Developing a method to generate an adaptive real-time camouflage pattern based on electro-chromic active devices

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ABSTRACT

Traditional camouflage faces limitations in modern combat, especially with moving targets or rapidly changing backgrounds. Adaptive camouflage, which adjusts colors and patterns in real time, provides a more flexible and effective solution. This paper presents a comprehensive study of popular adaptive camouflage principles worldwide and proposes a camouflage model for the visible light spectrum based on active electro-chromic principles. Evaluation results indicate that adaptive patterns achieve the lowest Camouflage Similarity Index (CSI) and the highest Universal Image Quality Index (UIQI) across various backgrounds, demonstrating the clear effectiveness of the proposed model. With 3 to 5 dominant colors, pattern generation time is under 1 second, and adaptive patterns exhibit the highest similarity to the background compared to fixed patterns.

Keywords: Camouflage patterns; Adaptive camouflage; CSI; UIQI.

1. INTRODUCTION

The commonly used camouflage devices or systems, such as nets, suits, coatings, and patterns, are passive, meaning they are unable to modify or adjust their camouflage properties as needed. In traditional camouflage methods, transitioning between different terrains alters the observational outcomes, significantly reducing camouflage effectiveness. Consequently, the main limitation of these methods is their suitability only for specific backgrounds. They lack the capacity for adaptive camouflage across varying stages of warfare, where battlefield conditions frequently change and backgrounds present complex variations in color and lighting [1].

A new camouflage method is being studied, which is adaptive camouflage or active camouflage so as to overcome the above disadvantages of traditional passive camouflage. Adaptive camouflage is a technique in which the camouflaged object undergoes continuous changes in color and pattern to adapt to its background and environment. Spectral adaptive camouflage differs from conventional camouflage in two key aspects. First, it replaces the appearance of the concealed object with one that closely resembles the surrounding environment. Second, adaptive camouflage performs this in real time [2].

In this article, the authors focus on studying comprehensively the principles of adaptive camouflage, thereby proposing an adaptive camouflage model in the visible area and conducting experiments to evaluate the results. Algorithmic evaluation of image quality, one aspect of camouflage evaluation is addressed in this study. A computational approach using the Camouflage Similarity Index (CSI) and the Universal Image Quality Index (UIQI) would be useful in overcoming the limitations of evaluating camouflage in human observation.

2. PRINCIPLES OF ADAPTIVE CAMOUFLAGE

In this section, the authors synthesize the principles of adaptive camouflage that have been researched and applied globally. This serves as the basis for proposing a visible-spectrum adaptive camouflage model that is appropriate in principle and for developing a prototype for further research and evaluation.

2.1. Principles of adaptive camouflage

Research on adaptive camouflage can be summarized with the basic principles as follows:

- Mechanical-chromic principle: This principle can alter color, pattern, or optical reflectivity across various spectral ranges by reversing coatings like nets, canvas, or textiles [3]. It is most effective in the visible spectrum but can also be applied in the thermal imaging range (8-12μm) by adjusting surface absorption or gloss. Its advantages include durability, flexibility, and longevity, similar to military materials. However, it is limited by traditional camouflage constraints, as a single outfit can only adapt to two predefined combat environments, making it ineffective in rapidly changing conditions.

- Thermo-chromic principle: This method leverages thermochromic materials, which change color with temperature variations due to shifts in their molecular or crystalline structure. Temperature changes can be passively triggered by the environment or actively induced by integrated heating components [4]. The advantage is the minimal added mass. However, a key limitation is the slow response time of passive systems (ranging from tens of seconds to minutes), while active thermochromic systems are still under development.

- Electro-chromic passive principle: This approach uses material panels that change color when voltage is applied, altering the surface's reflection spectrum rather than emitting light [3]. It offers high mechanical durability and low power consumption. However, it adapts slowly to background changes, with response times from seconds to minutes. The high gloss of electrochromic displays impairs camouflage, and poor color rendering limits color perception.

- Electro-chromic active principle: This principle uses materials that change color by altering their emission spectrum, including LED matrices, POLED, OLED, and LCD displays [2]. It offers flexible color display, low cost, and integration with control modules for adaptive camouflage. However, device durability depends on the robustness of electrical connections, often the weakest point, and requires a continuous power supply and stable operation under conditions like rain and humidity.

- Mechanical/electro-thermic principle: This approach is primarily applied in infrared camouflage, utilizing circulation pumps for gas or liquid flow, or Peltier thermoelectric plates, combined with sensors and control systems to modulate the surface temperature of the object [5]. The key advantage is its ability to actively regulate temperature, enabling camouflage even when the target is cooler than the background - something traditional infrared camouflage cannot achieve. However, large-scale deployment of this method is resource-intensive and requires significant energy, resulting in high costs.

- Other principles: There have been many recent studies to create artificial leather products [6], material plates that can adapt to color and ambient temperature, using other principles [7] in addition to the typical principles mentioned above, a promising great potential for future adaptive camouflage products.

2.2. Selection of the principle of adaptive camouflage

Based on the research results, along with the evaluation of advantages, disadvantages, and key characteristics of the application range, the research team has selected an approach based on the "**Electro-chromic active**" principle. This choice is justified by the following reasons:

Firstly, this issue has attracted significant global attention and research efforts. The approach based on the "**Electro-chromic active**" principle offers several advantages, particularly in terms of flexibility, cost-effectiveness, and ease of experimental implementation. Moreover, the active electrochromic model is highly feasible and aligns well with the current research capabilities and conditions of the authors' team.

In the following section, the research team will present the adaptive camouflage model within the visible spectrum, along with the research findings and evaluations derived from the proposed model.

3. SIMULATION, CALCULATION, DISCUSSION

3.1. Developing an adaptive camouflage model in the visible area

The research team proposes to develop an adaptive camouflage model in the visible light area based on the electro-chromic active principle [8], including 3 main parts, as shown in Figure 1.

Figure 1. *The adaptive camouflage model in the visible area.*

Part 1: Camera system to capture the background images.

Part 2: Computer, including the adaptive camouflage pattern software. Images captured from the camera system will be transmitted to the computer via USB connection, the camouflage pattern software will receive the images from the camera system as input images to process, extract characteristic colors and create camouflage patterns respectively, and create adaptive camouflage pattern images displayed on the display.

Part 3: The display screen, as LED matrix panel and computer screen. Images of adaptive camouflage patterns designed from the software will be displayed on LED screens and computer displays.

The computer used has a configuration of i7-7600U CPU, 12 GB RAM, Windows 10 Home 64 bit. The LED screen used is outdoors 06 Module LED P4, with a resolution of 96x128. The LED screen may not accurately display the colors of the adaptive patterns due to limited saturation levels and low resolution. However, the LED screen is used to demonstrate the operating principle and prove the feasibility of the camouflage model.

The operating mechanism of the adaptive camouflage model is as follows: when the adaptive camouflage system operates, the background images will be continuously received and processed by the image capturing and processing module, creating the camouflage patterns and displaying them onto the display module, which is overlaid onto the camouflaged object. In case of the object in movement or the background in change, the background image is always captured, processed to create a corresponding pattern (adaptive) and displayed on the display screen continuously to match the background, ensuring effective camouflage for the object.

3.2. Creating adaptive and experimental camouflage patterns

The typical methods for determining the dominant colors of a background are the principal component analysis [9], the linear block algorithm [10], the K-means clustering [11], and the Fuzzy C-Means (FCM) clustering algorithm [12]. For simplicity, we use the K-means clustering algorithm and choose 5 dominant colors to extract. Based on the block diagram of the adaptive camouflage model, the research team has developed the adaptive camouflage pattern software, using Qt Creator, C++, and OpenCV libraries, as shown in the diagram in Figure 2.

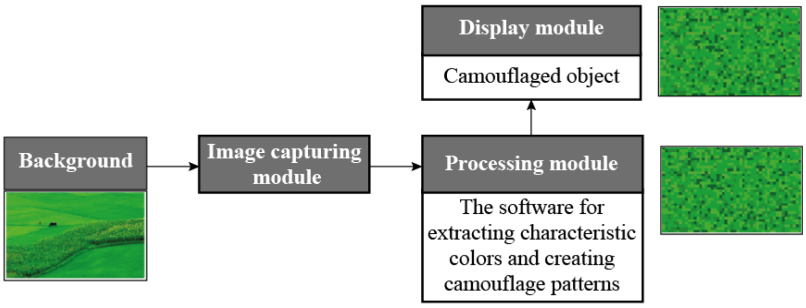

Figure 2. *Block diagram of the adaptive camouflage model.*

3.3. Simulation results and comments

Testing and evaluating product effectiveness are based on two criteria: Evaluating adaptive patterns and response time. For evaluating the patterns, the research team uses the visual evaluation method, using CSI and UIQI.

3.3.1. Pattern adaptation results

Figure 3. *The images of the camouflage pattern Off, On and Camouflage modes.*

The research team conducted experiments using the developed camouflage pattern software with various background images. Figure 3 presents the camouflage pattern in Off-mode, On-mode, and Camouflage-mode. The results indicate that the camouflage patterns accurately replicate the colors and lines of the original images.

3.3.2. Response time for pattern generation

Adaptive camouflage, not only simply adapts to a variety of backgrounds, but also adapts over time. That's why the response time factor is also extremely important in adaptive camouflage. The number of dominant colors, K is the input variable of the K-means clustering algorithm. In which, the more K increases, the more clustering time it takes, resulting in longer extraction of typical colors. The computer's processing speed also needs to be taken into account. It can be evaluated based on two variables including pixel size and number of dominant colors to evaluate the image processing time of adaptive camouflage software.

When keeping the number of dominant colors unchanged, changing the pixel size does not greatly affect image processing time. The testing results obtained in case of the number of dominant colors K=5, pixel size is 10 pixels and 30 pixels, the image processing time fluctuates around 0.65 seconds.

When keeping the pixel size fixed and increasing the number of dominant colors, it can be seen that the image processing time increases significantly. However, the image processing time is still usually guaranteed to be less than 1 second with the number of typical colors from 3 to 5 colors. The results of image processing time calculated for each K value are shown in figure 4.

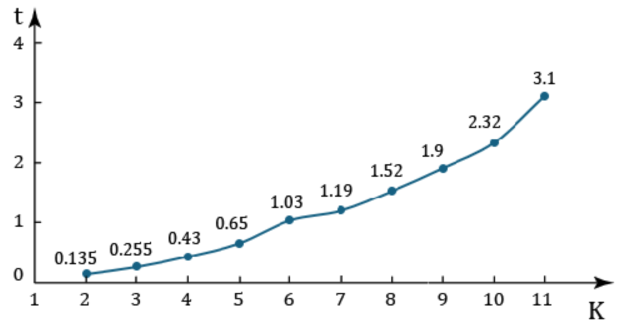

***Figure 4.** The dependence of processing time to create the adaptive patterns with the number of typical colors K.*

3.3.3. Evaluating the effectiveness of adaptive patterns using CSI and UIQI

a) Collecting and taking samples of the background images

a. Background 1 *b. Background 2* *c. Background 3* *d. Background 4*

***Figure 5.** Survey background (top) and corresponding adaptive pattern (bottom).*

The background images collected by the camera system of the adaptive camouflage model include 04 background samples, a combination of green grass mixed with tree roots, mixed background between grass and stone road, and opaque white wall background combined with stainless steel doors, as shown in figure 5.

To compare with the adaptive pattern, the research team uses 05 available camouflage pattern samples with the same size of 1920 x 1080 pixels, numbered from 1 to 5, as shown in figure 6.

a. Pattern 1. *b. Pattern 2.* *c. Pattern 3.* *d. Pattern 4.* *e. Pattern 5.*

Figure 6. *Available camouflage patterns.*

In addition, we also used two large-scale background images, which are general and representative of typical backgrounds, namely forest and urban areas, taken from above with a Sony a6400 camera at a resolution of 6000 x 3376, as shown in Figure 8. For these two backgrounds, we used the “randomWindow2d” function in Matlab to select 100 random positions. At each position, we extracted images of the same size as the pattern images to evaluate the camouflage patterns.

a. Background 5 *b. Background 6*

Figure 7. *Aerial photograph of forest and urban backgrounds.*

b) Camouflage similarity index CSI

The camouflage similarity index CSI is commonly used to evaluate existing military camouflage designs [13]. CSI ranges from 0 to 1, and the best value of 0 is achieved if the camouflage is blended perfectly with the background, calculated as follows:

$$CSI = \frac{\Delta E_{bc}}{\Delta E_{max}} \quad (1)$$

$$\Delta E_{bc} = \frac{1}{n}\sum_{i=1}^{n}\{(L_{bi} - L_{ci})^2 + (a_{bi} - a_{ci})^2 + (b_{bi} - b_{ci})^2\}^{1/2}$$

$$\Delta E_{max} = \max_{0\le i\le n}\{(L_{bi} - L_{ci})^2 + (a_{bi} - a_{ci})^2 + (b_{bi} - b_{ci})^2\}^{1/2}$$

in which L_{ci}, a_{ci} and b_{ci} are the CIE Lab value of the i^{th} point of the camouflage image. L_{bi}, a_{bi} and b_{bi} are the CIE Lab value of the i^{th} point of the background image.

Conduct CSI evaluation using the Matlab tool with the background and patterns collected. The calculation results are listed in table 1

Table 1. *The CSI value between the available camouflage pattern image and the adaptive pattern compared to the background.*

	Pattern No. 1	Pattern No. 2	Pattern No. 3	Pattern No. 4	Pattern No. 5	Adaption
Background 1	0.3688	0.3598	0.4099	0.4141	0.4438	**0.2597**
Background 2	0.4005	0.4886	0.3947	0.4115	0.4454	**0.0594**
Background 3	0.4190	0.4617	0.4497	0.4383	0.4549	**0.1724**
Background 4	0.4030	0.4024	0.4402	0.4402	0.4321	**0.1629**
Background 5	0.2987	0.3244	0.3542	0.4316	0.4884	**0.1613**
Background 6	0.4155	0.4339	0.3568	0.3554	0.3429	**0.1948**

In comparing the results obtained, we can see:

+ Adaptive patterns have the smallest CSI. Particularly for background 2, when the background has a different color than the existing camouflage pattern, the adaptive pattern shows outstanding effectiveness.

+ For forest background, green grass, patterns number 1 and 2 are more effective than patterns number 3, 4 and 5, consistent with visual evaluation, because pattern number 1 has the dominant colors of green nugget, olive green, dark green and earth brown. Pattern number 2 also has the dominant colors quite similar to pattern number 1, with an overall green tone and brightness [14].

+ For the urban background, the results can be seen as almost the opposite of the forest background. Overall, the urban background has a composite nature of colors and brightness, with the dominant colors being the gray and white patches of roads and concrete walls. Therefore, pattern number 5 and 4 have a higher camouflage effectiveness compared to pattern number 1 and 2.

c) Universal Image Quality Index UIQI

The Universal Image Quality Index (UIQI) quantifies the distortion of the processed image compared to the original version. The distortion metric is defined as a combination of three factors: loss of correlation $C(x,y)$, luminance distortion $l(x,y)$ and contrast distortion $S(x,y)$ [15]:

$$UIQI = C(x,y)\cdot l(x,y)\cdot S(x,y) = \frac{\sigma_{xy}}{\sigma_x\sigma_y}\cdot\frac{2\overline{x}\,\overline{y}}{(\overline{x})^2+(\overline{y})^2}\cdot\frac{2\sigma_x\sigma_y}{\sigma_x{}^2+\sigma_y{}^2} \quad (2)$$

In which, x_i and y_i are the gray level of the i^{th} pixel of the background and camouflage image and:

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i\,, \qquad \overline{y} = \frac{1}{N}\sum_{i=1}^{N} y_i\,,$$

$$\sigma_x = \frac{1}{N-1}\sum_{i=1}^{N}(x_i-\overline{x})^2\,, \quad \sigma_y = \frac{1}{N-1}\sum_{i=1}^{N}(y_i-\overline{y})^2\,,$$

$$\sigma_{xy} = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})(y_i - \overline{y})$$

The UIQI value ranges from -1 to 1. The best value is 1 when $x_i = y_i$.

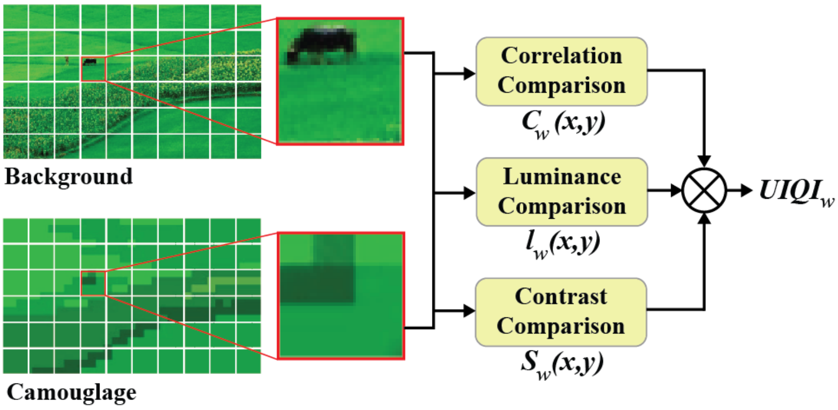

Figure 8. *UIQI calculation chart.*

The first component $C(x, y)$ is the correlation coefficient between x and y, measures the degree of linear correlation between x and y, and the value range is [-1 1]. The best value $C(x, y) = 1$ reaches when $y_i = ax_i + b$ with $i = 1,2, \dots, N$, in which a and b are constants and a > 0. Even when x and y have a linear relationship, image distortion can still be evaluated in the second and third components. The second component $l(x, y)$ with a value range of [0 1], measures the average luminance difference between two images, $l(x, y) = 1$ when $\overline{x} = \overline{y}$. The values σ_x and σ_y can be thought of as the contrast of x and y, so the third component measures the contrast level of the images. Its value range is between [0 1], and has the best value $S(x, y) = 1$ reached when $\sigma_x = \sigma_y$.

UIQI is applied using a sliding window *w* of size N×N, starting from the upper left corner of the image, moving pixel by pixel horizontally and vertically through all rows and columns of the image until when reaching the bottom right corner, as shown in figure 8. The UIQI value obtained is the average of all values $UIQI_w$ for each sliding window [16].

The results of calculating UIQI are listed in table 2 below:

Table 2. *The UIQI value between the available camouflage pattern image and the adaptive pattern compared to the background.*

	Pattern No. 1	Pattern No. 2	Pattern No. 3	Pattern No. 4	Pattern No. 5	Adaption
Background 1	-0.0003	-0.0001	0.0013	0.0003	0.0003	**0.0032**
Background 2	0.0255	0.0134	0.0135	0.0117	0.0130	**0.0716**
Background 3	0.0742	0.0403	0.0408	0.0369	0.0255	**0.2963**
Background 4	0.0002	0.0007	-0.0001	0.0001	-0.0004	**0.0014**
Background 5	0.0005	0.0003	0.0003	0.0004	0.0003	**0.0053**
Background 6	0.0006	0.0004	0.0004	0.0004	0.0004	**0.0049**

In comparing the results obtained, we can see:

+ Compared to the camouflage patterns on the same background, the adaptive patterns have the largest UIQI, showing the best structural similarity.

+ The camouflage patterns have different color tones, but the patterns are the same, leading to not much difference in the UIQI values of the 5 camouflage patterns.

Evaluations of the impact of the number of dominant colors on CSI and UIQI values were carried out. The results are summarized in table 3 below:

Table 3. *CSI and UIQI values of the background and adaptive pattern when changing the number of typical colors K.*

	CSI			UIQI		
	K = 3	**K = 4**	**K = 5**	**K = 3**	**K = 4**	**K = 5**
Background 1	0.02955	0.02729	**0.2597**	**0.0039**	0.0038	0.0032
Background 2	0.0796	0.0700	**0.0594**	0.0711	0.0714	**0.0716**
Background 3	0.2000	0.1768	**0.1724**	0.2959	0.2962	**0.2963**
Background 4	0.1825	0.1672	**0.1629**	0.0016	**0.0020**	0.0014
Background 5	0.1771	0.1639	**0.1613**	0.0053	**0.0066**	0.0053
Background 6	0.2122	0.2094	**0.1948**	0.0049	0.0049	0.0049

From Table 3, it can be seen that when increasing the number of dominant colors K, the CSI index gets a smaller value, showing the similarity in camouflage color. However, the adaptive patterns have different numbers of dominant colors, but the texture of the pattern is the same. This leads to an insignificantly changed value of UIQI.

Thus, it can be seen that adaptive patterns show their similarities in both color and texture through CSI and UIQI calculated between the pattern compared to the changing background. Besides, the calculated simulation results have made it clear that UIQI will be appropriate to evaluate the pattern compared to the background in case of the patterns in different textures.

4. CONCLUSIONS

In this article, the authors provide an evaluation of adaptive camouflage principles currently being researched worldwide. Based on the analysis of the advantages, disadvantages, and key characteristics of their application scope, the research team selected the "**Electro-chromic active**" principle for the visible light spectrum and conducted experiments to evaluate the results.

The research results have shown that the generated digital camouflage patterns, in addition to matching the background in both color and texture, also possess the ability to adapt when the background changes. In the model proposed by the authors, the pattern-generating software operates with low latency, achieving a response time of under 1 second, thereby reducing the likelihood of detection and identification by adversaries. Furthermore, image quality assessments indicate that adaptive patterns achieve the lowest CSI and the highest UIQI values across different backgrounds. These results demonstrate the effectiveness of using adaptive camouflage patterns for various backgrounds. Additionally, evaluating camouflage patterns using the UIQI index is only suitable when the patterns exhibit distinct texture differences.

The initial research results obtained have demonstrated the feasibility of applying the adaptive camouflage model. In the coming time, it is necessary to further research and develop adaptive camouflage models for application as well as improve the existing camouflage methods.

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TÓM TẮT

Phát triển một phương pháp tạo họa tiết ngụy trang thích nghi theo thời gian thực dựa trên các thiết bị điện màu chủ động

Ngụy trang truyền thống có những hạn chế trong tác chiến hiện đại, đặc biệt khi mục tiêu di chuyển hoặc phông nền thay đổi nhanh chóng. Ngụy trang thích nghi, với khả năng điều chỉnh màu sắc và họa tiết theo thời gian thực, mang lại giải pháp linh hoạt và hiệu quả. Bài báo này trình bày nghiên cứu tổng hợp các nguyên lý ngụy trang thích phổ biến trên thế giới và đề xuất một mô hình ngụy trang cho vùng ánh sáng khả kiến dựa trên nguyên lý điện màu chủ động. Kết quả đánh giá cho thấy họa tiết thích nghi đạt Chỉ số tương đồng ngụy trang CSI thấp nhất và Chỉ số chất lượng hình ảnh phổ quát UIQI cao nhất trên các phông nền khác nhau. Qua đó cho thấy cho thấy sự hiệu quả rõ rệt của mô hình ngụy trang thích nghi. Với số lượng màu chủ đạo từ 3 đến 5, thời gian tạo họa tiết dưới 1 giây, và so với các họa tiết cố định thì họa tiết thích nghi có mức độ tương đồng với phông nền tốt nhất.

Từ khóa: Họa tiết ngụy trang; Ngụy trang thích nghi; CSI; UIQI.