Effectiveness Evaluation of Anti-terrorism Operation of Small Unmanned Aerial Vehicle with Integrated Detection and Attack

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Abstract: Small unmanned aerial vehicle UAV is playing an increasingly important role in the anti-terrorism operation of the armed police. How to accurately evaluate its anti-terrorism operational effectiveness in order to achieve its optimal configuration and efficient use in the anti-terrorism operation has become the focus of current research. By using the fuzzy analytic hierarchy process, the effectiveness evaluation model of its anti-terrorism operation is established, which is quantified by combining qualitative indicators with quantitative indicators, and evaluated with an example. Finally, combined with data analysis, some suggestions are put forward to further improve the effectiveness of its anti-terrorism operations, which will provide theoretical support for the better use of this kind of UAV in the next anti-terrorism operations.

Keywords: Reconnaissance and Strike Integrated UAV; Anti-Terrorism Operation; Fuzzy Hierarchy Evaluation Method; Evaluation Model; Operational Effectiveness

1. Introduction

In recent years, under China's sustained high-pressure crackdown on terrorism, a small number of terrorists have infiltrated plateau and mountainous regions, attempting to hide in complex terrains and seize opportunities to launch terrorist criminal activities, posing severe challenges to China's security and stability. In 2021, during the Afghan anti-terrorism war, drones were first used to carry weapons to attack ground targets, ushering in a new era of "integrated reconnaissance and strike" capabilities [1]. Small reconnaissance and strike integrated UAVs, as an emerging type of weaponry, have gradually become versatile tools for performing anti-terrorism tasks such as reconnaissance, communication relay, and firepower strikes. They can provide special operations teams with efficient and precise intelligence support and powerful firepower strike capabilities. Currently, most evaluations of UAV effectiveness focus solely on the UAV itself, without considering the diverse missions it performs. However, battlefield missions are diverse. For example, even for time-sensitive reconnaissance and strike missions, the requirements for UAV performance indicators may vary depending on the time, space, and the situation between enemy and friendly forces [2]. By introducing the fuzzy analytic hierarchy process into the evaluation of UAV anti-terrorism operational effectiveness, this paper constructs a comprehensive evaluation index system for the anti-terrorism operational effectiveness of small reconnaissance and strike integrated UAVs and proposes a comprehensive evaluation method. Practical applications have proven the method's practicality and operability.

2. Introduction to the Fuzzy Analytic Hierarchy Process

The Fuzzy Analytic Hierarchy Process (FAHP) represents a sophisticated evaluation methodology that harmoniously integrates the Fuzzy Comprehensive Evaluation Method with the Analytic Hierarchy Process (AHP), bridging the gap between quantitative and qualitative analyses. The AHP serves as a pivotal tool for assigning weights to indicators within a hierarchical framework. Once the indicator system is meticulously established, the journey unfolds through the construction of a judgment matrix, the calculation of the maximum eigenvalue, the execution of hierarchical single sorting, and the rigorous consistency check. The FAHP excels in assessing intricate problems that span multiple factors and levels, delivering results that are rich in information and transcend the confines of traditional mathematical methods, which often yield simplistic, single-valued outcomes. The core steps of the FAHP encompass the formulation of the factor set U pertaining to the evaluation object, the establishment of the evaluation set V, the crafting of the single-factor evaluation matrix R, the determination of the weight distribution A, and the ultimate conduct of the evaluation [3].

3. Application of the Fuzzy Analytic Hierarchy Process to Evaluate the Anti-Terrorism Operational Effectiveness of Small Reconnaissance and Strike Integrated UAVs

3.1 Construction of the Anti-Terrorism Operational Effectiveness Index System for Small Reconnaissance and Strike Integrated UAVs

Based on an in-depth analysis of the essential components contributing to the counter-terrorism operational efficacy of small reconnaissance and strike unmanned aerial vehicles (UAVs), and integrating insights from an exploration of UAV counter-terrorism operational characteristics alongside counter-terrorism exercise scenarios, this study has meticulously discerned four pivotal elements that exert a substantial influence on the operational prowess of these UAVs in counter-terrorism contexts. These elements encompass command and control communication proficiencies, reconnaissance and search adeptness, firepower strike capabilities, and mobility coupled with survivability. Each of these core indicators has been meticulously decomposed into a multitude of subordinate indicators, tailored to their unique attributes, thereby crafting a holistic and comprehensive evaluation index system for assessing the counter-terrorism operational effectiveness of small reconnaissance and strike UAVs. This system is depicted in Figure 1, with due reference to pertinent literature [4-10].

1) Command, Control, and Communication Capabilities: This refers to the commanders' adeptness in conveying information with precision, efficiency, timeliness, and reliability through the sophisticated command and control communication system amidst UAV counter-terrorism operations. This capability empowers the seamless management and control of UAVs, ensuring the successful execution of combat missions. It primarily encompasses a keen situational awareness, proficient command and control skills, and robust auxiliary decision-making abilities.

2) Reconnaissance and Search Capabilities: This refers to the ability of unmanned aerial vehicles (UAVs) to carry advanced reconnaissance equipment, such as infrared thermal imagers and high-definition cameras, enabling real-time tracking, localization, and prediction of target trajectories of terrorist activities under long-distance, complex terrain, and adverse weather conditions. This capability primarily encompasses detection capability, tracking capability, and identification and localization capability.

3) Firepower Strike Capabilities: This refers to the UAV's ability to conduct high-precision strikes against terrorists. The evaluation indicators include destructive power, accuracy, and operational capabilities. Operational capabilities include bomb-loading time, bomb-loading equipment, personnel requirements for bomb-loading, and mean time between failures.

4) Maneuverability and Survivability: This refers to the UAV's ability to move quickly and avoid obstacles in various complex environments. Its evaluation indicators are categorized into maneuverability, environmental adaptability, and endurance capability.

3.2 Establishment of the Evaluation Set

Based on the evaluation needs, the evaluation set is divided into four levels: Excellent (v_1), Good (v_2), Average (v_3), and Poor (v_4). The evaluation language set is as follows:

$$V = \{v_1, v_2, v_3, v_4\} \quad (1)$$

3.3 Construction of the Judgment Matrix

After establishing the hierarchical structure model for the anti-terrorism operational effectiveness of small reconnaissance and strike integrated UAVs, the four first-level indicators C_1, C_2, C_3, and C_4 are used as criteria to construct the second-level indicators D_1, $D_2 \ldots D_i$ (where i=1,2...12). When constructing the judgment matrix, 10 experts were invited to score the relative importance of each capability in the context of anti-terrorism operations using small reconnaissance and strike integrated UAVs.

The classic 1-9 scale method was used, with the meanings shown in Table 1.

The maximum eigenvalue λ was calculated by inputting the judgment matrix into the cloud computing network. The weight vector corresponds to the eigenvector of the maximum eigenvalue λ_{max} of the judgment matrix, and after normalization, the weights for each capability are ω.

3.4 Consistency Check

Calculate the consistency index *CI*:

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \quad (2)$$

Where *n* is the order of the judgment matrix.

In Table 2, *n* is the order of the judgment matrix, and the average random consistency index *RI* can be queried.

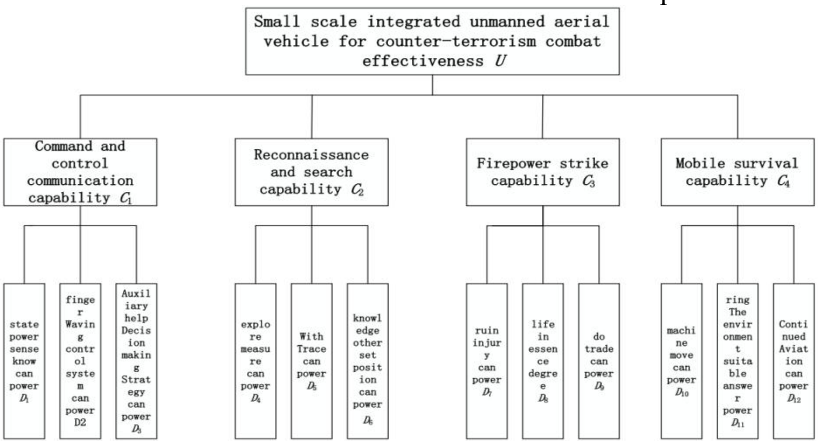

Figure 1. Structural Model of Anti-terrorism Operational Effectiveness of Small Unmanned Aerial Vehicle with Integrated Detection and Attack

Table 1. 1-9 Scaling Method

Scale	Meaning
1	Indicates that factor u_i is equally important as factor u_j
3	Indicates that factor u_i is slightly more important than factor u_j
5	Indicates that factor u_i is significantly more important than factor u_j
7	Indicates that factor u_i is strongly more important than factor u_j
9	Indicates that factor u_i is extremely more important than factor u_j
2,4,6,8 (Reciprocal)	Represents intermediate values between the two adjacent scales. If the importance ratio of factor u_i to factor u_j is v_{ij}, then the importance ratio of factor u_j to factor u_i is $1/v_{ij}$.

Table 2. Average Random Consistency Index Value

ORDER *n*	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

Calculate the consistency ratio *CR*:

$$CR = \frac{CI}{RI} \quad (3)$$

When $CR < 0.1$, the judgment matrix is consistent; otherwise, if $CR \geq 0.1$, the judgment matrix does not meet the consistency check.

3.5 Determination of the Weight Vector

The Analytic Hierarchy Process (AHP) is employed to ascertain the weights of the factor sets at each hierarchical level. Based on the Saaty scaling method, pairwise comparisons are conducted among the elements within the same level of the evaluation index system for the counter-terrorism combat effectiveness of small reconnaissance and strike integrated unmanned aerial vehicles (UAVs), and the judgment matrix was constructed to determine the corresponding indicator weights. The first-level factor set *U* and the second-level factor sets C_1、C_2、C_3 and C_4 have their respective judgment matrices, as presented in Tables 3 through 7. The maximum eigenvalues λ_{max} of the judgment matrices for each level of the factor set were solved using the cloud computing network, and the consistency index *CI* was calculated using formula (1). The average random consistency index *RI* is retrieved from Table 2 based on the order *n* of the judgment matrix, and is substituted into

Equation (3) to derive the consistency ratio *CR*. The computation results indicate that $CR<0.1$, confirming that all judgment matrices meet the consistency requirements.

Table 3. Judgment Matrix *U*

U	C_1	C_2	C_3	C_4	ω_0
C_1	1	2	3	4	0.8135
C_2	1/2	1	2	3	0.4826
C_3	1/3	1/2	1	2	0.2787
C_4	1/4	1/3	1/2	1	0.1661
Consistency check: n=4, λ_{max}=4.0310, CI=0.0103, RI=0.9, CR= 0.011<0.1					

Table 4. Judgment Matrix *C*₁

C_1	D_1	D_2	D_3	ω_1
D_1	1	2	3	0.8468
D_2	1/2	1	2	0.4660
D_3	1/3	1/2	1	0.2565
Consistency check: n=3, λ_{max}=3.0092, CI=0.0046, RI=0.58, CR= 0.008<0.1				

Table 5. Judgment Matrix *C*₂

C_2	D_4	D_5	D_6	ω_2
D_4	1	4	3	0.9154
D_5	1/4	1	1/2	0.1999
D_6	1/3	2	1	0.3493
Consistency check: n=3, λ_{max}=3.0183, CI=0.009, RI=0.58, CR= 0.0158<0.1				

Table 6. Judgment Matrix *C*₃

C_3	D_7	D_8	D_9	ω_3
D_7	1	1/3	2	0.3493
D_8	3	1	4	0.9154
D_9	1/2	1/4	1	0.1999
Consistency check: n=3, λ_{max}=3.0183, CI=0.009, RI=0.58, CR=0.0158<0.1				

Table 7. Judgment Matrix *C*₄

C_4	D_{10}	D_{11}	D_{12}	ω_4
D_{10}	1	1/3	1/2	0.2565
D_{11}	3	1	2	0.8468
D_{12}	2	1/2	1	0.4660
Consistency check: n=3, λ_{max}=3.0092, CI=0.0046, RI=0.58, CR= 0.008<0.1				

After normalization:

The weight vector for the first-level factor set ***U*** is:

$$A = (0.4673, 0.2772, 0.1601, 0.0954) \tag{4}$$

The weight vectors for the second-level factor sets $\boldsymbol{C_1}$ to $\boldsymbol{C_4}$ are:

$$\begin{cases} A_1 = (0.5396, 0.2969, 0.1635) \\ A_2 = (0.6250, 0.1365, 0.2385) \\ A_3 = (0.2385, 0.6250, 0.1365) \\ A_4 = (0.1635, 0.5396, 0.2969) \end{cases} \tag{5}$$

3.6 Determination of the Single-Factor Evaluation Set

Based on the performance of a particular small reconnaissance and strike integrated unmanned aerial vehicle (UAV) during a counter-terrorism exercise, we enlisted the expertise of 10 seasoned professionals took who part in the drill to assess its combat effectiveness in counter-terrorism operations. Drawing upon the UAV's proficiency in executing the mission, its qualitative indicators were rated on a scale, with grades ranging from "Excellent" (90≤P≤100) to "Poor" (0≤P<60), as illustrated in Table 8, which showcases the expert scores for selected qualitative aspects. The quantitative indicators, on the other hand, were categorized into two distinct types: benefit-oriented indicators, where a higher test value signifies enhanced combat prowess, and cost-oriented indicators, where a lower value denotes superior capability. To ensure accuracy, we consulted with special forces personnel who boast extensive experience in UAV exercises, and based on their insights, we classified the single-factor quantitative indicators into grades. Taking into account key data indicators such as flight speed, combat radius, effective payload, effective kill range, wind resistance, temperature adaptability, endurance time, and hit area radius, we established grade ranges and conducted evaluations according to the tiers of "Excellent", "Good", "Average", and "Poor". This comprehensive assessment is presented in Table 9, while the correlation between these data indicators and combat capabilities is elegantly mapped out in Table 10.

$$\begin{cases} \boldsymbol{Z}_{Benefit} = 100 \times \frac{Y_i}{\boldsymbol{P_{max}}} \\ Z_{Cost} = 100 \times \frac{\boldsymbol{P_{max}} - Y_i}{\boldsymbol{P_{max}}} \end{cases} \tag{6}$$

Taking the environmental adaptability index as an example, first calculate the weights of the subordinate indicators. Subsequently, the numerical values of the tested quantitative indicators are computed to obtain corresponding scores. Finally, each score is multiplied by its respective weight vector, and the results are summed to obtain the capability value. Specifically, the wind resistance capability is denoted as E_t, the temperature adaptability capability as E_b, and the stability capability of the reconnaissance altitude is

represented by E_h, as shown in Table 11.
Similarly, the following scores can be obtained: the damage capability scores 87.5, the hit accuracy scores 80, the operational capability scores 84, the maneuverability capability scores 90.6, and the endurance capability scores 60.

Table 8. Expert Scoring Statistics

Indicator \ Expert	1	2	3	4	5	6	7	8	9	10	X
Situation Awareness Capability	88	87	81	85	83	82	82	85	86	83	84.1
Command and Control Capability	71	79	80	78	75	77	78	79	79	76	77.6
Decision Support Capability	72	72	67	73	73	70	69	70	72	71	71.1
Detection capability	85	88	86	81	83	87	87	86	88	86	86
Tracking Capability	78	81	85	86	80	79	80	79	83	85	81.5
Identification and Localization Capability	78	80	79	79	82	77	81	83	82	79	80
Remove the maximum and minimum values from each row, sum up the remaining values, and then calculate the average to obtain the mean value X											

Table 9. Single-factor Index Grading

Parameter p \ Evaluation	Good	Better	Average	Bad
Flight speed v meters per second	15＜ v ≤20	10＜ v ≤15	5＜v≤10	v≤5
Combat radius r meters	10＜r≤12	8≤r≤10	5≤r＜8	r＜5
Effective payload m kilograms	20＜m≤25	15＜r≤20	5＜r≤15	r≤5
Effective killing range \(s\) meters	10＜s≤12	8≤s≤10	6＜s＜8	s≤6
Wind resistance ability, Grade b	6＜b≤7	5＜b≤6	4＜b≤5	b≤4
Adaptable temperature t degrees	-40≤t≤40	-30≤t≤30	-25≤t≤25	-20≤t≤20
Endurance time m minutes	70＜m	50＜m≤70	40≤m≤50	m＜40
Reconnaissance stability: h kilometers	h＜0.5	0.5≤h≤2	2＜h＜4	4≤h
Radius of the hit area smeters	s≤3	3＜s≤6	6＜s≤30	30＜s
Time taken to destroy the target: \(n\) minutes	m＜3	3≤m≤5	5＜m≤25	25＜m

Table 10. Data Index Mapping Ability of a Small UAV with Integrated Inspection and Shooting

Test data Y \ Capability	Damage Capability	Firing accuracy	Operational ability	Maneuverability	Environmental adaptability	Endurance
Flight speed: 18 meters per second				√		
Combat radius: 11 kilometers				√		
Effective payload: 25 kilograms	√					
Endurance: 42 minutes						√
Effective killing range: 10 meters	√					
Wind resistance ability: Grade 6					√	
It can adapt to temperatures ranging from -33°C to 40°C.					√	
Reconnaissance altitude: 0.4 km					√	
Radius of the hit area: 6 meters		√				
Payload loading time: 4 minutes			√			

Table 11. Judgment Matrix D_{11}

D_{11}	E_t	E_b	E_h	ω	dimensionality reduction	Z
E_t	1	2	3	0.5396	6/7	85.7
E_b	1/2	1	2	0.2969	33/40	82.5
E_h	1/3	1/2	1	0.1635	0.9	90
Consistency Check: n=3, λ_{max}=3.0092, CI=0.0046, RI=0.58, CR= 0.008<0.1						

$$E_{Environment} = A_{Environment} \times R_{Environment}$$

$$= (0.5396, 0.2969, 0.1635) \cdot \begin{bmatrix} 85.7 \\ 82.5 \\ 90 \end{bmatrix} = 85.5 \quad (7)$$

3.7 Calculate the Evaluation Score

Carry out the first-level fuzzy evaluation for the second-layer indicators. The process is as follows:

$$B_1 = A_1 \times R_1 = (0.5396, 0.2969, 0.1635) \begin{bmatrix} 84.1 \\ 77.6 \\ 71.1 \end{bmatrix} = 80 \quad (8)$$

Similarly, the first-level fuzzy evaluations of C2 to C5 can be obtained successively as follows:

$$\begin{cases} B_2 = A_2 \times R_2 \\ = (0.6250, 0.1365, 0.2385) \cdot \begin{bmatrix} 86 \\ 81.5 \\ 80 \end{bmatrix} = 83.9 \\ B_3 = A_3 \times R_3 \\ = (0.2385, 0.6250, 0.1365) \cdot \begin{bmatrix} 87.5 \\ 80 \\ 84 \end{bmatrix} = 82.3 \\ B_4 = A_4 \times R_4 \\ = (0.1635, 0.5396, 0.2969) \cdot \begin{bmatrix} 90.6 \\ 85.5 \\ 60 \end{bmatrix} = 78.8 \end{cases} \quad (9)$$

Second-Level Fuzzy Evaluation

Combine the Bi to form the second-level evaluation matrix:

$$R = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix} \quad (10)$$

Thus, the second-level fuzzy evaluation can be calculated as B:

$$B = A \times R = (0.4673, 0.2772, 0.1601, 0.0954) \cdot \begin{bmatrix} 80 \\ 83.9 \\ 82.3 \\ 78.8 \end{bmatrix} = 81.3 \quad (11)$$

The calculated score for the counter-terrorism combat effectiveness of a particular unmanned aerial vehicle (UAV) is 81.3, which is evaluated as "good". Specifically, the command and communication control capability scores 80, the reconnaissance and search capability scores 83.9, the firepower strike capability scores 82.3, and the maneuverability and survival capability scores 78.8. It can be concluded that the UAV's secondary indicators of command and communication control capability, reconnaissance and search capability, and firepower strike capability are all rated as "good", while the maneuverability and survival capability is at an average level. The capability of its tertiary indicators is illustrated in Figure 2.

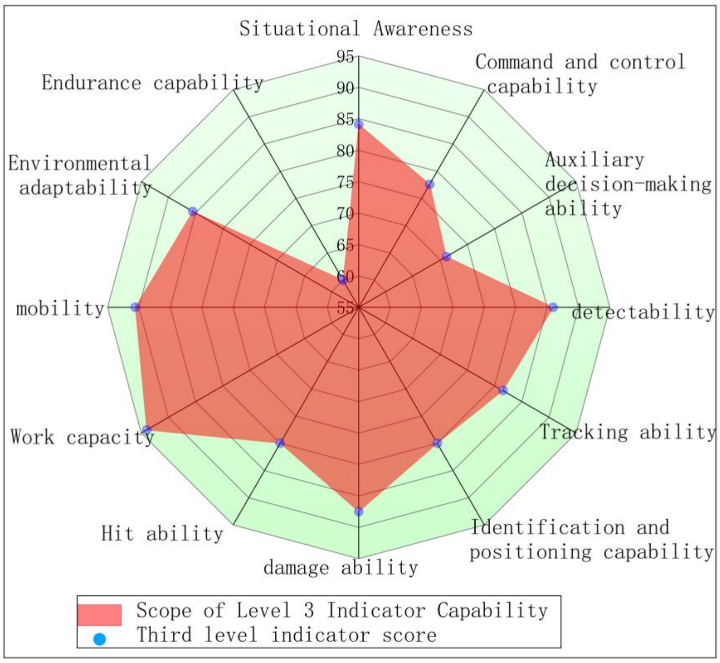

Figure 2. Three-level Index Capability Radar Chart

4. Conclusion

For the assessment of counter-terrorism combat effectiveness of small reconnaissance and strike integrated unmanned aerial vehicles (UAVs), a bespoke evaluation index system has been meticulously crafted, upon which a quantitative evaluation model is firmly established. By leveraging the Fuzzy Analytic Hierarchy Process (FAHP), this model offers a tangible yardstick for gauging the UAVs' prowess in counter-terrorism operations, serving as a valuable guide for refining their operational capabilities. The FAHP adeptly tackles the intricate task of quantifying and appraising the counter-terrorism combat effectiveness of these versatile UAVs. To embark on this endeavor, 10 esteemed experts were enlisted to scrutinize and evaluate the factor sets at each tier of the judgment matrix. Following their diligent work, special operations experts who had firsthand experience in the exercise were summoned to assign scores to various qualitative indicators of the UAVs' combat effectiveness and compute scores for select quantitative indicators. Ultimately, a fuzzy evaluation of the counter-terrorism combat effectiveness indicators was carried out, yielding results that are notably objective and reliable. It bears mentioning that the significance of various combat effectiveness indicators may fluctuate according to the specific counter-terrorism missions undertaken in diverse geographical terrains, underscoring the importance of a tailored approach to each unique scenario. The computation results reveal that the UAV's counter-terrorism combat effectiveness score, as ascertained by the FAHP, stands at 81.3, a commendable rating of "good". A thorough analysis of the data uncovers that the UAV's maneuverability and survival capability, along with its auxiliary decision-making prowess, are deemed average. The primary deficiencies lie in its inadequate endurance, feeble reconnaissance and communication signals in plateau and mountainous regions, and the adverse impact of oxygen concentration and airflow on its stability. Hence, future endeavors should concentrate on advancing battery endurance technology, optimizing the flight control system, enhancing flight stability, and bolstering communication support.

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