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UAV Combat Effectiveness Evaluation in Complex Mountain Environments Based on AHP-EWM

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Abstract: To address the challenge of evaluating the operational effectiveness of unmanned aerial vehicle (UAV) cooperative reconnaissance and strike missions against ground tactical targets in complex mountainous environments, this study constructs a scientific and highly adaptive comprehensive evaluation framework. Based on a subjective-objective combined weighting strategy integrating the Analytic Hierarchy Process (AHP) and the Entropy Weight Method (EWM), a multi-dimensional comprehensive evaluation index system is established, which covers six core dimensions: information acquisition, target recognition, command and decision-making, strike effectiveness, cooperative efficiency, and mountain adaptability. Weighting results indicate that strike effectiveness and mountain adaptability are the dominant dimensions that determine the overall operational effectiveness of UAVs. Specifically, the terrain-corrected circular error probable and the terrain-matched flight index occupy core positions in the strike effectiveness and mountain adaptability dimensions, respectively. This proposed framework provides an operable theoretical foundation and practical guidance for the quantitative evaluation of UAV cooperative reconnaissance and strike effectiveness, identification of system shortcomings, optimization of resource allocation, and formulation of tactical decisions in complex mountainous environments.

Keywords: Complex Mountainous Environment; UAV; Cooperative Reconnaissance and Strike; Operational Effectiveness Evaluation; AHP-EWM; Evaluation Index System.

1. Introduction

With the development of UAV operations towards "clustering and intelligence", when performing cooperative reconnaissance and strike missions in complex mountainous environments, UAVs are faced with severe challenges such as signal attenuation caused by terrain occlusion, dynamic electromagnetic interference, and multi-UAV mission allocation conflicts. Constructing a scientific operational effectiveness evaluation system is of great significance for optimizing resource allocation and improving tactical decision-making levels [1-2].

At present, the existing operational effectiveness evaluation index systems have significant limitations in application to complex mountainous environments: insufficient environmental adaptability, generally lacking targeted consideration of mountain terrain (such as slope effect and occlusion effect) and special electromagnetic and meteorological environments; weakened dynamic antagonism, failing to effectively quantify the effectiveness attenuation of enemy active interference on key links such as reconnaissance, communication, and positioning; insufficient interpretability and verifiability, and the evaluation results are often difficult to directly correlate with specific tactical shortcomings [3-4]. In addition, most existing methods adopt a single weighting strategy, which is difficult to balance the complementarity between expert experience and data-driven, resulting in insufficient rationality and robustness of index weights.

Aiming at the above problems, this study focuses on the characteristics of complex mountainous environments and the requirements of UAV cooperative reconnaissance and strike missions, and constructs an evaluation system with environmental pertinence, index quantifiability and comprehensive effectiveness. The research contents include: strengthening environmental adaptability by adding the mountain adaptability dimension and indicators such as the terrain-matched flight index; conducting dynamic antagonism modeling by introducing indicators such as formation electromagnetic survivability; introducing subjective-objective combined weighting and adopting the AHP-Entropy Weight Method combined weighting strategy. In summary, this study makes up for some defects of the existing system in complex mountainous environments by enhancing environmental adaptability, dynamic antagonism modeling and innovative combined modeling, and provides a scientific basis for the capability optimization and tactical application of UAV systems in mountain battlefield environments.

2. Evaluation Indicators for UAV Operational Effectiveness in Complex Mountainous Environments

This paper focuses on the operational effectiveness evaluation of unmanned equipment, introduces military domain standards, and references the U.S. military JADC2 (Joint All-Domain Command and Control) indicator system to construct a set of indicator system (C) applicable to UAV cooperative reconnaissance and strike against ground tactical targets, as shown in Figure 1, so as to provide a more scientific and reasonable basis for the evaluation of UAV operational effectiveness.

2.1. Information Acquisition Dimension

Information acquisition is the foundation of UAV operations, and its timeliness, accuracy, and completeness directly determine the success or failure of subsequent operational actions. In this dimension, payload performance indicators are the core, which directly determine the UAV's

ability to perceive targets and situations in complex environments. This study constructs an evaluation system including the following 5 key indicators:

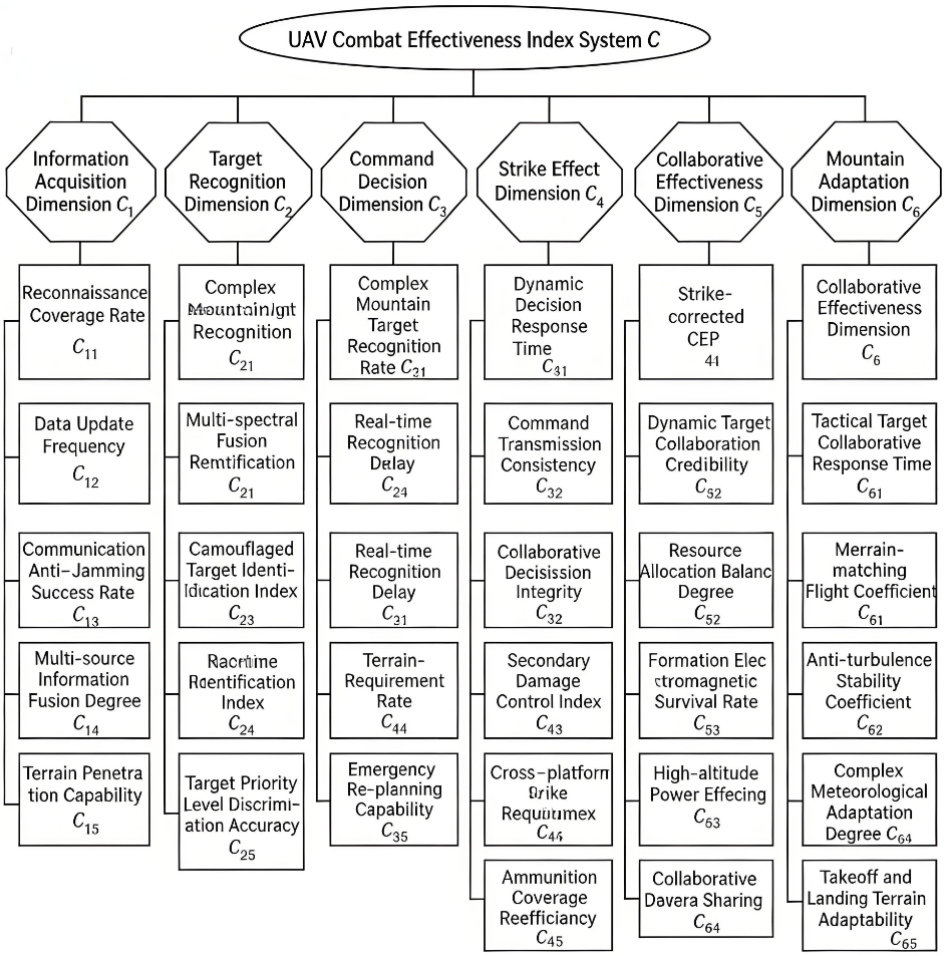


Fig 1. UAV Operational Effectiveness Indicator System

2.1.1. Reconnaissance Coverage Rate

Indicator Definition: The proportion of the real-time detection area of the UAV formation to the mission area.

Professional Description: This indicator characterizes the coverage breadth of the UAV cluster to the predetermined reconnaissance area per unit time, reflecting the comprehensiveness of battlefield situation awareness.

2.1.2. Data Update Frequency

Indicator Definition: The data refresh rate of a single UAV sensor.

Professional Description: This indicator measures the response speed of the reconnaissance payload to dynamic targets or environmental changes, and is a key parameter to ensure the timeliness of tactical decision-making.

2.1.3. Communication Anti-Jamming Success Rate

Indicator Definition: The effective data transmission rate in complex electromagnetic environments.

Professional Description: This indicator quantifies the communication reliability of the data link under enemy active interference or complex channel conditions, ensuring that reconnaissance information can be accurately transmitted back.

2.1.4. Multi-Source Information Fusion Degree

Indicator Definition: The effectiveness index of multi-modal data fusion such as optics/infrared/radar.

Professional Description: This indicator evaluates the information complementarity and confidence of heterogeneous sensor data after spatial-temporal registration, feature-level or decision-level fusion processing, aiming to improve the accuracy of target recognition.

2.1.5. Terrain Perspective Capability

Indicator Definition: The target detection probability of penetrating vegetation/rock occlusion using Synthetic Aperture Radar (SAR) obstacle-penetrating imaging technology.

Professional Description: This indicator specifically refers to the probability of discovering concealed/semi-concealed targets by penetrating surface cover (such as jungles, camouflage nets) or overcoming terrain occlusion using microwave remote sensing technology, and is a key performance indicator in complex mountainous or urban combat environments.

2.2. Target Recognition Dimension

Accurate target recognition is a core link in the effectiveness of UAV reconnaissance and strike operations, and its accuracy and robustness directly determine the success or failure of subsequent strike missions. In complex mountainous environments, the high fusion degree between targets and the background significantly increases the difficulty of recognition, putting forward higher requirements for the recognition effectiveness and adaptability of algorithms. This dimension includes 5 core indicators, which are specifically constructed as follows:

2.2.1. Complex Mountain Target Recognition Rate

Indicator Definition: The correct recognition rate in

scenarios with a slope greater than 25°.

Professional Description: This indicator quantifies the ability of the algorithm to correctly detect real targets when targets are mixed with complex backgrounds (such as rocks, vegetation, and shadows) in steep mountain terrain. Its evaluation needs to combine terrain feature compensation technology, focusing on the generalization performance and false detection rate of the deep learning model under slope changes.

2.2.2. Multi-Spectral Fusion Recognition Rate

Indicator Definition: The resolution ability against infrared/ optical occlusion camouflage.

Professional Description: This indicator evaluates the recognition effectiveness of the system for enemy targets using infrared camouflage or optical camouflage under multi-modal (such as visible light, infrared, millimeter wave) data fusion. Its calculation needs to comprehensively consider the complementarity of different spectral characteristics, and improve the penetrating recognition ability of camouflaged targets through feature-level fusion algorithms.

2.2.3. Camouflaged Target Discrimination Index

Indicator Definition: The recognition ability against infrared/optical camouflage.

Professional Description: This indicator specifically evaluates the detection and classification performance of the system for targets covered with infrared suppression materials or optical camouflage nets in complex mountainous environments. Its measurement needs to be based on adversarial sample training and physical characteristic modeling, quantifying the algorithm's ability to distinguish camouflage textures and thermal features, and it is a key indicator for countering enemy concealment tactics.

2.2.4. Real-Time Recognition Delay

Indicator Definition: The delay from sensor acquisition to output results.

Professional Description: This indicator characterizes the response speed of the target recognition algorithm, including the total time consumption of image preprocessing, feature extraction, and reasoning and judgment. In dynamic battlefields, low latency is the key to realizing the "reconnaissance and strike immediately" closed loop, which needs to be optimized through edge computing acceleration or model lightweight technology.

2.2.5. Target Priority Discrimination Accuracy

Indicator Definition: The correct rate of high-value target recognition and sorting.

Professional Description: This indicator evaluates the system's ability to automatically sort targets based on a tactical value model (such as threat level, mission priority) in multi-target scenarios. Its accuracy depends on the real-time reasoning of the battlefield situation by deep reinforcement learning or Bayesian networks, ensuring that limited firepower resources are preferentially allocated to high-threat targets, which is a core element to improve operational effectiveness.

2.3. Command and Decision-Making Dimension

Command and decision-making is the core hub of the UAV combat system, and its timeliness, accuracy, and rationality directly determine the success or failure of combat operations. In complex mountainous environments, the battlefield situation changes rapidly, putting forward strict requirements for the rapid response, collaborative consistency, and anti-interference ability of command and decision-making. This dimension includes 5 key indicators, which are specifically designed as follows:

2.3.1. Dynamic Decision Response Time

Indicator Definition: The time from the perception of battlefield situation changes to the generation of new combat commands.

Professional Description: This indicator characterizes the response speed of the command and decision-making system to dynamic threats or sudden environmental changes (such as adjustments in enemy deployment, sudden changes in meteorology), covering the end-to-end delay from situation perception, threat assessment, plan generation to command issuance. Its optimization needs to integrate technologies such as edge computing and reinforcement learning to achieve millisecond-level response of the "perception-decision-action" closed loop, ensuring the timeliness of decision-making and adaptability to the battlefield.

2.3.2. Collaborative Decision Consistency

Indicator Definition: The conflict rate of multi-UAV mission allocation.

Professional Description: This indicator quantifies the collaborative effectiveness of mission allocation schemes in cluster systems, focusing on evaluating whether there are target duplicate allocation, path conflicts, or resource competition among multiple UAVs when performing reconnaissance and strike missions. Its calculation is based on multi-agent collaborative algorithms (such as distributed constraint satisfaction problem solving), and through conflict detection and resolution mechanisms, it ensures the temporal and spatial consistency of mission allocation, avoiding the loss of combat effectiveness caused by collaborative failure.

2.3.3. Command Transmission Integrity

Indicator Definition: The command packet loss rate in mountain occlusion environments.

Professional Description: This indicator is specifically used to evaluate the communication reliability of the command and control link in complex mountainous environments (such as canyons, mountain occlusion). Its measurement needs to consider the influence of terrain on electromagnetic wave multipath effect, shadow effect, and enemy interference. Through anti-interference coding (such as LDPC codes), relay node deployment, or cognitive radio technology, the bit error rate and packet loss rate of command transmission are reduced, ensuring the accurate delivery of command instructions.

2.3.4. Human-Machine Collaboration Credibility

Indicator Definition: The probability that automated decisions are adopted by commanders.

Professional Description: This indicator measures the degree to which the combat plans generated by artificial intelligence (such as target allocation, path planning) are trusted and adopted by commanders in the human-machine hybrid decision-making system. Its evaluation needs to construct a trust model based on Explainable AI (XAI), and enhance the commander's confidence in the automated system through interpretable decision reasoning processes (such as Bayesian networks, SHAP value analysis), realizing efficient collaboration of "human-in-the-loop".

2.3.5. Emergency Replanning Capability

Indicator Definition: The probability of generating feasible plans under sudden threats.

Professional Description: This indicator characterizes the success rate of the system in quickly generating alternative combat plans when encountering sudden threats (such as enemy air defense fire interception, sudden meteorological disasters). Its evaluation needs to combine real-time environmental modeling, risk prediction, and multi-objective optimization algorithms, and through online rolling planning technology, generate the optimal or satisfactory solution that meets the constraints (such as time window, resource limit) within a limited time, ensuring the dynamic executability of combat missions.

2.4. Strike Effect Dimension

Strike accuracy and damage effect are the ultimate indicators to measure UAV operational effectiveness, directly reflecting the completion quality of combat missions. In complex mountainous environments, terrain undulation, occlusion effect and target mobility significantly affect the ammunition impact point accuracy and damage effectiveness. To accurately quantify the strike effect in mountainous environments, this dimension designs the following 5 key indicators:

2.4.1. Terrain-Corrected Circular Error Probable

Indicator Definition: The Circular Error Probable (CEP) after correcting the influence of terrain in mountainous environments.

Professional Description: On the basis of the traditional CEP, this indicator compensates for the influence of terrain undulation on ammunition trajectory and guidance accuracy by integrating Digital Terrain Model (DTM) data and elevation correction algorithms. Its calculation needs to comprehensively consider gravity anomalies, airflow disturbances, and navigation errors caused by terrain occlusion to more truly reflect the distribution characteristics of strike accuracy in mountain combat. The correction model can be quantitatively evaluated based on the ray tracing method or terrain influence function.

2.4.2. Dynamic Target Damage Probability

Indicator Definition: The hit and damage probability of moving targets.

Professional Description: This indicator evaluates the strike effectiveness of the UAV system against highly maneuverable targets (such as moving vehicles, rapidly deployed fire points) in mountainous environments. Its measurement needs to combine target tracking and filtering algorithms (such as Kalman filtering), ammunition guidance accuracy, and target motion prediction models. Through Monte Carlo simulation or actual equipment testing, the hit probability and damage effectiveness under given maneuver parameters are counted, which is a key parameter to verify the dynamic strike capability.

2.4.3. Collateral Damage Control Index

Indicator Definition: The proportion of collateral damage area in non-target areas.

Professional Description: This indicator quantifies the degree of collateral damage caused by strike operations to non-target areas, focusing on the combined impact of ammunition power radius and terrain occlusion effect on the damage range. Its calculation needs to be based on the damage radius model (such as blast radius, fragment kill zone) and terrain occlusion analysis. Through GIS spatial analysis technology, the proportion of damaged area in non-target areas around the impact point is evaluated, which is a core indicator to measure the legality of combat operations and humanitarian risks.

2.4.4. Secondary Strike Demand Rate

Indicator Definition: The probability of needing supplementary attack after the first strike.

Professional Description: This indicator reflects the success rate of the first strike, and its value is affected by multiple factors such as target detection accuracy, ammunition effectiveness, and terrain occlusion. By counting the proportion of missions that require secondary strikes in historical combat data or simulation results, the consumption efficiency of combat resources and the reliability of mission completion can be quantified. In mountainous environments, this indicator is particularly sensitive to target detection stability, ammunition penetration capability, and terrain compensation accuracy.

2.4.5. Ammunition Mountain Adaptation Coefficient

Indicator Definition: The matching degree between ammunition type and terrain characteristics.

Professional Description: This indicator evaluates the adaptability between ammunition characteristics (such as penetration capability, blast mode, terminal sensitive characteristics) and mountain terrain characteristics (such as rock hardness, vegetation density, slope). By constructing an ammunition-terrain matching model, combining damage mechanism simulation (such as penetration depth calculation, shock wave propagation simulation) and terrain classification data, the effectiveness of different ammunition in specific terrain is quantified. For example, armor-piercing projectiles have better adaptability to rock targets than high-explosive projectiles, while cluster bombs are suitable for cluster targets in open mountainous areas.

2.5. Cooperative Effectiveness Dimension

Tactical target cooperative response, resource allocation, anti-interference capability, information sharing, and detection coverage are the core elements for evaluating the operational effectiveness of UAV clusters. In complex battlefield environments, the cooperative capability of multi-UAV systems directly affects mission completion efficiency and survivability. This dimension includes 5 key indicators, which are specifically designed as follows:

2.5.1. Tactical Target Cooperative Response Time

Indicator Definition: The total time consumption of the entire process from target detection to strike implementation.

Professional Description: This indicator quantifies the rapid response capability of the cluster system to tactical targets, covering the time delay of each link in the "detection-recognition-decision-strike" kill chain. Its evaluation needs to comprehensively consider target positioning accuracy, communication link delay, mission planning efficiency, and weapon launch preparation time. In mountainous environments, additional consideration should be given to the impact of terrain occlusion on communication relays and target tracking stability. By means of technical measures such as edge computing node prepositioning and distributed decision-making, the response time can be significantly shortened, and the "reconnaissance and strike immediately" capability can be improved.

2.5.2. Resource Allocation Balance Degree

Indicator Definition: The load difference coefficient of the UAV cluster.

Professional Description: This indicator measures the

balance of mission allocation schemes, and evaluates the rationality of resource allocation by quantifying the differences in computing resources, energy consumption, mission load, and other aspects among various UAVs. Its calculation can adopt indicators such as standard deviation, Gini coefficient, or variation coefficient, and realize dynamic optimization combined with the two-stage greedy auction algorithm. Through iterative game and mission dynamic migration mechanisms, the system effectiveness bottleneck caused by unbalanced load is reduced, and the overall efficiency of the cluster is maximized.

2.5.3. Formation Electromagnetic Survival Rate

Indicator Definition: The continuous combat probability of the cluster in an electronic countermeasure environment.

Professional Description: This indicator evaluates the survival and combat capability of the system under enemy electronic interference, suppression, or deception. Its measurement needs to comprehensively consider the effectiveness of technical means such as communication anti-jamming (such as frequency hopping, cognitive radio), navigation anti-deception (such as GNSS/INS deep integration), and cooperative anti-jamming strategies (such as distributed spectrum sensing). By constructing an electromagnetic countermeasure simulation environment, the cluster mission completion rate and link connectivity under different interference patterns are simulated, and the survivability of the formation in complex electromagnetic environments is quantified.

2.5.4. Cross-Platform Data Sharing Rate

Indicator Definition: The proportion of intelligence data effectively shared among heterogeneous UAV platforms.

Professional Description: This indicator reflects the information fusion and sharing capability among UAVs with different architectures and sensor configurations. Its calculation needs to be based on unified data standards (such as STANAG 4586), secure transmission protocols (such as IPsec), and edge computing gateways, and count the ratio of shared data volume (such as target coordinates, environmental perception data) to total data volume. A high sharing rate can improve the accuracy of global situation awareness, reduce information blind areas, and support cooperative detection and distributed decision-making.

2.5.5. Cooperative Coverage Redundancy Degree

Indicator Definition: The area proportion of the overlapping coverage area of multi-UAV sensors.

Professional Description: This indicator balances detection reliability and resource consumption, and evaluates the rationality of redundant coverage by quantifying the proportion of overlapping area of sensor coverage areas. Its calculation needs to combine sensor field of view, installation height, and terrain occlusion model, and optimize deployment using set cover problem solving algorithms. Redundant coverage can improve target detection probability and fault tolerance, but it is necessary to avoid resource waste caused by excessive redundancy, and establish a dynamic balance model between mission requirements and energy consumption constraints.

2.6. Mountain Adaptability Dimension

Mountain environment adaptability is the basic guarantee for UAVs to fly stably and perform missions in complex mountainous environments, directly affecting operational effectiveness and survivability. Focusing on the comprehensive adaptability of UAVs to terrain, meteorology, and take-off and landing conditions, this dimension designs the following 5 key indicators to ensure system environmental robustness through quantitative evaluation:

2.6.1. Terrain-Matched Flight Index

Indicator Definition: Quantify the dynamic matching degree between the UAV's flight trajectory and terrain characteristics to ensure safe flight altitude and obstacle avoidance capability.

Professional Description: Based on terrain elevation data (such as Digital Elevation Model (DEM)/Digital Terrain Model (DTM)) and combined with the UAV's real-time flight trajectory, this indicator evaluates terrain following and obstacle avoidance performance. Its core is to verify the aircraft's adaptability to mountain slopes and obstacles (such as mountain peaks, cliffs). Through adaptive terrain tracking algorithms (such as Terrain-Aware Path Planning), the deviation rate between the flight trajectory and the safe terrain altitude is calculated. A high matching degree must meet the following requirements: the flight profile is dynamically adapted to terrain undulation, the obstacle avoidance distance meets the safety threshold, and the route smoothness meets the mission requirements.

2.6.2. Anti-Turbulence Stability Coefficient

Indicator Definition: The stability and accuracy of UAV attitude control under gust interference.

Professional Description: This indicator characterizes the ability of the flight control system to resist mountain turbulence (such as valley winds, thermal currents), focusing on evaluating the control error of attitude angles (pitch, roll, yaw) under sudden wind shear. Dynamic stability indicators (such as time-domain overshoot, adjustment time) combined with wind field simulation models are used to quantify the attitude recovery speed and steady-state accuracy of the UAV under gust interference. Its evaluation needs to consider different wind speed levels (such as gust intensity ≥15m/s) and sudden wind direction change scenarios to verify the disturbance suppression efficiency of the flight control system (such as PID + robust control).

2.6.3. High-Altitude Dynamic Efficiency

Indicator Definition: The retention rate of thrust (or power) of the power system in environments above 4000 meters above sea level.

Professional Description: This indicator is specifically used to evaluate the impact of thin air at high altitudes on the performance of power systems (such as turbofan engines, electric propulsion systems). Its measurement needs to compare the maximum thrust/power under standard sea-level conditions and calculate the efficiency attenuation ratio in high-altitude environments. For fuel engines, attention should be paid to power loss caused by reduced air intake; for electric systems, the battery discharge efficiency and motor heat dissipation under low-temperature environments need to be considered. Through high-altitude tests or numerical simulations, the continuous output capability of the power system at extreme altitudes is verified.

2.6.4. Complex Meteorological Adaptability

Indicator Definition: Quantify the impact of severe weather such as rain, snow, and fog on sensor detection and communication links.

Professional Description: This indicator targets the performance attenuation of electro-optical/infrared sensors, radar, and communication modules under severe weather. By

constructing meteorological attenuation models (such as rain attenuation models, fog attenuation coefficients), the sensor detection distance reduction rate, image Signal-to-Noise Ratio (SNR) decrease, and communication Bit Error Rate (BER) change are evaluated. For example, the scattering effect of rain and fog on LiDAR, and the reflection interference of snow on infrared radiation. Its evaluation needs to distinguish meteorological levels (such as rainfall intensity, visibility), and quantify the degree of system function degradation combined with adaptive image enhancement algorithms (such as rain/fog removal processing) and signal compensation technologies.

2.6.5. Take-off and Landing Terrain Adaptability

Indicator Definition: Evaluate the safe take-off and landing capability of UAVs on non-standard sites such as steep slopes and rocky areas.

Professional Description: This indicator comprehensively considers the adaptability of the landing gear structure (such as multi-legged/variable configuration), terrain reconstruction algorithms, and landing accuracy. By simulating or measuring different slopes (≥30°) and surface roughness scenarios, the UAV's landing stability (such as overturning probability), impact load, and positioning accuracy (such as GPS/visual SLAM fusion positioning error) are verified. Emphasis should be placed on evaluating the adaptability of Vertical Take-Off and Landing (VTOL) mode in complex terrains to ensure that the attitude control and energy management during the landing process meet the safety threshold.

3. Construction of UAV Operational Effectiveness System in Complex Mountainous Environments

3.1. Determining Indicator Weights via AHP

The Analytic Hierarchy Process (AHP) is a research method that combines qualitative and quantitative approaches to calculate decision weights for solving complex multi-objective problems [5]. It is suitable for decision-making problems with relatively complex structures, numerous decision criteria, and difficulties in quantification, and can avoid logical reasoning errors by decision-makers. Its analysis process is shown in Figure 2.

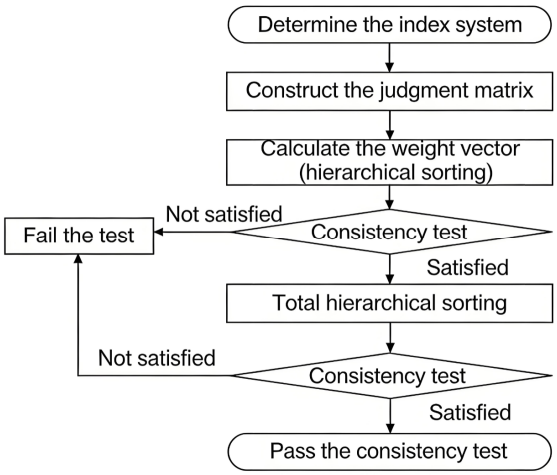


Fig 2. Flowchart of AHP

3.2. Establishment of the Judgment Matrix

Based on the hierarchical model constructed by the AHP analytic hierarchy process, this study systematically analyzes the hierarchical relationships and logical connections among the various elements of UAV cooperative operational effectiveness in complex mountainous environments. Through pairwise comparison and judgment of elements between the criterion layer and the indicator layer, the relative importance of indicators is quantified and assigned according to the 9-point scale (1–9 and their reciprocals) proposed by T. L. Saaty (as shown in Table 1), and judgment matrices are established to accurately characterize the influence weights of each factor on operational effectiveness.

Table 1. Values of the 1–9 Scale Method

Scale Value	Meaning
1	Equal importance
3	Moderately more important
5	Strongly more important
7	Very strongly more important
9	Extremely more important
2, 4, 6, 8	Intermediate states between adjacent scale values
Reciprocals	If the importance ratio of factor i to factor j is C_{ij}, then the importance ratio of factor j to factor i is $C_{ji}=1/C_{ij}$

3.3. Calculate the Weights

(1) Calculate the geometric mean of each row in matrix C, where C_{ij} is the corresponding element in the matrix:

$$\boldsymbol{\omega}_i = \sqrt[n]{\prod_{j=1}^{n} \mathbf{C}_{ij}}$$

(2)Normalization:

$$W_i = \frac{\boldsymbol{\omega}_i}{\sum_{k=1}^{n} \boldsymbol{\omega}_i}$$

By normalizing the vector $\boldsymbol{\omega}_i$, the weight vector $\mathbf{W} = [w_1, \ w_2, \ \ldots w_n]^T$ of each factor is obtained.

(3)Calculate the maximum eigenvalue $\lambda_{\max}$:

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n} \frac{(C \bullet W)_i}{W_i}$$

3.4. Determining Weights via the EWM

The entropy weight method is an objective weighting approach that measures the degree of dispersion of each indicator by calculating the information entropy of each indicator and assigns weights accordingly. The UAV operational effectiveness indicator system contains a large number of quantifiable parameters. The entropy weight method objectively reflects the degree of dispersion of each indicator in measured or simulated data by calculating the information entropy of indicator data, avoiding cognitive biases that may be introduced by subjective weighting [6].

(1) Calculate the information utility value g_j: It reflects the ability of an indicator to distinguish between different decision outcomes. The larger g_j is, the higher the weight.

$$g_j = 1 - e_j$$

(2) Calculate the entropy weights:

$$\omega_j^{ent} = \frac{g_j}{\sum_{j=1}^{n} g_j}$$

Where: n is the total number of indicators, and ω_j^{ent} is the weight of the j-th indicator, satisfying $\sum_{j=1}^{n} \omega_j^{ent} = 1$.

Through the SPSSPRO software, the information entropy value, information utility value and weight coefficient of the operational effectiveness indicators for UAV cooperative reconnaissance and strike against ground tactical targets were calculated, as shown in Figure 3.

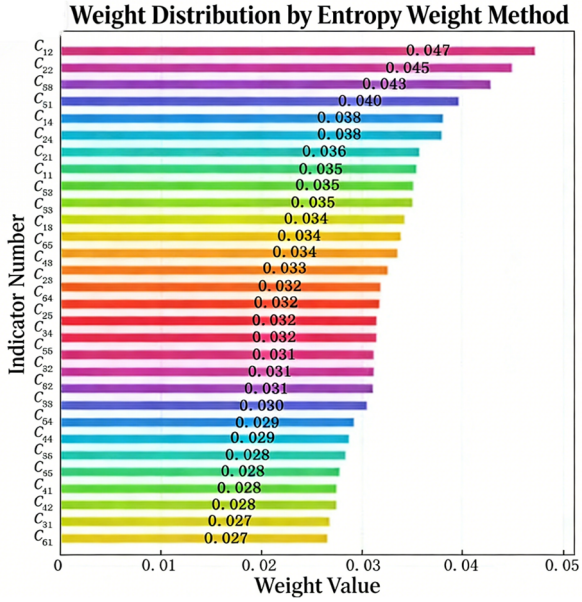


Fig 3. Weight Chart Based on the Entropy Weight Method

3.5. Determining Combined Weights via the AHP-EWM

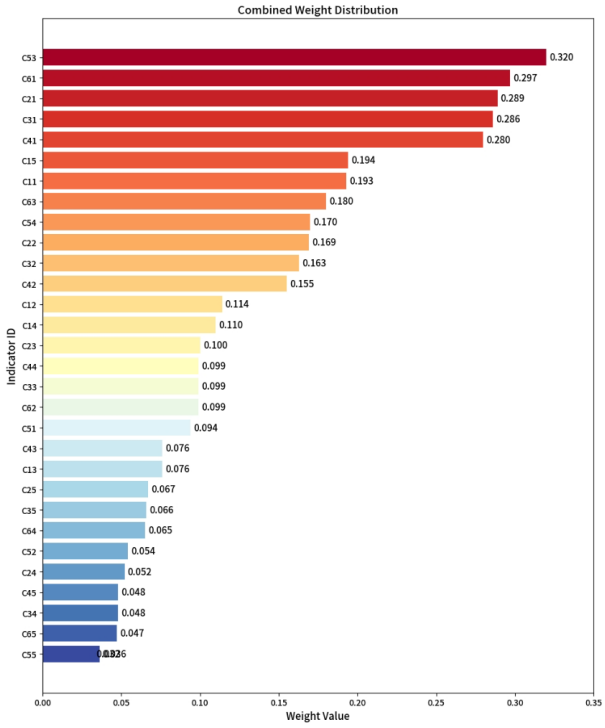


Fig 4. Weight diagram based on combined weighting

The weights of the operational effectiveness evaluation indicators for UAV cooperative reconnaissance and strike against ground tactical targets are determined separately by the AHP and the EWM. However, there are certain differences in the importance of subjective and objective weights. Therefore, the linear weighted combination method is used to calculate the final operational effectiveness weights. The formula of the linear weighted combination method is as follows:

$$\omega_j^{comb} = \alpha\omega_j^{subj} + (1-\alpha)\omega_j^{ent}$$

where: ω_j^{subj} denotes the weight value obtained by the AHP, ω_j^{ent} denotes the weight value obtained by the EWM.

The combined weights are shown in Figure 4.

4. Result Analysis

Analysis of Combined Weighting Results for UAV Cooperative Reconnaissance and Strike Effectiveness in Complex Mountainous Environments.

The combined weighting results show that the cumulative weight of the two dimensions, strike effect and mountain adaptability, exceeds 60%, which are the core dominant factors determining the operational effectiveness of UAV cooperative reconnaissance and strike in complex mountainous environments. Their weight proportions are significantly higher than those of other dimensions such as target recognition, command decision-making, and cooperative effectiveness, fully highlighting the core position of "precision strike" and "environmental adaptation" in special mountainous combat scenarios. Among them, terrain-corrected CEP as the core indicator of the strike effect dimension, has a much higher weight than other indicators in the same dimension. This result profoundly reflects the characteristics of intense terrain undulation and complex landform features in complex mountainous areas, which have a significant interference effect on the flight trajectory and hit accuracy of guided weapons. At the same time, it also confirms the extreme importance of implementing dynamic terrain compensation and optimizing guidance correction algorithms in mountainous operations, which is highly consistent with the conclusions of existing relevant studies.

In the mountain adaptability dimension, the terrain matching flight index accounts for the highest weight in this dimension and becomes a key indicator affecting the adaptability of UAVs in mountainous operations. This is mainly because in complex mountainous environments, UAVs need to rely on precise terrain matching capabilities to achieve low-altitude penetration and concealed flight. The degree of fit between their flight trajectory and mountain landforms directly determines the task concealment, flight safety, and the smooth development of subsequent reconnaissance and strike operations, which is the basic premise for ensuring the successful implementation of the entire combat task. In addition, the complex mountain target recognition rate in the target recognition dimension, the dynamic response time in the command decision-making dimension, and the formation electromagnetic survival rate in the cooperative effectiveness dimension all have relatively high weights. This indicates that in complex mountainous combat scenarios, improving the ability to identify camouflaged targets and small tactical targets in complex backgrounds, shortening the OODA (Observe-Orient-Decide-Act) cycle time to enhance the agility of command decision-making, and strengthening the anti-interference ability and survival resilience of the formation in a strong

electromagnetic countermeasure environment are also indispensable key links for optimizing the effectiveness of UAV cooperative reconnaissance and strike.

Based on the above weighting analysis results, combined with the operational needs of complex mountainous environments and the characteristics of UAV cooperative reconnaissance and strike operations, improving its operational effectiveness needs to focus on core indicators and target efforts, focusing on advancing five major optimization directions: first, strengthening precision strike capabilities focusing on developing intelligent terrain correction algorithms, optimizing the adaptability and anti-interference ability of ammunition in mountainous environments, and specifically improving the terrain-corrected CEP accuracy and ammunition hit stability; second, improving the mountain adaptability of the flight platform, strengthening the research and development of UAV terrain following control technology, optimizing the power output performance in high-altitude areas, enhancing the stability against turbulence and gusts, and improving the accuracy and reliability of terrain matching flight; third, breaking through the bottleneck of complex target recognition, developing multi-spectral and SAR (Synthetic Aperture Radar) fusion recognition technology, optimizing the identification algorithms for camouflaged targets and mixed terrain targets, and improving the accuracy and speed of target recognition in complex backgrounds; fourth, constructing an agile command decision-making system, compressing the dynamic response time through intelligent decision-making algorithms, improving the emergency re-planning and cross-platform cooperative decision-making capabilities, and shortening the OODA cycle; fifth, enhancing the resilience of cooperative operations, focusing on strengthening the formation electromagnetic protection technology, improving the survival ability in electromagnetic countermeasure environments, improving the cross-platform data sharing mechanism, and ensuring the continuity and stability of cooperative reconnaissance and strike operations.

5. Conclusion

Based on the above analysis, strike effectiveness and mountain adaptability serve as the core dimensions of UAV collaborative reconnaissance and strike effectiveness in complex mountain environments, with their key indicator weights highlighting the coupling relationship between terrain compensation, environmental adaptation, and precision strikes. The dual high weights of terrain-corrected CEP and terrain-matching flight index further confirm the fundamental supporting role of the "dynamic environmental perception - intelligent terrain adaptation - precise mission execution" technical chain on operational effectiveness. To meet practical combat requirements, enhancing UAV collaborative effectiveness in complex mountain environments requires focusing on five key directions:

Strengthening intelligent terrain correction and ammunition adaptability to enhance strike precision;

Optimizing platform terrain following and high-altitude performance to enhance environmental adaptability;

Integrating multi-modal sensing technologies (e.g., multi-spectral/SAR fusion) to overcome complex target recognition bottlenecks;

Building agile decision-making systems to compress OODA (Observe-Orient-Decide-Act) cycle time;

Strengthening electromagnetic protection and data link resilience to ensure collaborative survivability.

These findings provide quantitative basis and technical pathways for the iterative development of UAV equipment and innovation of tactical methods, holding significant strategic value for breaking through the bottlenecks of complex mountain combat effectiveness and constructing a comprehensive three-dimensional defense and offense system. In the future, it is necessary to further deepen the integration of environmental perception and intelligent decision-making, promoting the transformation of technology verification into practical combat capabilities, to support the routine and highly effective use of UAV systems in complex mountain battlefields.

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