maximum eigenvalue of the corresponding decision matrix:

$$M_1 = \sqrt[5]{1 \times \frac{1}{3} \times \frac{1}{3} \times 1 \times \frac{1}{5}} = 0.467$$

$$M_2 = \sqrt[5]{3 \times 1 \times 1 \times 3 \times \frac{1}{3}} = 1.246$$

$$M_3 = \sqrt[5]{3 \times 1 \times 1 \times 3 \times \frac{1}{3}} = 1.246$$

$$M_4 = \sqrt[5]{1 \times \frac{1}{3} \times \frac{1}{3} \times 1 \times \frac{1}{5}} = 0.467$$

$$M_5 = \sqrt[5]{5 \times 3 \times 3 \times 5 \times 1} = 2.954$$

Perform normalization processing:

$$\sum_{i=1}^{5} M_i = 0.467 + 1.246 + 1.246 + 0.467 + 2.954 = 6.38$$

Calculate the weights of each of these 5 indicators:

$$M_1^{\xi} = \frac{M_1}{\sum_{i=1}^{5} M_i} = 0.073 \qquad M_2^{\xi} = \frac{M_2}{\sum_{i=1}^{5} M_i} = 0.195$$

$$M_3^{\xi} = \frac{M_3}{\sum_{i=1}^{5} M_i} = 0.195 \qquad M_4^{\xi} = \frac{M_4}{\sum_{i=1}^{5} M_i} = 0.073$$

$$M_5^{\xi} = \frac{M_5}{\sum_{i=1}^{5} M_i} = 0.464$$

Therefore, the eigenvector: MO '=[0.073, 0.195, 0.195, 0.073, 0.464], corresponding to the maximum eigenvalue

λmax=5.055. The consistency index of the judgment matrix is CI=0.014, and the relative consistency index CR=CI/RI=0.012<0.10, which meets the consistency requirements.

5.1.2. Secondary Indicator Weights

The expert's scoring of the importance of the secondary indicators under the five primary indicators. Abstracting the relationship between indicator elements filled in by experts into a judgment:

$$P_1 = \begin{bmatrix} 1 & 1/3 & 1/3 & 1/5 & 1 & 1 \\ 3 & 1 & 1 & 1/3 & 3 & 3 \\ 3 & 1 & 1 & 1/3 & 3 & 3 \\ 5 & 3 & 3 & 1 & 5 & 5 \\ 1 & 1/3 & 1/3 & 1/5 & 1 & 1 \\ 1 & 1/3 & 1/3 & 1/5 & 1 & 1 \end{bmatrix} \quad P_2 = \begin{bmatrix} 1 & 1 & 1/3 & 3 & 3 \\ 1 & 1 & 1/3 & 3 & 3 \\ 3 & 3 & 1 & 5 & 5 \\ 1/3 & 1/3 & 1/5 & 1 & 1 \\ 1/3 & 1/3 & 1/5 & 1 & 1 \end{bmatrix}$$

$$P_3 = \begin{bmatrix} 1 & 5 & 5 & 7 & 3 & 3 \\ 1/5 & 1 & 1 & 3 & 1/3 & 1/3 \\ 1/5 & 1 & 1 & 3 & 1/3 & 1/3 \\ 1/7 & 1/3 & 1/3 & 1 & 1/5 & 1/5 \\ 1/3 & 3 & 3 & 5 & 1 & 1 \\ 1/3 & 3 & 3 & 5 & 1 & 1 \end{bmatrix} \quad P_4 = \begin{bmatrix} 1 & 1 & 1/3 & 1/5 & 1/5 \\ 1 & 1 & 1/3 & 1/5 & 1/5 \\ 3 & 3 & 1 & 1/3 & 1/3 \\ 5 & 5 & 3 & 1 & 1 \\ 5 & 5 & 3 & 1 & 1 \end{bmatrix}$$

$$P_5 = \begin{bmatrix} 1 & 1/3 & 1/7 & 1/3 & 1/3 \\ 3 & 1 & 1/3 & 1 & 1 \\ 7 & 3 & 1 & 3 & 3 \\ 3 & 1 & 1/3 & 1 & 1 \\ 3 & 1 & 1/3 & 1 & 1 \end{bmatrix}$$

According to the calculation method of the weight eigenvectors and maximum eigenvalue of the secondary indicators mentioned above, it can be concluded that:

Eigenvector

$$W_{P1}^{\xi} = \begin{bmatrix} 0.069 & 0.186 & 0.186 & 0.416 & 0.069 & 0.074 \end{bmatrix}$$

corresponding to the maximum eigenvalueλ max=6.188. The indicator for judging matrix consistency is CI=0.038, and the relative consistency index CR=CI/RI=0.03<0.10, which meets the consistency requirements.

Eigenvector

$$W_{P2}^{\xi} = \begin{bmatrix} 0.195 & 0.195 & 0.464 & 0.073 & 0.073 \end{bmatrix}$$

corresponding to the maximum eigenvalue λ max=5.055. The indicator for judging matrix consistency is CI=0.014, and the relative consistency index CR=CI/RI=0.012<0.10, which meets the consistency requirements.

Eigenvector

$$W_{P3}^{\xi} = \begin{bmatrix} 0.420 & 0.078 & 0.078 & 0.036 & 0.194 & 0.194 \end{bmatrix}$$

corresponding to the maximum eigenvalue λ max=6.143. The index CI for judging matrix consistency is 0.028, and the relative consistency index CR is CI/RI=0.023<0.10, which meets the consistency requirements.

Eigenvector

$$W_{P4}^{\xi} = \begin{bmatrix} 0.064 & 0.064 & 0.152 & 0.360 & 0.360 \end{bmatrix}$$

corresponding to the maximum eigenvalue λ max=5.055. The indicator for judging matrix consistency is CI=0.014, and the relative consistency index CR=CI/RI=0.012<0.10, which meets the consistency requirements.

Eigenvector

$$W_{P5}^{\xi} = \begin{bmatrix} 0.057 & 0.161 & 0.460 & 0.161 & 0.161 \end{bmatrix}$$

corresponding to the maximum eigenvalue λ max=5.088. The indicator for judging matrix consistency is CI=0.002, and the relative consistency index CR=CI/RI=0.002<0.10, which meets the consistency requirements.

5.2. Adaptive evaluation based on fuzzy theory

5.2.1. Determine the evaluation factor set and evaluation set

To evaluate using fuzzy theory, the first step is to determine the evaluation factor set and the evaluation set. As shown in Figure 1, the factor set can be divided into two layers, as shown in Table 3.

Table 8. Secondary evaluation factors for combat effectiveness of unmanned aerial vehicle intelligent swarm system

First level evaluation factors	Second level evaluation factors
Battlefield maneuverability	Maximum flight range
	Maximum flight speed
	acceleration
	Precision of maneuvering positioning
	Turnability
	Emergency capability
	Cruise Time
Reconnaissance and surveillance capability	Discovery Target Probability
	Tracking and positioning error
	Reconnaissance height
	Reconnaissance distance
	Maximum communication distance
	Packet loss rate
Command and control capability	Transmission latency
	Response planning time
	Individual control accuracy
	Swarm control accuracy
Overall protection capability	Stealth Efficiency
	Interference efficiency
	Protective Disposal Time
	Anti-interference efficiency
	Anti-damage efficiency
Fire strike capability	Maximum Projection Distance
	Probability of breakout
	Impact accuracy
	Radius of kill
	Synergistic strike time

Six factor sets can be obtained:

First level factor set:

M={Battlefield mobility, reconnaissance and surveillance capabilities, command and control capabilities, overall protection capabilities, firepower strike capabilities}

Second level factor set:

M1={Maximum Flight Range, Maximum Flight Speed, Acceleration, Maneuvering Positioning Accuracy, Steering Ability, Emergency Capability}

M2={cruise time, target detection probability, tracking and positioning error, reconnaissance altitude, reconnaissance distance}

M3={Maximum communication distance, packet loss rate, transmission delay, response planning time, individual control accuracy, swarm control accuracy}

M4={stealth efficiency, interference efficiency, protection and disposal time, anti-interference efficiency, anti damage efficiency}

M5={maximum projection distance, breakthrough probability, strike accuracy, kill radius, coordinated strike time}.

5.2.2. Construct a judgment matrix and calculate the evaluation results

The fuzzy comments for each evaluation indicator can be obtained from the above method. Based on the values, the following fuzzy transformations can be performed:,.

$$A_i = W_{P_i}^{\xi} \bullet K_i,\ i = 1, 2, \ldots, n.$$

Fuzzy comments on the evaluation indicators P in the first layer:

$$A_1 = M_1^{\xi} \bullet K_1 = (0.069\ 0.186\ 0.186\ 0.416\ 0.069\ 0.074) \bullet \begin{bmatrix} 0.4 & 0.3 & 0.2 & 0.1 \\ 0.3 & 0.3 & 0.2 & 0.2 \\ 0.3 & 0.3 & 0.3 & 0.1 \\ 0.4 & 0.4 & 0.1 & 0.1 \\ 0.5 & 0.3 & 0.1 & 0.1 \\ 0.3 & 0.2 & 0.3 & 0.2 \end{bmatrix}$$

$$= (0.3623\ 0.3342\ 0.1775\ 0.1260)$$

Similarly, the following values can be obtained:

$$A_2 = (0.3731\ 0.2878\ 0.2122\ 0.1269)$$

$$A_3 = (0.4342\ 0.3388\ 0.1156\ 0.1114)$$

$$A_4 = (0.3128\ 0.3000\ 0.2152\ 0.1720)$$

$$A_5 = (0.3943\ 0.3517\ 0.1379\ 0.1161)$$

Combining A_i into Primary Judgement Matrix $A = [A_1, A_2, A_3, A_4, A_5]$, Then the second-level evaluation matrix is (weighted algorithm)[12] :

$$B = M_i^{\xi} A = (0.3897\ 0.3317\ 0.1566\ 0.1221)$$

The above results show that for the collaborative combat effectiveness of the drone intelligent swarm, 39% of people think it is excellent, 33% think it is good, 16% think it is qualified, and 12% think it is poor. The corresponding scores of the evaluation set are shown in Table 9 [13].

Table 10. Evaluation set and assignment score situation

Evaluation Set	**Excellent**	**Good**	**Qualified**	**Poor**
Assigned value	100	80	60	40

Finally, it is known that the score of the intelligent swarm cooperative combat system of the UAV is:

$$\omega = (0.3897\ 0.3317\ 0.1566\ 0.1221) \bullet \begin{bmatrix} 100 \\ 80 \\ 60 \\ 40 \end{bmatrix} = 79.786$$

6. Conclusion

This article analyzes multiple factors that affect the combat effectiveness of unmanned aerial vehicle intelligent swarm systems, establishes a comprehensive effectiveness evaluation system model, and combines the Analytic Hierarchy Process and Fuzzy Comprehensive Evaluation Method to provide ideas and methods for evaluating the combat effectiveness of unmanned aerial vehicle intelligent swarm systems. The evaluation results have a certain objectivity and can provide a basis for optimizing and developing unmanned aerial vehicle intelligent swarm systems in the next step.

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