# Overview of Research on Camouflage Effect Evaluation Technology

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**Abstract: With the rapid development of modern reconnaissance technology, the battlefield environment has put forward higher requirements for the evaluation of camouflage effectiveness. The widespread application of multi-sensor collaborative reconnaissance such as optics, infrared, and radar makes it difficult to fully reflect the stealth ability of targets in complex environments by evaluating the camouflage effect of a single band. The evaluation of camouflage effect, as a key link in verifying the effectiveness of camouflage technology, not only provides a basis for optimizing camouflage design, but also directly affects the survival ability and combat effectiveness of military targets. This article focuses on the evaluation of camouflage effects, starting from the evaluation mechanisms of optical, infrared, and radar bands. It systematically reviews the current application status of evaluation methods, deeply explores the key technologies and challenges of multispectral fusion evaluation technology, and analyzes the application value of evaluation technology with practical cases. Finally, it looks forward to future development trends, in order to provide comprehensive references for theoretical innovation and technological progress in camouflage effect evaluation.**

**Keywords: Camouflage Effect Evaluation; Multispectral Fusion; Optical Camouflage; Infrared Camouflage; Radar Camouflage; Information Fusion; Deep Learning**

## 1. Introduction

In modern warfare, the rapid advancement of reconnaissance technology has significantly improved the transparency of the battlefield, posing unprecedented exposure risks to military targets. Optical imaging devices capture the shape of targets through visible light, infrared thermal imagers use thermal radiation to detect concealed targets, and radar systems use microwave signals to achieve all-weather long-distance detection [1,2]. The collaborative application of these sensors has formed a full spectrum reconnaissance network, and evaluating the camouflage effect of a single band is no longer sufficient to meet practical needs [3]. The evaluation of camouflage effect, as a core link in the development and application of camouflage technology, directly affects the optimization of camouflage schemes and the improvement of combat effectiveness due to its scientific and accurate nature [4, 5].

Traditional camouflage effect evaluation methods mostly focus on single band or static scenes, such as visible light camouflage evaluation based on human eye observation or radar stealth evaluation based on RCS measurement. However, with the diversification and intelligence of reconnaissance methods, the limitations of a single evaluation method are becoming increasingly prominent [6]. Multi spectral fusion camouflage effect evaluation, which integrates multi band information such as optics, infrared, and radar, has become an inevitable trend in dealing with complex reconnaissance threats [7]. However, multispectral evaluation faces multiple challenges: the differences in physical mechanisms between different bands lead to a complex evaluation index system; The fusion processing of multi-source heterogeneous data is difficult; The real-time evaluation technology in dynamic battlefield environments is not yet mature [8]. In recent years, the introduction of technologies such as data fusion, deep learning, and unmanned aerial vehicle platforms has brought new opportunities for the evaluation of multispectral camouflage effects, promoting the transformation of this field from single dimensional static analysis to comprehensive dynamic evaluation [9,10,11].

This article takes camouflage effect evaluation technology as the research object, and systematically discusses it from five aspects: evaluation mechanism, current application status of methods, multispectral fusion evaluation technology, practical application cases, and future development directions, aiming to provide theoretical basis and technical reference for related research.

## 2. Evaluation Mechanism of Camouflage Effect

The scientific of camouflage effect evaluation depends on a deep understanding of camouflage mechanisms in different frequency bands. The camouflage mechanisms of optical, infrared, and radar bands are different, and their evaluation methods need to be designed based on corresponding physical characteristics. The following analyzes the evaluation mechanism from three bands and explores the compatibility challenges of multispectral fusion evaluation.

### 2.1 Evaluation Mechanism of Optical Camouflage Effect

The evaluation of optical camouflage effect mainly focuses on the visible light band (0.38-0.76 μ m), aiming to quantify the concealment of targets in human eyes or optical reconnaissance equipment. The mechanism is based on the similarity between the target and the background in visual features such as color, brightness, texture, and shape [12].

Color and brightness differences. The core of optical evaluation is to compare the differences between the target and background in color space (such as RGB, HSV, Lab). Color histograms, average color differences, and other indicators are commonly used to quantify similarity [13,5]. For example, digital camouflage achieves spatial color mixing through pixelated color blocks, allowing the target to blend with the background when viewed from a distance [6,12].

Texture and Shape Analysis. Texture features (such as the energy and contrast of the gray level co-occurrence matrix GLCM) reflect the detail patterns of the target surface, while the continuity of edge contours affects the probability of target recognition [14,5]. The evaluation method compares the texture consistency between the target and the background to determine whether the camouflage effectively destroys the target's recognizability.

Environment and observation conditions. The evaluation results are significantly affected by lighting conditions (such as diurnal variations, sunny and cloudy weather), observation angles, and distances. For example, shadows under strong light may expose the shape of the target, while color differences under weak light may be magnified [10]. Multi perspective reconnaissance (such as drone overhead) requires evaluation methods that consider the concealment of three-dimensional space.

The challenge of optical evaluation lies in its high dependence on human perception characteristics and susceptibility to environmental changes, making it difficult to adapt to dynamic scenes or multi perspective reconnaissance [15].

### 2.2 Evaluation Mechanism of Infrared Camouflage Effect

The evaluation of infrared camouflage effect is aimed at the infrared band (0.76 μ m-1 mm, military applications focus on 3-5 μ m and 8-14 μ m), and the core is to evaluate the matching degree between the target's thermal radiation characteristics and the background, and reduce its detectability in thermal imagers [16,17].

Differences in thermal radiation. According to Stephen Boltzmann's law, infrared radiation is closely related to surface temperature and emissivity. The evaluation method quantifies the concealment effect by measuring indicators such as the average temperature difference (MTD) and radiance difference between the target and background [3,17]. For example, MTD less than 4K is often considered a good infrared camouflage standard [17].

Temperature distribution and dynamic characteristics. Infrared evaluation needs to consider the temperature distribution of the background (such as uniform low temperature in forests vs. complex heat sources in cities) and dynamic changes (such as frictional heating caused by target motion) [16]. The temperature field model predicts the infrared characteristics of targets by simulating heat conduction, convection, and radiation, providing a theoretical basis for evaluation [17].

 

Environmental impact. Environmental factors such as solar radiation, wind speed, and humidity affect the propagation of infrared signals and the apparent characteristics of targets. For example, low temperature environments at night may mask the thermal characteristics of targets, while the heat dissipation performance of camouflage materials becomes crucial in high temperature environments [2].

The advantage of infrared evaluation lies in its clear physical meaning, but its compatibility with optical evaluation is poor. For example, low emissivity coatings may reflect light under visible light, increasing exposure risk [7].

### 2.3 Evaluation Mechanism of Radar Camouflage Effect

The evaluation of radar camouflage effect is aimed at the microwave band (1-1000 mm, commonly used frequency bands include X, Ku, etc.), aiming to evaluate the radar cross section (RCS) reduction effect or deception interference performance of targets [18,19].

RCS reduction assessment. RCS is the core indicator for measuring the strength of target radar echoes. The evaluation method quantifies the stealth effect by comparing the changes in RCS before and after camouflage [8]. For example, absorbing materials can reduce RCS by more than 10 dB, significantly reducing the detection probability.

Deception interference assessment. Passive equipment such as corner reflectors, foil strips, or active jamming devices can create false targets or clutter, which can interfere with radar systems [20,21]. The evaluation method analyzes the number, distribution, and duration of interference of false targets to determine the effectiveness of deception.

Environmental and system factors. Radar waves are affected by background clutter, terrain obscuration, and atmospheric attenuation. The evaluation needs to consider the radar's operating frequency band, polarization mode, and battlefield electromagnetic environment [22,23]. For example, soil cover can attenuate radar waves and enhance concealment effects [22].

The challenge of radar evaluation lies in the popularization of wideband and multifunctional radar, which requires evaluation methods to cover a wider spectrum range [24].

### 2.4 Compatibility Challenges of Multispectral Fusion Evaluation

Multi spectral fusion evaluation requires the integration of multi band information such as optics, infrared, and radar to construct a comprehensive evaluation system. However, the differences in physical mechanisms among different bands result in a complex indicator system. For example, optical evaluation focuses on visual similarity, infrared evaluation focuses on thermal features, and radar evaluation is mainly based on electromagnetic scattering [7]. In addition, the registration, fusion, and weight determination of multi-source data are key challenges. The evaluation system needs to balance the importance of each band to ensure that the results fully reflect the level of concealment of the target.

## 3. Application Status of Camouflage Effect Evaluation Methods

The evaluation method of camouflage effect directly affects the optimization and application effect of camouflage technology. Currently, evaluation methods for optical, infrared, and radar bands each have their own characteristics, and multispectral fusion evaluation technology has gradually become a research hotspot.

### 3.1 Evaluation Method for Optical Camouflage Effect

The evaluation of optical camouflage effect is mainly based on image analysis technology, and the following main methods have been developed:

Evaluation based on image features. Extract color histograms, grayscale contrast, texture features (such as GLCM energy and contrast) between the target and background, and calculate similarity or difference [5,13,14]. For example, Yang et al. (2019) evaluated the camouflage effect of fixed targets using H and S histograms in HSV space, verifying their effectiveness in static scenes [13]. This method is intuitive and easy to implement, but it is sensitive to changes in lighting and complex backgrounds.

Evaluation based on visual saliency. Simulate the human eye attention mechanism, generate saliency maps using saliency detection algorithms, and analyze whether the target becomes the visual focus [2,10,11]. The Multi-

Dimensional Feature Visual saliency Fusion Model (MFVS) proposed by Ding (2023) improves evaluation accuracy by generating pixel level saliency maps through neural networks [10]. This method is closer to human perception, but the selection and parameter adjustment of significance models increase computational complexity.

Evaluation based on eye movement data. Quantify the difficulty of searching for disguised targets by recording the observer's gaze point, scanning path, and time to first fixation (TTFF) using a high-precision eye tracker [15]. Wang Kaidi's (2022) study found that camouflage schemes with fewer fixation points and longer search times have better effects [15]. This method has strong objectivity, but the experimental equipment cost is high and the data analysis is complex.

These methods each have their own advantages and disadvantages: image feature methods are suitable for rapid evaluation but have poor robustness; The significance method is more in line with visual perception but has higher computational costs; Eye tracking data provides behavioral evidence, but its application scenarios are limited.

### 3.2 Evaluation Method for Infrared Camouflage Effect

The evaluation of infrared camouflage effect focuses on the thermal radiation characteristics of the target. Common methods include:

Evaluation based on differences in thermal characteristics. Measure the average temperature difference (MTD), radiance difference, equivalent blackbody temperature difference, and other indicators between the target and background to quantify the infrared concealment effect [3,17]. Gaofei Yin et al. (2004) measured the difference in thermal radiation before and after camouflage of missile positions, calculated the probability of discovery, and verified the camouflage effect [3]. This method has a clear physical meaning, but is susceptible to environmental temperature and target operating conditions.

Evaluation based on temperature field model. Establish a heat transfer model that comprehensively considers factors such as solar radiation, atmospheric radiation, and internal heat sources of the target to predict the temperature distribution of the target [17]. Yu Youjun (2021) simulated the temperature field of a camouflage net using finite element method and verified the accuracy of the model through field experiments [17]. This method is suitable for dynamic scenes, but the model complexity is high and parameter acquisition is difficult.

Evaluation based on the degree of fusion between the target and background. Evaluate the fusion between the target and background based on multidimensional features such as temperature, texture, and patch shape [2,16]. Luo (2024) proposed a fusion degree model that combines time series and spatial distribution consistency indices to enhance the comprehensiveness of evaluation [16]. This method is closer to the actual perception effect of infrared reconnaissance, but the data processing is complex.

The infrared evaluation method has evolved from simple temperature difference comparison to multi feature fusion, and further improvement is needed to enhance its adaptability to complex backgrounds.

### 3.3 Evaluation Method for Radar Camouflage Effect

The evaluation of radar camouflage effect is based on RCS, and commonly used methods include:

Evaluation based on RCS measurement. Measure the RCS changes before and after camouflage through microwave anechoic chamber or field testing, and quantify the stealth effect [18]. For example, absorbing materials can significantly reduce the target RCS and decrease the radar detection range [8]. This method has strong objectivity, but the testing cost is high.

Evaluation based on Ground based Synthetic Aperture Radar (GB-SAR). Using GB-SAR to simulate airborne or space-based SAR reconnaissance and obtain the scattering characteristics of targets [10]. Zhang and Huang (2011) validated the application of GB-SAR in ground target camouflage evaluation, which is suitable for complex terrain scenes [25].

Evaluation based on interference performance. Analyze the interference effects of deception methods such as foil strips and corner reflectors, such as the generation rate of false targets and the duration of interference [24,21]. Ling et al. (2023) evaluated the distance deception interference performance through simulation, providing a basis for active interference optimization [24].

The challenge of radar evaluation methods lies in addressing the complexity of wideband and multifunctional radar, requiring the development of more flexible testing techniques.

### 3.4 Current Status of Multispectral Fusion Evaluation Methods

Multispectral fusion evaluation aims to integrate multi band information such as optics, infrared, and radar to provide comprehensive evaluation results. The main methods include:

Multi source data fusion technology. It is divided into three levels: data layer (pixel level fusion), feature layer (feature combination), and decision layer (result integration) [8]. Data layer fusion generates enhanced images through weighted averaging or wavelet transform; Feature layer fusion extracts key features (such as color, temperature, RCS) from each band and combines them; Decision level fusion integrates the evaluation results of each band to form the final conclusion [8]. Feature layer fusion is widely used due to its balance between efficiency and accuracy.

Evaluation based on deep learning. Utilizing models such as Convolutional Neural Networks (CNN) and Transformers to automatically extract and fuse multimodal features, achieving end-to-end evaluation [9,10]. Riberolles et al. (n.d.) demonstrated the potential of deep learning in multimodal analysis by detecting radar data anomalies using LSTM autoencoders [9]. This type of method can handle complex nonlinear relationships, but requires a large amount of annotated data support.

The challenges of multispectral fusion evaluation include data registration accuracy, difficulty in feature selection, and insufficient model generalization ability, but its comprehensiveness makes it a key direction for future development.

## 4. Application Cases of Camouflage Effect Evaluation Technology

The value of camouflage effect evaluation technology lies in its practical application ability. The application of evaluation methods in different scenarios is analyzed through typical cases, and verification methods are explored.

### 4.1 Evaluation of Ground Fixed Targets

Ground fixed targets (such as missile positions and command posts) need to be deeply integrated with the background terrain. Gaofei Yin et al. (2004) analyzed the optical, infrared, and radar characteristics of ground to air missile positions, using camouflage coatings, low emissivity materials, and absorbing nets. The camouflage effect was verified by measuring the probability of discovery [3]. Yang et al. (2019) collected multiple frames of images for defense works exits, proposed a dynamic detection model based on HSV histograms and statistical features, and achieved real-time evaluation of camouflage status [13].

### 4.2 Evaluation of Mobile Targets

Motor vehicles (such as tanks and military trucks) increase the difficulty of evaluation due to their motion characteristics. Yang Di (2023) utilized digital twin technology to construct three-dimensional dynamic scenes in Unity 3D, evaluated the effectiveness of digital camouflage in multiple perspectives, and proposed a new indicator system [6]. Wen (2023) developed a multi background evaluation model for optical adaptive camouflage vehicles by comprehensively analyzing the effects of motion speed and background interference [14].

### 4.3 Verification Methods

The scientific of the evaluation method needs to be verified through the following means:

Simulation verification: Simulate the camouflage effect through models such as electromagnetic scattering and heat transfer to verify the algorithm logic [6,11].

Field experiments: Testing disguised targets in real environments to obtain actual data [13,17].

Subjective objective consistency analysis: Comparing the consistency between objective indicators and subjective evaluations (such as human eye observation) [10,15].

These cases demonstrate the diversity and specificity of evaluation techniques, and the combination of verification methods ensures the reliability of the results.

## 5. Summary and Prospect

The evaluation technology of camouflage effect is a key support for the development of camouflage technology, and its mechanism involves the complex physical characteristics of optical, infrared, and radar bands. Currently, single band evaluation methods are relatively mature, while multispectral fusion evaluation has achieved comprehensive breakthroughs through data fusion and deep learning. Application cases have shown that evaluation techniques are widely used in both fixed and mobile targets, and their scientific is ensured through verification methods such as simulation and field experiments.

However, the field still faces challenges: the scarcity of high-quality multispectral datasets limits model training; Insufficient robustness in dynamic environments; The interpretability of intelligent evaluation models needs to be improved. In the future, camouflage effect evaluation technology will develop in the following directions:

Intelligence: End to end evaluation systems based on deep learning will enhance automation levels; Multimodal fusion: Efficient fusion of multi band information to enhance the comprehensiveness of evaluation. Dynamic real-time: Develop real-time online evaluation technology to meet the needs of the battlefield. Standardization: Establish a unified indicator system and testing platform to promote technology dissemination.

Through interdisciplinary collaboration and benchmark platform construction, camouflage effect evaluation technology is expected to achieve greater breakthroughs, providing strong support for modern military stealth technology.

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