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Virtual Methods of Testing Automatically Generated Camouflage Patterns Created Using Cellular Automata

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Abstract. The article presents a method of designing and assessing the camouflage effectiveness of a novel camouflage pattern used in military uniforms. “Artificial intelligence”, namely cellular automata, which, based on terrain imaging, allowed the authors to obtain dedicated, tailor-made, or universal camouflage patterns, was used as the design method. On the other hand, the study on camouflage effectiveness was based on tests with the participation of observers in a virtual environment using a personal computer.

Introduction

Camouflage is one of the most effective and, simultaneously, more economical methods of concealing the forces, and thus gaining an offensive and defensive advantage over the enemy, both in defense and in an attack [i] Given the technological progress, especially in the field of sensors, on today's battlefield the reconnaissance can conducted via hyperspectral imaging, i.e. from a wide range of the electromagnetic spectrum, covering not only the visible spectrum but also near- and far-infrared (thermal vision) and microwave (radar) radiation wavebands.

On the other hand, multispectral methods are also employed for this purpose. These are based on the acquisition of data from selected characteristic frequencies (channels), e.g. where spectral characteristics of live flora include the minimum locally 670 nm (VIS red) and maximum 800 nm (NIR). So a good battle dress uniform (BDU), an effective camouflage coating, or proper vehicle camouflage painting should fit into the background in a wide range of electromagnetic spectra.

The Eye as a Tool

However, the human eye remains the essential reconnaissance instrument. It is equipped with a retina, on the surface of which two types of sensors are located: rod cells responsible for monochromatic and night vision (scotopic vision) and cone cells[ii] responsible for color vision and functioning in daylight (photopic vision). The former (amounting to about 120 million), due to their location outside of the central part of the retina, do not provide acute vision but are about 100 times more sensitive to light than the cone cells and react well to movement. On the other hand, the cone cells (about 6 million), thanks to their huge concentration – mainly in the central part of the retina[iii], near the macula (macula lutea) – ensure sharp vision, especially up to 20 degrees in the visual axis of the human eye.

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Moreover, due to their sensory characteristics, the cone cells have a particularly good but selective color sensitivity[iv]. Hence, there are cone receptors sensitized to visible shortwave radiation (short-preferring (S), with peak spectral sensitivity at approx. 420 nm) responsible for the perception of blue color, those sensitive to colors with medium wavelengths, such as green (mid-preferring (M), with the peak at approx. 530 nm)) and the ones sensitive to colors with long wavelengths (long-preferring (L), with the peak at around 565 nm)), such as red.

Stimulating these three types of cones in the right proportions allows the eye to perceive (trichromatism). In the case of sufficiently intense and balance stimulation of all three types of cone cells, humans are capable of seeing the color white (white light).

Considering the limitations and inadequacies of the human sense of sight – trichromatism, and not detecting a continuous signal in the visible range (400-700 nm), the CIE 1931 XYZ color space was developed to correspond to human perception. To obtain a perceptually uniform space, one in which the colors could be compared easily, the CIE XYZ model underwent mathematical transformations, resulting in the CIELAB model, where “L” is light, “a” is a color from green to crimson, and “b” corresponds to the colors blue to yellow. This model is used as the primary device-independent model for describing and comparing colors.

Camouflage Patterns

We can therefore distinguish central and peripheral vision. In terms of the camouflage itself, its goal is to neutralize distinctive features of the object to be camouflaged. These physical properties make the object stand out from the background and focus the observer’s attention. They include, among others, the color, shape, size, gloss (shine), contrast, and interrupted continuity of the background. Three main types of patterns can be distinguished (Fig. 1):

– the mimetic pattern, whose function is to cause the object to blend into its background of the terrain (crypsis). Detection is minimized while the observer makes an eye sweep;
– the disruptive (dazzle) pattern is to break the shape of the given object so that the observer has greater difficulty focusing their attention on the given object and, what follows, recognizing or even identifying this object.
– the mixed pattern, i.e., mimetic-disruptive pattern, where the mimetic camouflage is obtained by applying intricate details referring to the terrain background, and the disruptive element is its proper aggregation.

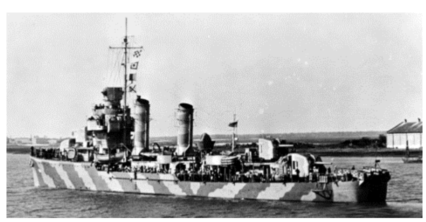
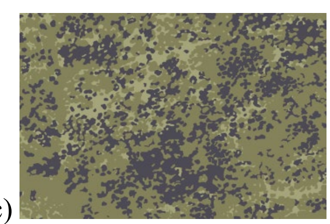
a)  b)  c) 

Fig 1. *Types of camouflage: a) mimetic – bird [*v*]; b) dazzle – USS Hobson [*vi*]; c) mixed – Danish M84 [*vii*]*

Camouflage patterns are usually dedicated to a selected environment: forest, desert, an agricultural area, urban surroundings, etc. One extreme case is the photorealistic camouflage used by nature observers or hunters. Attempts were also made to design and implement a universal camouflage pattern to provide adequate protection in diverse environments, e.g., forests and rocky areas. However, their universality was revealed to be questionable.

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Currently, in several research centers worldwide, including WITI (Fig. 2), work is underway on technologies that would enable the creation of adaptive camouflage, which would automatically adjust itself to its background.

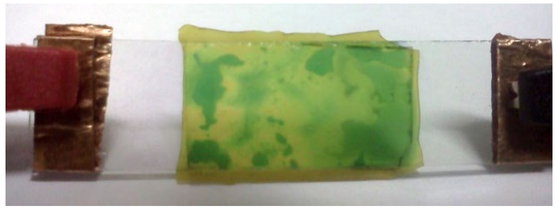

Fig. 2. *Electrochromic cells change their color with the voltage applied*

Generation of Camouflage Pattern

The main goal of the camouflage pattern designed by the authors was its effectiveness and applicability, which meant the possibility of using it in specific military applications (uniforms, camouflage nets, mobile camouflage, camouflage painting of vehicles). However, several limitations have been imposed on the design, including the guidelines on the nature of camouflage and the technological requirements resulting from the assumed perceptual model of the human eye. These included:

– reduction of the number of colors to only a few;
– creating a micro-pattern with mimetic functions;
– obtaining a macro-pattern disrupting the silhouette outline;
– avoidance of a noticeably repetitive pattern;
– the pattern has to blend well with the given environment.

To meet the above requirements, the authors chose a method based on processing representative images of the selected environment. The work used only images that meet the above requirements. At least five photographs were selected for a given type of environment (such as a Central European forest) and season (e.g., summer). Only the areas that could serve as the proper background were cut out of these images for further processing, and so, for example, forest areas, sky, or ground were discarded. In contrast, fragments showing forest vegetation were left (Fig. 3).

Fig. 3. *Fragment of the photograph selected for further processing*

The next step was to reduce the color palette too, but a few – in the works, it was decided to use 4, as this is the most common number of colors for uniforms and camouflage covers. After

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analyzing various methods, the global algorithm with the minimal variance (the so-called Otsu method of automatic image thresholding) was selected and tested, which enabled the selection of colors representative for the entire set of representative frames. The method is based on dividing the color space into areas with a minimum variance inside each area and with maximum variance between the areas. Afterward, a color representative for each area is indicated. This can be done, among others, using the median or weighted average method to obtain the colors that are most different from one another and with the greatest possible optical contrast between them.

This method yielded not only four representative color coordinates in the CIELAB color space model but also the percentage share of individual colors, and the processed images with a reduced number of colors assumed the form of textures containing a large number of fine spots (micropattern) and no macro pattern (Fig. 4).

Fig. 4. *Image with the colors reduced to four*

To obtain the macro pattern, the authors reviewed the techniques of grouping pixels and decided that cellular automata (CA)would be employed for further investigations.

Similarly, as artificial neural networks, cellular automata facilitate replacing complex descriptions of complicated circuits with a system of numerous simple circuits with simple rules [viii] Cellular automata are constructed of neighboring cells, forming a network of d-dimensions, where each cell at a given moment (cycle) can assume one of the defined states at a given moment (cycle). The way states alter between successive cycles is determined by simple rules relating to the state of the cell and its neighbors (Fig. 5).

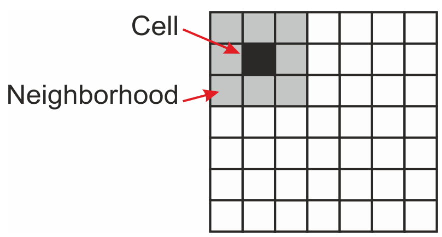
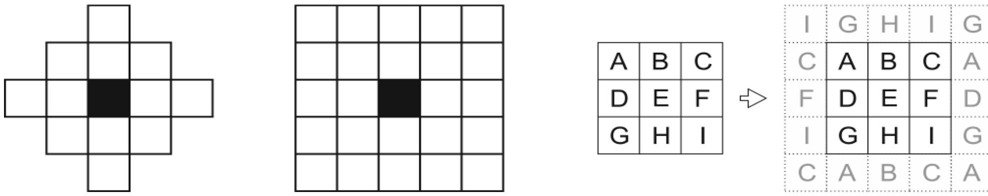


Fig. 5. *Cellular automata system model*

In the adopted camouflage design methodology, what follows the stage of reducing the number of colors is graphics described as pairs of two-dimensional arrays:
– a color matrix with dimensions of n×3, where *n* specifies the number of colors used; in the authors' case, it was 4, and the number 3 corresponds to the color coordinates of the CIELAB color space model, where L can assume the values from 0-100, and *a* and *b* – from 128 to 127;
– pixel matrix with dimensions $x \times y$, where x and y are the width and height of the graphic expressed in pixels, respectively, the colors of the graphic are described by the color index from the color matrix; in the authors' case, there were four colors, from 0 to 3.

The image model adopted in this manner made it possible to directly translate them into the cellular automata model, in which a 2-dimensional network of cellular automata was incorporated. The network corresponded to the pixel matrix, with states defined by the index from the color matrix.

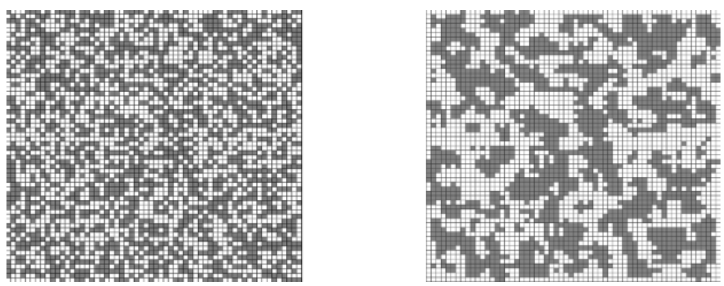
Among the distinct types of neighborhoods (Fig. 6a and Fig. 6b), the von Neumann neighborhood was selected (Fig. 6c), and in the case of cells at the margins, they were supplemented with cells from the opposite side of the network that was to surround them.



a) b) c)

Fig. 6. *a) the Moor and b) von Neumann neighborhood; c) surrounding the cells at the margins*

As the result of the review and testing of diverse types of CA, the majority-vote CE type, with r = 1, and 4 states, was used in work. The transition rule (function) determined the new state as the one which obtained the highest number (sum) of states in the previous cycle for the cell and its neighborhood (Fig. 7).



a) Random image b) Image after two cycles

Fig. 7. *Operation of the majority vote-type cellular automata*

Further image processing using CA, involved an averaged image created out of n (min. 5) images with a reduced number of colors k (k = 4). The images were unified in terms of the scale of the elements in the photo so that in each image, 1 px corresponds to the same dimension in each image (px/cm = constant). All images have also been cropped to one size x×y.

Then, a 3-dimensional array with dimensions [y×x×n] was created from those layers, and it corresponded to the size of the frame and the number of images and contained images (pixels) in the form of successive layers (Fig. 8a). To obtain an averaged image, the 3-dimension array [y×x×n] was reduced to a 2-dimension matrix [y×x], taking the value for the [y, x] cell as the most frequent value for all the layers n of the array for this index in the matrix (Fig. 8b).

a) b)

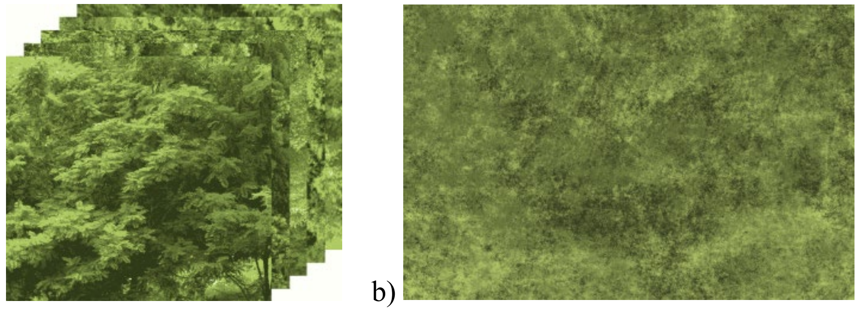


Fig. 8. *3-dimensional table created out of several images and a) its averaged version b)*

After several cycles of cellular automata operation, the authors received a macro pattern. CA operation was stopped when the size of the larger macro pattern spots reached the intended maximum size for a given application. Per the defensive standard [ix], this threshold was set at 0.3 of the dimension of the camouflaged object. For example, for uniforms – 0.3×200 cm = 60 cm, and for medium-sized armed personnel carrier – 0.3×800 cm = 240 cm. The generated pattern is shown in Figure 9.

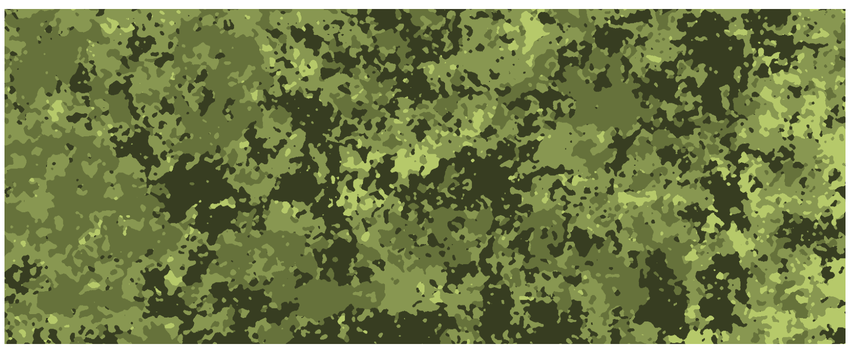


Fig. 9. *Camouflage pattern generated using CA*

The next step was to verify the camouflage effectiveness of the newly created pattern. For this purpose, the camouflage had to be applied to the military facility/object for which it was intended (e.g., a uniform, camouflage net, etc.) and then assessed. Initial tests could be conducted in a virtual environment using camouflage patterns and 3D models of military objects (Fig. 10), and the final tests, once verifying the camouflage on real objects during field tests using observers.

Fig. 10. *Application of the camouflage pattern onto a 3D object*

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Virtual Environment

Bearing in mind the constraints of human vision, the concepts of a virtual environment [x] were presented to assess camouflage effectiveness of the newly designed camouflage patterns, which, based on modern computer systems and displays, could largely replace the onerous and quite expensive field research (Fig. 11), in particular at the initial stage of designing camouflage patterns

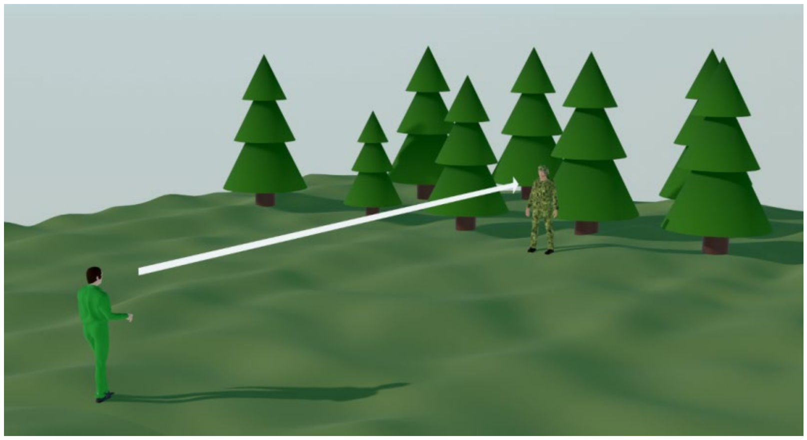

Fig. 11. *Graphic representation of field tests*

Virtual environment studies are based on presenting the observers with images containing the background (most often real images) from a given distance with a model of a camouflage pattern on the background (Fig. 12) and performing a typical detection-recognition-identification (DRI) assessment during which the observer states, whether the object has been detected (D), recognized (R) or identified (I). Detection is understood to mean the presence of an object, recognition – the ability to determine the type of object spotted (e.g., a tank), and identification, where the observer can provide details of the kind of object spotted (e.g., an M1 Abrams main battle tank).

Fig. 12. Typical virtual test display

Additionally, the time measurement for each observer from the start of the observation to the occurrence of either D, R, or I, for each image under observation.

One of the measures of central tendencies is taken as the test results. Usually, it is the average, or in the case of a large spread – the median of the distance, and the average or median of the detection, recognition and identification times for a given pattern against a given background. This is recorded for at least 6 observers.

To ensure the conditions for virtual tests resemble those in the natural environment the most, quite a few conditions have to be met and the researchers have to have at their disposal the following:

- images that have to meet most of the requirements [xi] in terms of quality – appropriate spatial and tonal resolution, correct model and color space, good sharpness, lighting, white balance, and be with the attached metadata on the environmental and atmospheric conditions, location (geographical), direction (NSEW) and time of when the image was taken, distance from the background (observation border), as well as its photographic parameters (focal length of the lens, size of the matrix, shutter, diaphragm);
- models of objects with the tested camouflage applied to them, and the camouflage colors are in a tightly controlled color scheme;
- a test station ensuring the correct colors representation (calibration and color management system) and appropriate simulation of the observation distance, which results from the image geometry and which in virtual testing means the distance from the display to the observer, and one which will also enable testing in accordance with selected methodologies and registration of test parameters.

In addition, it is also necessary to visually synchronize the model and the background to ensure that their sizes, lighting, and color space are consistent. The benefits of research studies performed in virtual environments include, first of all:

- becoming independent from the availability of training areas (proving grounds) with the required background, for which the camouflage pattern is dedicated. The desired terrain may not be accessible due to e.g., military operations and weather conditions.
- independence from weather conditions and the season;
- allowing research to be conducted in safe and comfortable conditions where observers can focus on reconnaissance;
- access to a convenient and immediate preview of the test results, thanks to the analytical module, which is a part of the virtual research management system;
- availability of military equipment and soldiers necessary to carry out field research is no longer an issue.

Summary

The proposed method of generating and testing camouflage patterns enables the design of novel patterns containing both the micro-pattern responsible for blending the camouflaged object into the background, thus reducing the likelihood of detection and the macro-pattern, which disrupts the silhouette outline and makes the object recognition challenging. The discussed methods can be used to design camouflages for various military objects: uniforms, camouflage covers, mobile camouflages, or vehicles with camouflage painting. The investigated pattern-generating method allows obtaining patterns both strictly dedicated to specific environments and seasons, as well as more universal patterns, depending on the provided initial images.

Together with the virtual testing method, which enables economic and quick testing, several individual solutions can be evaluated, not only limited to different types of cellular automata but also using morphological transformations, genetic algorithms, or artificial neural networks to find the most optimal solutions. In the future, it would be worthwhile to perform further cognitive science research in the field of image perception and recognition to replace human observers with their artificial counterparts, which would reduce the testing costs even further and which would lead to obtaining even more effective camouflage solutions using various camouflage patterns. The presented methods do not have to be constrained to the visible spectrum, and if the researchers had at their disposal an appropriate library of images from other electromagnetic spectra, that would allow them to design and examine solutions for the different ranges as well.

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