A method for designing pixelated camouflage patterns for forest terrain backgrounds

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ABSTRACT

Camouflage is a critical component of modern military operations, enabling objects to blend visually into their surroundings. Traditional disruptive patterns used widely from the 1970s to early 2000s are increasingly replaced by pixelated camouflage. This study proposes a design method for pixelated camouflage patterns tailored to forest terrain. Effectiveness is evaluated using Peak Signal-to-Noise Ratio (PSNR) and Histogram Intersection (HI), which assess visual and color similarity. Results show the designed patterns resemble forest backgrounds in color and texture, indicating practical potential.

Keywords: Pixelated camouflage pattern; Evaluation metrics; PSNR; Histogram intersection.

1. INTRODUCTION

Camouflage plays a crucial role in modern military operations by concealing personnel and equipment through effective visual integration with the surrounding environment. In forested and mountainous terrains, where lighting conditions and background textures vary considerably, well-designed camouflage reduces the likelihood of detection and delays enemy response [1].

Traditional patterns composed of large, irregular patches were widely used in the 20th century but have proven less effective against contemporary surveillance technologies. With advancements in optics and digital image processing, pixelated camouflage has gained prominence due to its multiscale structure and improved capacity to disrupt visual perception [2].

This trend is reflected in designs such as MARPAT (used by the U.S. Marine Corps) and UCP (formerly of the U.S. Army), which use square pixels to enhance blending and edge disruption across environments [3]. Representative patterns are shown in figure 1 [4].

a. Marine pattern. *b. Universal camouflage pattern.*

Figure 1. *Common digital camouflage patterns used worldwide.*

Despite these developments, designing camouflage optimized for specific terrains remains a complex challenge. In forest environments, both color and structure must simulate natural foliage and shadows, while the pattern scale should match typical observation distances and visual resolution.

This study proposes a method for generating pixelated camouflage tailored for forest terrain. The approach integrates image analysis, digital synthesis, and quantitative evaluation to enhance concealment performance and support future adaptive camouflage design.

2. THEORETICAL APPROACH

2.1. Basic unit size

Pixelated camouflage patterns are constructed from square units of uniform size and shape. These were chosen for their ease of fabrication, compatibility with digital image processing, and ability to form seamless, repeatable patterns across large surfaces.

From a visual perception perspective, object detection depends on the eye's minimum angular resolution, described by the Rayleigh criterion [5]:

$$\theta \approx \frac{Y}{L} \tag{1}$$

where θ is the angular resolution, Y is the size of the observed object, and L is the viewing distance.

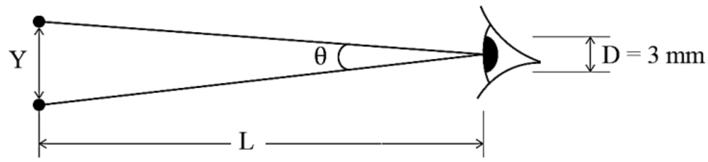


Figure 2. *Angular resolution and visual sensitivity at distance L.*

In daylight, the human eye resolves angles down to about one arcminute, corresponding to a wavelength of 550 nm and a pupil diameter of 3 mm [6, 7]. At 15 meters, this equates to a detectable object size of approximately 4 mm. This value supports the selected 4 mm unit size, aligning with military camouflage standards such as the MARPAT pattern (4 - 5 mm) [4].

While not fixed, the unit size should reflect expected viewing distances: smaller units for short-range concealment, larger ones for long-range. The 4 mm dimension offers a practical balance for typical forest engagements at distances ranging from 10 to 20 meters.

2.2. Colors and shapes of spots

a. Color constraints

Color selection must ensure effective blending with the background while minimizing detection. This includes using diverse color combinations to break up object outlines and hinder shape recognition. In addition, the brightness of the camouflage pattern should be slightly lower than that of the background to reduce visibility.

b. Shape constraints

The geometric shapes of camouflage spots should mimic natural background features. Spots must be distributed in an irregular manner to obscure the object's contours and introduce visual disruption. Regular forms such as large rectangles and long straight lines should be avoided because they can expose the artificial nature of the pattern.

2.3. Research methodology and techniques employed

In this study, digital camouflage patterns were developed with the goal of creating a generalizable model adaptable to various forest terrain backgrounds. The approach combined theoretical analysis, computational synthesis, and digital design, all aligned with the technical and operational requirements of camouflage systems.

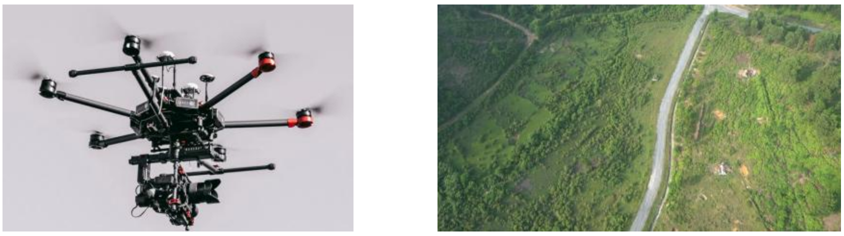
To connect physical measurements with digital implementation, each pattern image was divided into square blocks of r × r pixels, where r corresponds to the pixel count representing a 4 mm visual unit. The overall resolution was set to 2048 × 2048 pixels, with each block defined as 15 × 15 pixels. This setup ensures that the printed pattern maintains a consistent 4 mm spot size, matching human visual resolution and meeting practical requirements for camouflage fabric production.

For pattern creation, the team used Substance 3D Designer, a specialized tool for generating digital materials. It is valued for producing seamless, tileable, and highly customizable camouflage designs.

To validate the method, representative forest terrain images were selected, and corresponding pixelated patterns were generated. These were then evaluated based on their visual blending and concealment effectiveness.

2.4. Background data collection method

To collect representative forest background data, aerial imagery was acquired using a drone equipped with a high-resolution camera (Sony Alpha A6400, 24.2 MP, 6000 × 4000 pixels). The drone was operated at altitudes of up to 4000 meters to ensure wide terrain coverage.



a. UAV with integrated camera system. *b. Selected forest terrain.*

Figure 3. *Drone-based system for background data collection.*

Figure 3 presents the drone system and a typical forest image acquired during data collection. The image includes both sunlit and shaded areas, providing diverse texture and color information that is critical for camouflage analysis and pattern generation.

3. SIMULATION, CALCULATION, AND DISCUSSION

3.1. Analysis of characteristic colors in forest terrain

Characteristic colors of forest backgrounds were extracted using the K-means clustering algorithm, which partitions data into K groups by minimizing within-cluster variance [8].

The analysis identified five primary color groups with the following proportions: olive green (30%), dark green (27%), grayish green (24%), light green (15%), and white-gray (4%). A survey of global camouflage designs confirms that most visible-spectrum patterns utilize between three and five characteristic colors [9, 10].

Simulations revealed that $K = 3$ produced overly generalized results, while $K = 5$ introduced minor color groups with low frequency (under 5%). Thus, $K = 4$ was selected as the optimal choice, providing a good balance between fidelity and practical design use.

Olive green 30%. *Dark green 27%.* *Grayish green 24%.* *Light green 15%.* *White-gray 4%.*

Figure 4. *Color distribution extracted from the forest background image.*

This selection captures key characteristics of forest color composition, thereby enhancing the realism and operational effectiveness of the generated camouflage patterns.

3.2. Design of visible-spectrum pixelated camouflage patterns

This study formulates an algorithm based on two key constraints identified in earlier analysis: color accuracy and shape distribution. The process is summarized in Figure 5. First, characteristic background colors are extracted using the K-means algorithm to define the base palette.

Using Substance 3D Designer, various patterns were generated from forest background images. Contour blocks were obtained through point cloud generation, grayscale conversion, and binary segmentation. These were combined with color blocks to form the final camouflage design.

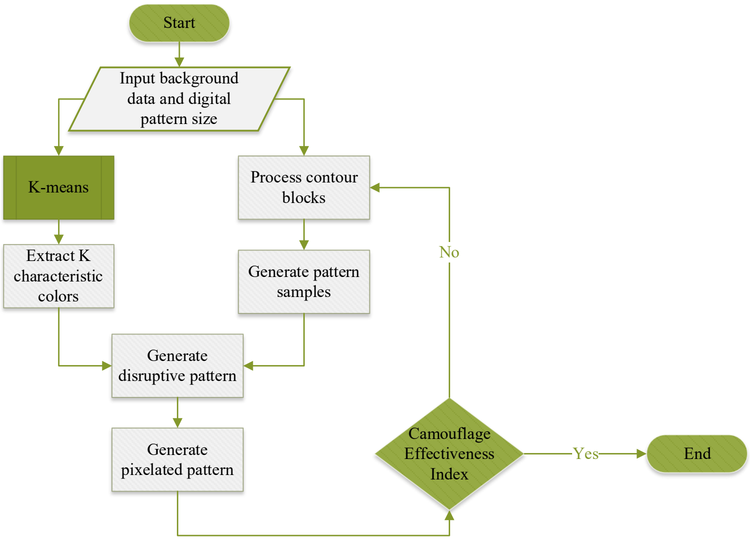


Figure 5. *Flowchart of the proposed pixelated camouflage pattern design algorithm.*

The image is segmented into square blocks, each assigned the closest color to its region for visual consistency. For an image of size $M \times N$ pixels and block size $r \times r$, it is divided into $m \times n$ blocks, where $m = M/r$ and $n = N/r$. When M or N is not divisible by r, the image is partitioned into $(m + 1) \times (n + 1)$ blocks. These include: $m \times n$ standard blocks of size $r \times r$; $1 \times n$ edge blocks of size $(M - mr) \times r$; $m \times 1$ blocks of size $r \times (N - nr)$; and one corner block of size $(M - mr) \times (N - nr)$.

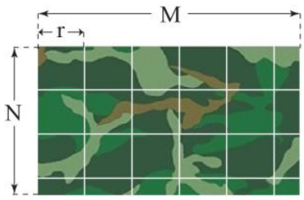
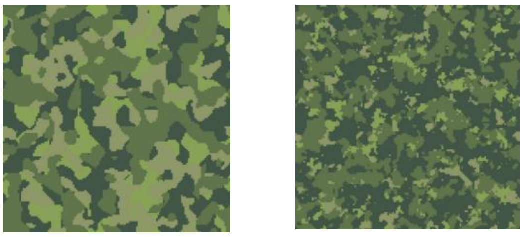


Figure 6. *Image segmentation into square blocks defined by parameter r.*

To optimize the pixelated camouflage patterns, the research team applied two key indices: Camouflage Similarity Index (CSI) and Universal Image Quality Index (UIQI), which quantify visual blending and similarity with mountainous forest backgrounds. These indices were previously introduced by the authors for evaluating camouflage performance [11]. Based on this method, two patterns were generated: Design 1 with lighter tones for sunlit areas, and design 2 with darker tones for shaded environments (Figure 7).



a. Designed pattern 1. *b. Designed pattern 2.*

Figure 7. *Pixelated camouflage patterns for forest terrain.*

3.3. Quantitative evaluation of camouflage patterns

While the algorithm was optimized using CSI and UIQI, relying solely on these internal metrics may reduce evaluation objectivity [12, 13]. While initial results confirm the algorithm's effectiveness, complementary methods are needed for a comprehensive assessment. Prior studies have utilized visual inspection, image quality metrics, and decision-making techniques such as TOPSIS [14, 15].

This study aims to establish a reusable workflow, with future improvements planned for stages like data acquisition, color selection, and evaluation. At this stage, Peak Signal-to-Noise Ratio (PSNR) and Histogram Intersection (HI) are used to evaluate pixel-level blending and color similarity between camouflage patterns and forest backgrounds.

Two background image types are used: one representing an overhead view (e.g., UAVs or watchtowers), and the other simulating a horizontal viewpoint of a human observer in dense vegetation (Figure 8). For each pattern, PSNR and HI scores are computed using 1,000 randomly sampled patches per viewpoint.

Three K20 camouflage patterns (512 × 512 pixels) are included for comparison, alongside the proposed designs. These reference patterns are labeled 1 to 3 (Figure 9).

a. Background 1. *b. Background 2.*

Figure 8. *Forest background images for camouflage evaluation.*

a. Pattern 1 *b. Pattern 2* *c. Pattern 3*

Figure 9. *K20 camouflage pattern samples used for comparative evaluation.*

a. Peak signal-to-noise ratio (PSNR)

The PSNR quantifies the ratio between the maximum possible signal power and the average noise power. It is commonly used to assess image quality and is mathematically defined as:

$$PSNR(dB) = 10\log_{10}\left(\frac{D^2MN}{\sum_{i=1}^{M}\sum_{j=1}^{N}\left(b_{ij}-c_{ij}\right)^2}\right) \quad (2)$$

where D is the maximum pixel intensity (255 for 8-bit images), and b_{ij}, c_{ij} are the pixel values at position (i, j) in the background and camouflage images, respectively. $M \times N$ is the number of pixels in the comparison region. Higher PSNR indicates greater similarity between the images [16].

The PSNR values and corresponding standard deviations are summarized in table 1 and illustrated in Figure 10. In table 1, "Mean" indicates the average PSNR value over 1000 iterations, "SD" is the standard deviation, and "BG" represents the background number.

Table 1. *PSNR and standard deviation of camouflage patterns on two forest backgrounds.*

		Pattern 1	Pattern 2	Pattern 3	Design 1	Design 2
BG 1	Mean	14.5460	15.6957	13.2678	15.3509	16.1783
	SD	2.2548	2.3287	1.4206	1.1166	1.5651
BG 2	Mean	13.2842	13.8469	12.0344	14.4431	14.8786
	SD	1.2095	1.0632	0.6599	0.7895	1.0318

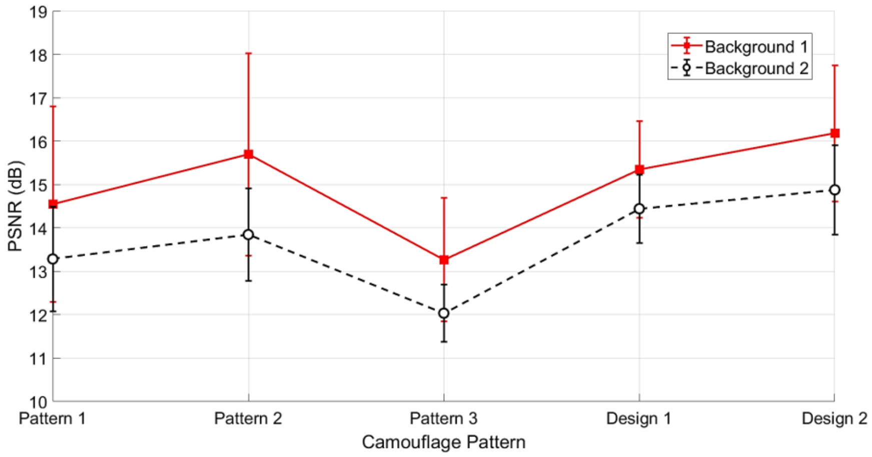


Figure 10. *Line graph of average PSNR with standard deviation for camouflage patterns on two backgrounds.*

The results indicate the following:

+ The camouflage patterns designed in this study exhibit higher PSNR values compared to the three pre-existing K20 camouflage patterns, reflecting superior visual blending with forest terrain.

+ Among all evaluated patterns, designed pattern 2 achieves the highest average PSNR value, indicating the most effective camouflage performance. This is followed by K20 pattern 2, designed pattern 1, and then K20 patterns 1 and 3.

+ Although designed pattern 1 and K20 pattern 2 yield similar average PSNR scores, the former demonstrates a lower standard deviation, indicating more stable and consistent performance across varied background conditions. In contrast, K20 pattern 2, despite its relatively high average PSNR, shows greater variability, suggesting that its effectiveness may be confined to specific locations and less reliable overall.

b. HI

While PSNR evaluates pixel-level similarity, it does not reflect overall color distribution. To address this, HI is used as a complementary metric for color blending assessment [17, 18].

HI measures the overlap between the normalized histograms of a camouflage pattern h_c and a background region h_b, calculated as:

$$HI(h_c, h_b) = \sum_{i=1}^{N} \min\left(h_c(i), h_b(i)\right) \tag{3}$$

Here, N is the total number of bins from concatenated red, green, and blue histograms. Each channel is divided into 32 bins, giving $N = 96$. Histograms are normalized to sum to 1. HI values range from 0 to 1, with higher scores indicating greater color similarity.

Figure 11 presents a line chart illustrating the mean HI values and corresponding standard deviations for each camouflage pattern, calculated from 1000 randomly selected positions across the two selected background types.

Table 2. *HI and standard deviation of camouflage patterns on two forest backgrounds.*

		Pattern 1	Pattern 2	Pattern 3	Design 1	Design 2
BG 1	Mean	0.3483	0.4052	0.3483	0.4431	0.4526
	SD	0.0964	0.1132	0.0539	0.0371	0.0616
BG 2	Mean	0.4307	0.3921	0.4312	0.4213	0.4402
	SD	0.0546	0.0323	0.0181	0.0292	0.0314

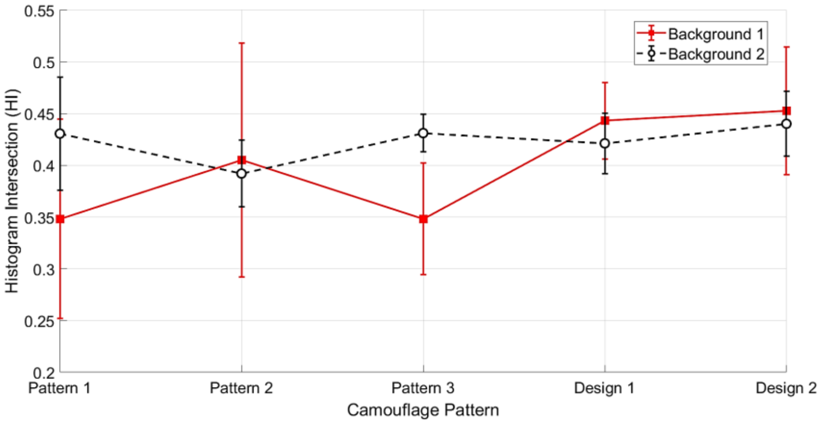


Figure 11. *Line graph of average HI with standard deviation for camouflage patterns on two backgrounds.*

The results from both HI and PSNR metrics consistently indicate that the camouflage patterns designed in this study outperform the pre-existing K20 patterns in terms of visual blending performance. K20 pattern 2 shows average HI and PSNR values that are comparable to those of designed pattern 1, but with significantly higher standard deviation. This suggests that the camouflage effectiveness of K20 pattern 2 is less consistent, performing well in certain positions but less effectively in others.

Among all evaluated patterns, designed pattern 2 demonstrates the highest levels of color similarity and stable blending performance, and is therefore selected as the optimal camouflage pattern in this study.

4. CONCLUSIONS

This study presents a structured approach for designing pixelated camouflage patterns tailored to forest environments. The proposed method integrates principles from optics, human visual perception, and digital image processing to achieve effective visual blending with natural backgrounds.

Dominant background colors were extracted using the K-means clustering algorithm, while pattern structures were procedurally generated through modeling in Substance 3D Designer. The pattern scale was calibrated to ensure consistency between digital resolution and physical production requirements. In addition, the workflow supports flexible scale adjustments to maintain concealment effectiveness at varying observation distances.

Quantitative evaluations using PSNR and Histogram Intersection confirmed that the designed patterns exhibited high color similarity and consistent visual integration under diverse terrain conditions.

These results provide a foundation for data-driven, terrain-specific camouflage development. Future research will focus on field validation, refinement of evaluation metrics, and enhancement of pattern adaptability for real-world deployment.

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TÓM TẮT

Phương pháp thiết kế họa tiết ngụy trang điểm ảnh phù hợp với phông nền địa hình rừng núi

Ngụy trang là yếu tố quan trọng trong các hoạt động quân sự hiện đại, giúp đối tượng hòa trộn trực quan với môi trường xung quanh. Các mẫu ngụy trang gây rối truyền thống, từng được sử dụng rộng rãi từ những năm 1970 đến đầu những năm 2000, đang dần được thay thế bởi họa tiết dạng điểm ảnh. Nghiên cứu này đề xuất một phương pháp thiết kế họa tiết ngụy trang điểm ảnh phù hợp với địa hình rừng. Hiệu quả được đánh giá thông qua hai chỉ số: Tỷ số tín hiệu trên nhiễu đỉnh (PSNR) và Đánh giá tương đồng phân bố màu bằng Histogram Intersection (HI), phản ánh mức độ tương đồng về thị giác và phân bố màu sắc. Kết quả cho thấy các họa tiết được thiết kế có màu sắc và kết cấu gần giống với nền rừng, cho thấy tiềm năng ứng dụng thực tiễn.

Từ khóa: Họa tiết ngụy trang dạng điểm ảnh; Chỉ số đánh giá; PSNR; Giao nhau biểu đồ màu.