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# Modeling and Simulation of Apparent Color and Apparent Patterning of Camouflage Fabrics

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Advanced camouflage patterns for military applications consist of highly detailed camouflage patterning and multiple tonal (blended) colors. The complexity of these camouflage patterns establishes a need for additional test methodologies for color and pattern evaluation. One metric for evaluation is apparent color, which is the combination of all visible wavelengths (380-700 nm) of light reflected from large (≥1m2) fabric sample sizes for a given standoff distance (25-100 ft). This follows in that camouflage patterns lose resolution with increasing standoff distance, and eventually all colors within the pattern appear monotone (the "apparent color" of the camouflage pattern). The concept of apparent color is based on far-field and statistical characteristics of camouflage patterns. In contrast, the concept of apparent camouflage patterning is associated with intermediate distances between observer and target. Accordingly, quantitative metrics for camouflage-pattern viability based on apparent patterns should be different than those for apparent color, thus providing additional criteria for evaluation This paper describes general algorithms for modeling apparent color and patterning of camouflage patterns that are relevant to evaluating camouflage fabrics.

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# Introduction

The concepts of apparent camouflage color and pattern within the visible range are examined with respect to their potential for practical utilization as a criterion for more realistic assessments of camouflaged-fabric viability, which should be with respect to field conditions and realistic distances from observers, as would occur during actual operations. The examination considers the potential use of parametric models for simulating camouflaged-fabric patterns as would be viewed at far field and as a function of distance from an observer, which would be a function of camouflage pattern and multiple tonal (blended) colors. Assessments of apparent colors and patterns for camouflaged-fabrics based on simulation should represent more quantitative criteria for their operational viability, which is in contrast to essentially qualitative assessments based on visual inspection at unrealistic distances from observers. Quantitative assessment of camouflaged-fabric viability according to apparent camouflage colors and patterns could establish a foundation for more cost saving evaluation procedures, as well as procedures for reevaluating camouflaged-fabric stockpiles resulting from failures to meet previously established criteria. General algorithms for modeling apparent colors and patterns are described. Prototype simulations of apparent camouflage color and patterns are presented to provide proof of concept for their modeling and simulation.

The concept of apparent camouflage pattern is related to that of apparent color, which is the combination of *all* visible wavelengths (380-700 nm) of light reflected from large ($\geq$1m$^2$) fabric sample sizes for a given standoff distance (25-100 ft). This follows in that camouflage patterns lose resolution with increasing standoff distance, and eventually all colors within the pattern appear monotone (the "apparent color" of the camouflage pattern). The concept of apparent color, however, is based on far-field and statistical (or space averaged) characteristics of camouflage patterns. In contrast, the concept of apparent camouflage pattern is to be associated with intermediate distances between observer and target, and resolution level of pattern details.

Problem Statement. Given a camouflage pattern and associated multiple tonal colors, determine its visual characteristics, i.e., apparent camouflage color at far field, and apparent camouflage pattern, as a function of observer-target separation, for given illumination conditions and background environment, using a parametric model. Accordingly, the viability of the camouflaged fabric with respect to specified field environments should be examined with respect to these visual characteristics, and not those associated with close visual inspection.

Quantitative assessments of apparent camouflage colors and patterns represent metrics for predicting target acquisition in the field (Ref. 1). Shown in Fig. 1 is a schematic representation of different types of input information that would be required for parametric modeling of apparent camouflage colors and patterns, respectively. As implied by these figures, camouflaged fabric as viewed under practical field conditions, due to the many different types of external factors, should appear significantly different in contrast to close visual inspection. The complexity of external factors influencing apparent camouflage colors and patterns suggests that their parametric modeling be in terms of pattern characteristics associated with far field and intermediate distances between observer and target, respectively, which are consistent with practical field conditions.

Shown in Figs. 2 is a schematic representation of simulating apparent colors at far field and apparent patterns as a function of distance, which is in terms of image-processing algorithms (Ref. 2). Again, the concept of apparent color concerns characterization at distances approaching far-field conditions. Far-field properties for development of specific algorithms, i.e., toward development of quantitative metrics for apparent color, are: 1) the relative percentage of covering

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by different color segments determines the dominant colors at far field; 2) the segment-area weighted average of reflectance for different segments provides an apparent-color model; and 3) the average color obtained by iterative mean filtering of a camouflage pattern implies the dominant colors at far field. Again, the concept of apparent pattern concerns pattern characterization at intermediate distances between target and detector, and not distances approaching far-field conditions. Viewer-observable characteristics of camouflage patterns for development of specific algorithms, i.e., toward development of quantitative metrics for apparent camouflage patterns, are: 1) the relative blending of different colors as a function of distance; 2) the relative blurring of pattern detail as a function of distance; and 3) blurring of patterns, i.e., reduction of pattern details, due to point spread functions (PSFs) associated with different types of imaging systems that are conceivable for field detection. The problem of camouflage fabric degradation suggests yet another simulation metric for assessing viability under field conditions, which is described in Fig. 2. This simulation metric is that of modeling either apparent color or patterning in combination with modeling of different types of degradation. Accordingly, the potential viability of a camouflage fabric can be assessed not only with respect to apparent color and pattern metrics, but also with respect to metrics based on possible extreme degradation modes, resulting from interaction with field environments occurring in the future.

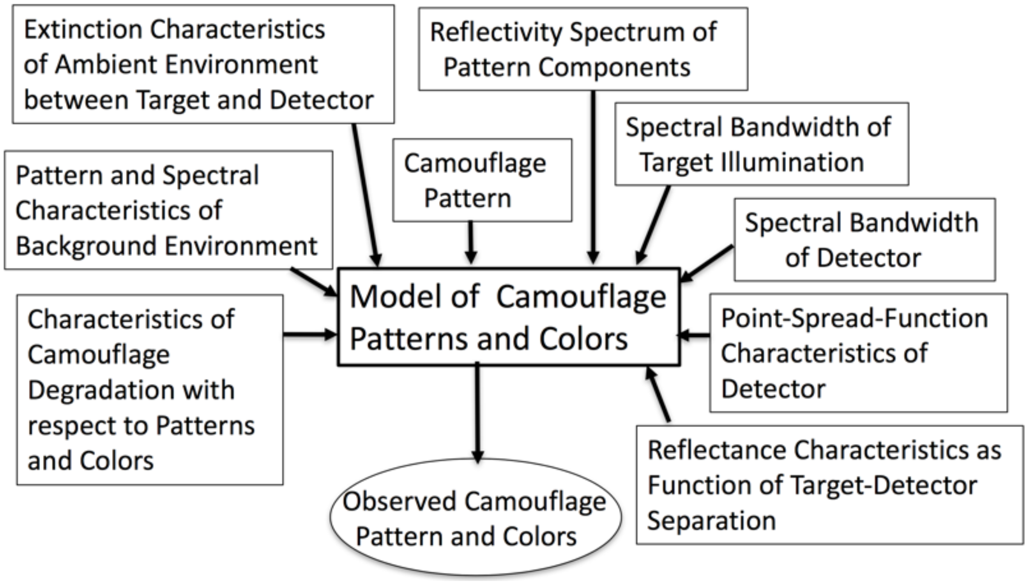

Figure 1. Input information required for parametric modeling of apparent color

With respect to simulation of apparent color and patterning using image processing algorithms, a general paradigm for simulation is that apparent color and patterning as a function of distance can be correlated with the level of image mean-filtering and comparative scaling (See Fig. 3), i.e., the number of iterations applied to an image for a given mean-filter-type or smoothing algorithm and size reduction of images relative to a reference size, respectively. Accordingly, apparent color at far field can be modeled by large numbers of mean-filter iterations approaching saturation. Referring to Fig. 3, it should be noted that the level of smoothing could possibly represent image blurring due to PSF characteristics of a viewing system or any simulated pattern degradation or degradation tolerance level for far-field comparison using image scaling. As seen in Fig. 3, image scaling demonstrates that at sufficiently far field, levels of degradation associated with close visualization and colored segments having relatively less coverage are not noticeable.

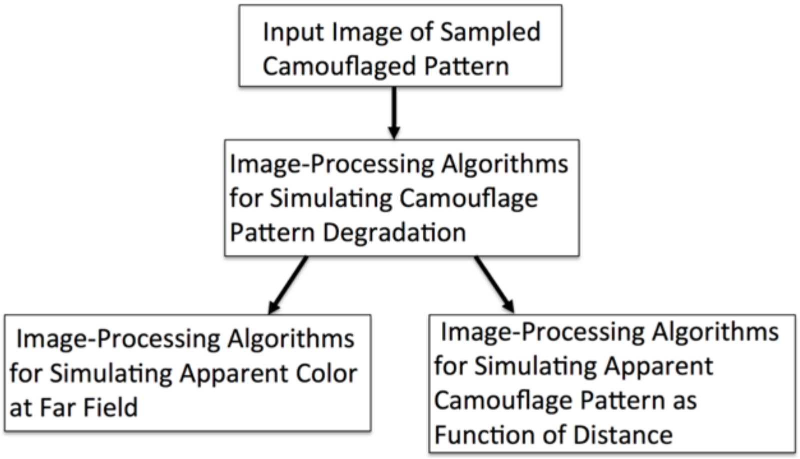

Figure 2. Schematic representation of simulating apparent colors and patterns in terms of image-processing algorithms.

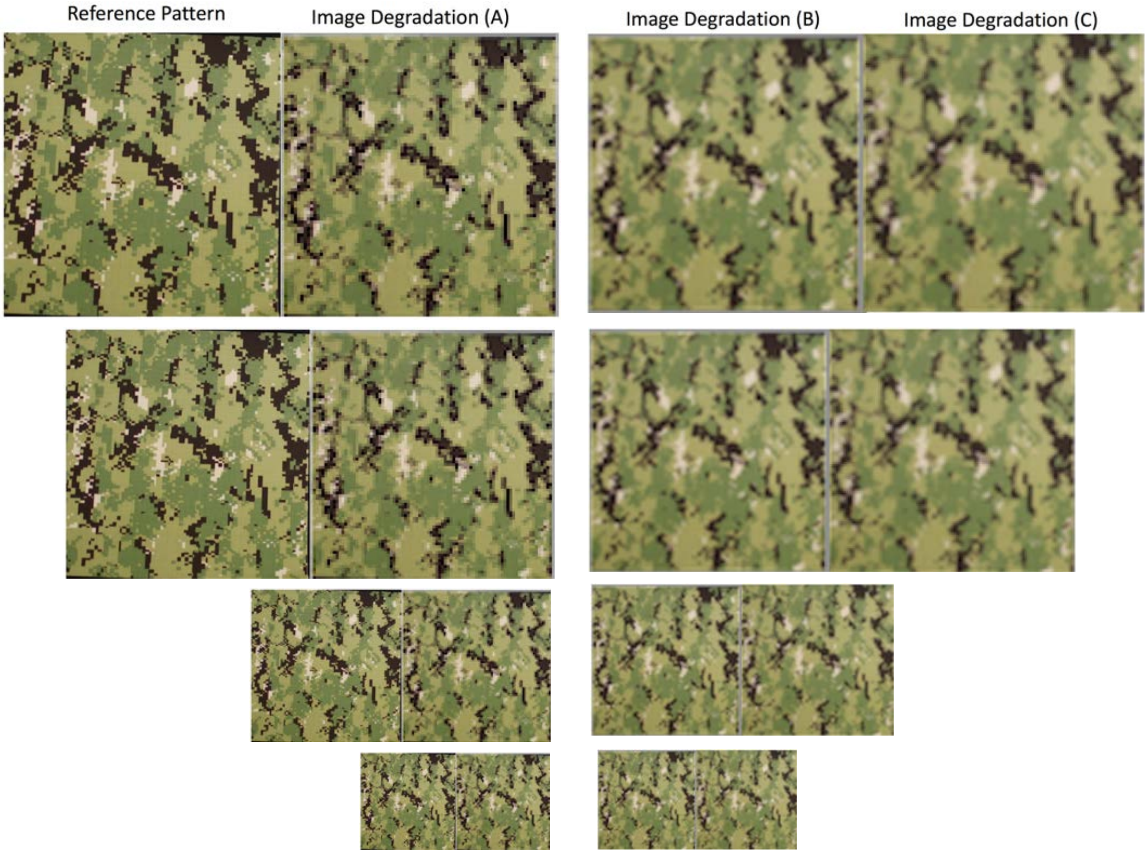

Figure 3. Simulation of apparent color and pattern using image smoothing and scaling.

## Laboratory simulation of camouflage-fabric patterns as function of distance and UV exposure

Accelerated Weathering via Exposure to Ultraviolet (UV) Radiation + Moisture

Fabric specimens (1 $ft^2$) were cut from random locations from two separate bolts of fabric in triplicate (N=3 per fabric bolt, for a total of 6 fabric specimens). The two fabrics used in the data set were:

1. Control fabric (from currently fielded combat uniforms), composed of 50% Nylon, 50% Cotton blend (NYCO), printed with the Area of Responsibility, Woodland (AOR2) camouflage pattern
2. Sample fabric (developmental), composed of 50% Nylon, 50% Cotton blend (NYCO), printed with the Area of Responsibility, Woodland (AOR2) camouflage pattern

The results of this simulation are given in Appendices 1 and 2.

### Imaging

Each of the six fabric specimens were fastened vertically to a 1 $m^2$ black acrylic target board and imaged individually using a Canon 5D Mark iii DSLR digital camera (35mm lens @ f/1.4, ISO 200, 1/160s) using RAW image capture in a series of standoff distances (3, 6, 12, 16, 20, 24, 36, and 42 ft) from the target. Two Spectralight D75 light sources were used to illuminate the fabric and target board at opposing 45-degree incidence to the target, each @ 5 ft standoff distance from the target board. The captured RAW images were calibrated using Photoshop CS5 and ACR calibration script for a 24-color Colorchecker chart imaged at 3 ft distance under identical lighting conditions as the fabrics. The initial set of images was captured from pristine fabric (unweathered), which provided a baseline from which images would be visually compared after subsequent exposure to UV+Moisture.

### Colorfastness

Color measurements of the test fabrics were performed in accordance with AATCC Evaluation Procedure 6, Section 2, utilizing an X-Rite™ ColorEye® 7000A color spectrophotometer (Newburgh, NY) as the measurement instrument (Color -Control® Software version 5.0). Fabric specimens were illuminated with a pulsed-xenon source that is conditioned to approximate UVD65 illumination. Each measurement was performed using a small area aperture (0.5" ID) with the specular component included. The instrument was calibrated against a series of color verification tiles prior to fabric testing. Instrument calibration using both white tile and black trap standards was also performed every four hours during colorfastness testing.

For each test fabric, a single color was measured at random, rotated and measured in 90° increments over 360° (0° and 360° being the same configuration and measured twice), for a total of five measurements per color, per test fabric). This process was repeated using a second test fabric, for a total of 10 measurements per AOR color. Therefore, for a 4-color AOR2 fabric, a total of 40 CIE Lab measurements were made for each duplicate set of test fabrics per weathering test (see Appendices 1 and 2). The *L*a*b** values were averaged and the resulting *dE** value calculated based on colorfastness against *L*a*b** values of respective baseline values from pristine (unweathered) fabric, where *dE** is defined as:

$$\boldsymbol{dE^{*}} = \left[(\boldsymbol{L_2^{*}} - \boldsymbol{L_1^{*}})^{2} + (\boldsymbol{a_2^{*}} - \boldsymbol{a_1^{*}})^{2} + (\boldsymbol{b_2^{*}} - \boldsymbol{b_1^{*}})^{2}\right] \qquad \text{(Eq.1)}$$

where $L_1^{*}$ = Lightness of control fabric
$L_2^{*}$ = Lightness of weathered fabric
$a_1^{*}$ = red-green hue of control fabric
$a_2^{*}$ = red-green hue of weathered fabric
$b_1^{*}$ = blue-yellow hue of control fabric
$b_2^{*}$ = blue-yellow hue of weathered fabric

A weathered specimen fabric with a *dE** value of ≤2.00 is considered visually indistiguishable against its respective pristine fabric (see Appendix 1).

**UV + Moisture Exposure**

The six test fabrics were exposed to 8 hours of ultraviolet (UV) light, followed by four hours of moisture in accordance with ASTM G151 and ASTM G154: Operating Fluorescent Light Apparatus for UV Exposure of Non-metallic Materials. The testing device used was a QLabs™ QUV® Accelerated Weathering Tester, Model QUV/Spray (Westlake, OH). To simulate outdoor weathering, the QUV tester exposes materials to alternating cycles of UV light and moisture at controlled, elevated temperatures. It simulates the effects of sunlight using special fluorescent UV lamps. It also simulates dew and rain with condensing humidity and/or water spray.[1] The QUV houses two banks of four UVA-340 lamps (eight total) that provides uniform broadband UV irradiance (see Fig. 4) (to fabric specimens located 2.54 cm from the light source. The QUV tester was preprogrammed to rotate between UV radiation exposure, followed by moisture exposure via condensation, in eight and four-hour cycles, respectively.

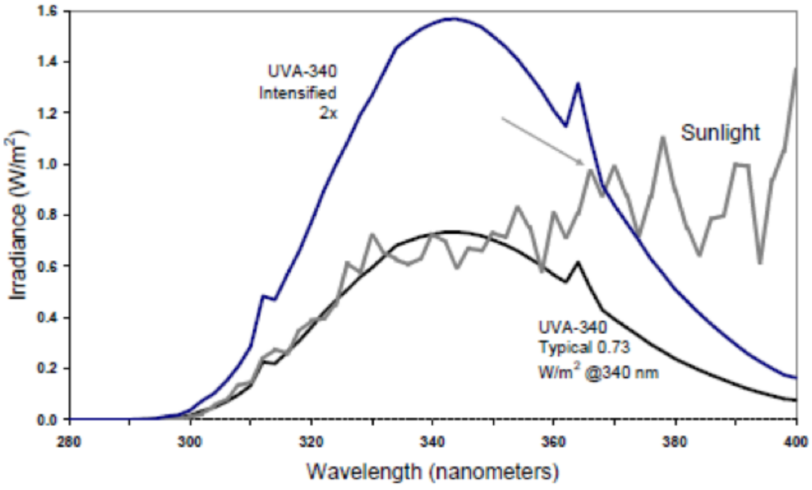

Figure 4. Broadband UV irradiance spectrum (300-400nm) of the eight UV-340 bulbs installed in the QUV tester; Lambda max is 340 nm.

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[1] http://www.q-lab.com/products/quv-weathering-tester/quv

Specimens were exposed to an average UV irradiance of 0.89 W/m$^2$, measured and continuously controlled electronically via SOLAR EYE® irradiance controller at four locations on the specimen testing racks (two locations per rack). The SOLAR EYE irradiance controller was calibrated prior to and after test fabric exposure tests with the CR-10® radiometer, a NIST traceable device that complies with ISO 9000 requirements. Test fabrics were mounted on aluminum specimen holders and rotated daily in the specimen racks prior to each UV exposure interval. Test fabric temperatures were monitored by a black panel thermometer (back exposed to air) located adjacent to the test racks. Fabrics were exposed to moisture via condensation using DI water as the source. Moisture control was monitored via Kestrel humidity sensor.

**Table 1. UV + Moisture Exposure Test Specifications**

| **ASTM G151 Specification for UV + Moisture Exposure** | **Test Conditions** |
|---|---|
| Light Source | UV-340 bulbs |
| Wattage (W) | Quantity 8 x 40 Watt (T12 x 121cm long) |
| UV radiation (nm) | 300-400nm (340nm lambda max) |
| Irradiance Setpoint (W/m$^2$) | 0.89 W/m$^2$ |
| Specimen surface temp for UV exposure (°C) | 60 ± 2°C |
| UV exposure interval (hrs) | 8 hrs |
| UV exposure intervals | 1 |
| Rel. Humidity Setpoint (%) | 95 ± 5 % |
| Specimen surface temp for moisture exposure (°C) | 50 ± 2°C |
| Humidity exposure interval (hrs) | 4 hrs |
| Humidity exposure intervals | 1 |

Following each UV + moisture exposure cycle, test fabrics were removed from the QUV tester and air-dried. The six test fabrics were individually re-imaged under identical lighting conditions and camera settings using the standoff distances listed above. Subsequent to imaging, colorfastness (400-700nm) was measured for each of the four colors on each fabric and $dE^*$ calculated. The imaging, colorfastness and UV + moisture exposure sequence was repeated for a total of ten (10) cycles for all six test fabrics to complete the data set.

### Simulation of apparent camouflage patterns with respect to degradation

When a camouflage fabric is exposed to different environments such as sea water and solar exposure, the fabric becomes degraded. The ImageJ software (see Ref. 3), an open source image processing program that can display, edit, analyze, process and save images, can be used to simulate the degradation of a camouflage fabric under different environments. This process of simulation can reduce the labor time required to analyze the degradation of camouflage fabrics in the lab in order to determine the proper acquisition of camouflage materials. The first step in the simulation process is to photograph or scan the pristine fabric into a digital image. The second step is to transform the camouflage patterns in the digitized version of the unworn fabric, via ImageJ, to closely match those of its degraded version. The last step would involve rescaling or performing pattern smoothing of the digitized version of the unworn or degraded fabric in order to simulate the degradation of the fabric due to distance.

In the first step, an unworn camouflage fabric would be digitally photographed or scanned as a 24-bit RGB image (8-bit per color) and then processed with the ImageJ software. Figure 5 illustrates the general simulation framework, with the use of a scanner.

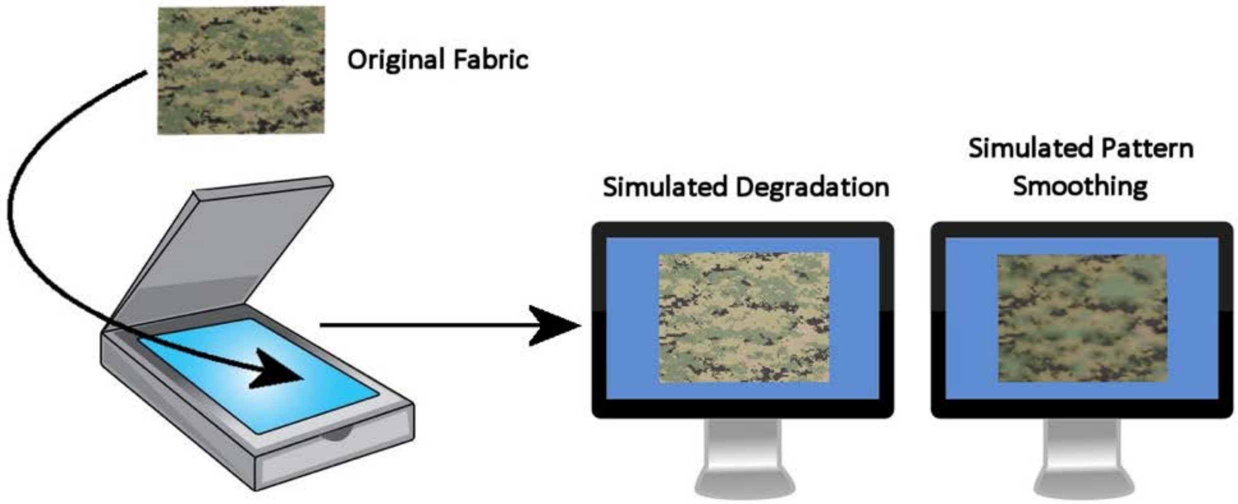


Figure 5. A fabric that is new and unworn is processed as a graphical image in order to simulate its image degradation under different environments and distances.

The second step involves transforming the 24-bit digital image of the fabric to one that represents a degraded version, using the ImageJ software. During this process, adjustments to the RGB values of the pixels in the digital image of the unworn fabric are made where the 8-bit values (i.e. 0 to 255) of each one or all of the three channels of red, green and blue are compelled to lie within a new range of 8-bit values that are established by the user. This process will linearly map the original 8-bit values of each RGB channel that lie within the range to new values in accordance with the relation **g(x,y) = a f(x,y)+b** where **g** is the new 8-bit color value of a channel (red, green or blue) in a 24-bit pixel at location **(x,y)** in the image, **a** is the slope of the linear mapping that is dependent on minimum and maximum values of the range set by the user, **f** is the original 8-bit value of the 24-bit pixel and **b** is parameter that is automatically adjusted by ImageJ to increase or decrease the brightness of the image . Any 8-bit value that lies outside the range is automatically assigned a value of 255, if the original value is greater than the maximum value in the range or 0 if the original value is less than the minimum value of the range. This will result in transforming the colors of the unworn fabric to ones that are apparent in the degraded fabric. This process is called “Adjusting the Color Balance,” and is repeated many times by trial and error, until the transformed colors in the image of the unworn fabric closely matches those found in the image of the degraded fabric.

The last step of simulating degradation is only employed if we are simulating the apparent degradation of a camouflage fabric due to distance. When a camouflage fabric is viewed from a distance, it would appear fuzzy due to distance-dependent degradation. The simulation of this type of degradation can be performed with ImageJ software by either downscaling or applying a smoothing operation many times on the image of the camouflage fabric. In downscaling the image, the image is resized to a smaller version of the same image that was obtained by digitally photographing the fabric as various distances. Here the number of pixels along the width and height of the image is reduced to closely match those of the smaller image obtained from the digital photographs. The bilinear interpolation process is employed during the resizing of the image. The bilinear interpolation process works in two directions (vertical and horizontal), and tries to achieve a best approximation of a pixel's color value in the reduced image, based on the values at surrounding pixels. Mathematically, according to the bilinear interpolation process, the color value $f$ at some point $(x, y)$ due to resizing of an image determined by:

$$f(x,y) \approx \frac{y_2 - y}{y_2 - y_1} f(x,y_1) + \frac{y - y_1}{y_2 - y_1} f(x,y_2). \qquad \text{(Eq. 2)}$$

where

$$f(x,y_1) \approx \frac{x_2 - x}{x_2 - x_1} f(Q_{11}) + \frac{x - x_1}{x_2 - x_1} f(Q_{21}), \qquad \text{(Eq. 3)}$$

$$f(x,y_2) \approx \frac{x_2 - x}{x_2 - x_1} f(Q_{12}) + \frac{x - x_1}{x_2 - x_1} f(Q_{22}). \qquad \text{(Eq. 4)}$$

and $Q_{11}=(x_1,y_1)$, $Q_{12}=(x_1,y_2)$, $Q_{21}=(x_2,y_1)$ and $Q_{22}=(x_2,y_2)$ are all known points in the original image with known color values. This algorithm reduces some of the visual distortion caused by resizing an image to a non-integral zoom factor, as opposed to nearest-neighbor interpolation, which will make some pixels appear larger than others in the resized image. In the smoothing operation, ImageJ will replace the value of each pixel in an image with the average of color values of surrounding pixels in a 3x3 pixel neighborhood. This produces a slight blur in the image, which is what is observed when an object is observed from a distance. For the simulations of distance degradation discussed in this paper, we have developed an ImageJ macro to apply the smoothing operation 100 times to an image in an effort to simulate distance-dependent image degradation.

We have digitally photographed two camouflage fabrics. One fabric is unworn and serves at the baseline for the simulation of degradation while the other fabric, that is identical to the unworn fabric, has been exposed to solar radiation long enough to produce noticeable degradation. Digital photographs of the two fabrics were also taken as various distances to observe the effects that distance has on the two fabrics. We have taken the digital images of the unworn fabric and applied our ImageJ processes, discussed above, in an effort to simulate degradation due to solar exposure and distance. The results of our simulation in comparison with the image of the actual degraded fabric are presented in the following figures.

## Prototype simulation of an apparent pattern

Presented in this section is prototype simulation of an apparent camouflage pattern using an image processing procedure. This prototype simulation is of an apparent pattern associated with the camouflage pattern AOR2 (Ref. 1). Image processing algorithms represent a convenient modeling approach for simulating apparent patterns as a function of distance between target and observer. In contrast to image processing procedures whose goal is that of image enhancement, our goal is simulation of blurring, fading and color changes of known camouflage patterns as a function of distance from observer, ambient environment and viewing-system point spread function (PSF).

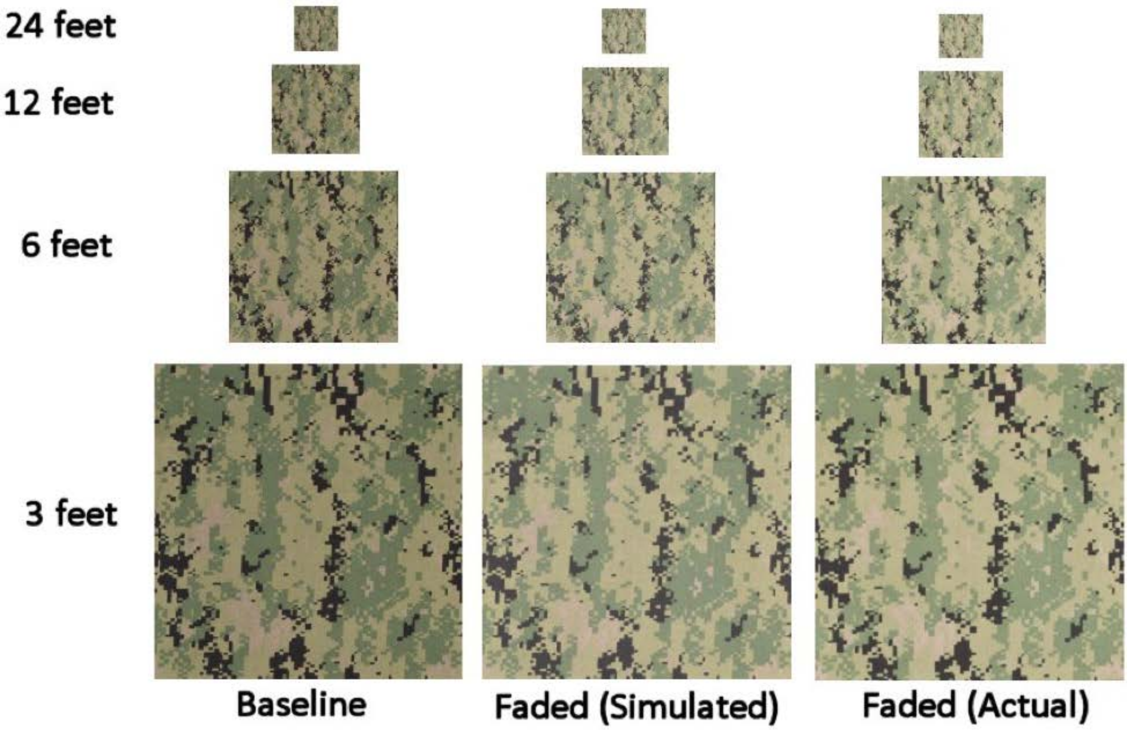


Figure 6. The baseline fabric at various distances in comparison with the simulated degradation of a like fabric and an actual fabric that was degraded via solar exposure. Note that 3 feet is considered the baseline distance.

There exist a wide range of image processing algorithms (Ref. 2) that can be used for simulating image degradation. Among these is the conceptually simple procedure of image blurring by pixel averaging using image downscaling, which is described schematically in Fig. 9. Referring to Fig. 9, which is with respect to a gray color-scale, it should be noted that although black and white are used for schematic description, image downscaling is in general associated with blurring between different colors.

Shown in Fig. 10 is simulated degrading of a camouflage-fabric image by repeated application of image downscaling as described in Fig. 9. Shown in Fig. 11 are comparisons of a camouflage-fabric image and its simulated degradation as a function of distance relative to an observer. The important point of this comparison is that for distances that are not very large, the apparent camouflage patterns of both original and degraded fabrics can in principle be the same. And further, that the similarity of original and degraded camouflage patterns can be assessed a priori using image processing algorithms.

Next, a camouflage-fabric specimen was exposed to 8 hours of ultraviolet (UV) light, followed by four hours of moisture in accordance with ASTM G151 and ASTM G154: Operating Fluorescent Light Apparatus for UV Exposure of Non-metallic Materials. The testing device used was a QLabs™ QUV® Accelerated Weathering Tester, Model QUV/Spray (Westlake, OH). To simulate outdoor weathering, the QUV tester exposes materials to alternating cycles of UV light and moisture at controlled, elevated temperatures. It simulates the effects of sunlight using special fluorescent UV lamps. It also simulates dew and rain with condensing humidity and/or water spray. Shown in Fig. 12 are image comparisons of the baseline camouflage fabric before and after UV exposure as a function of relative distance. Shown in Fig. 13 are image comparisons of the UV-exposed and simulated UV-exposed fabric specimens as a function of relative distance. Simulated UV exposure was achieved by application of color mapping from the measured UV exposed image onto the baseline image.

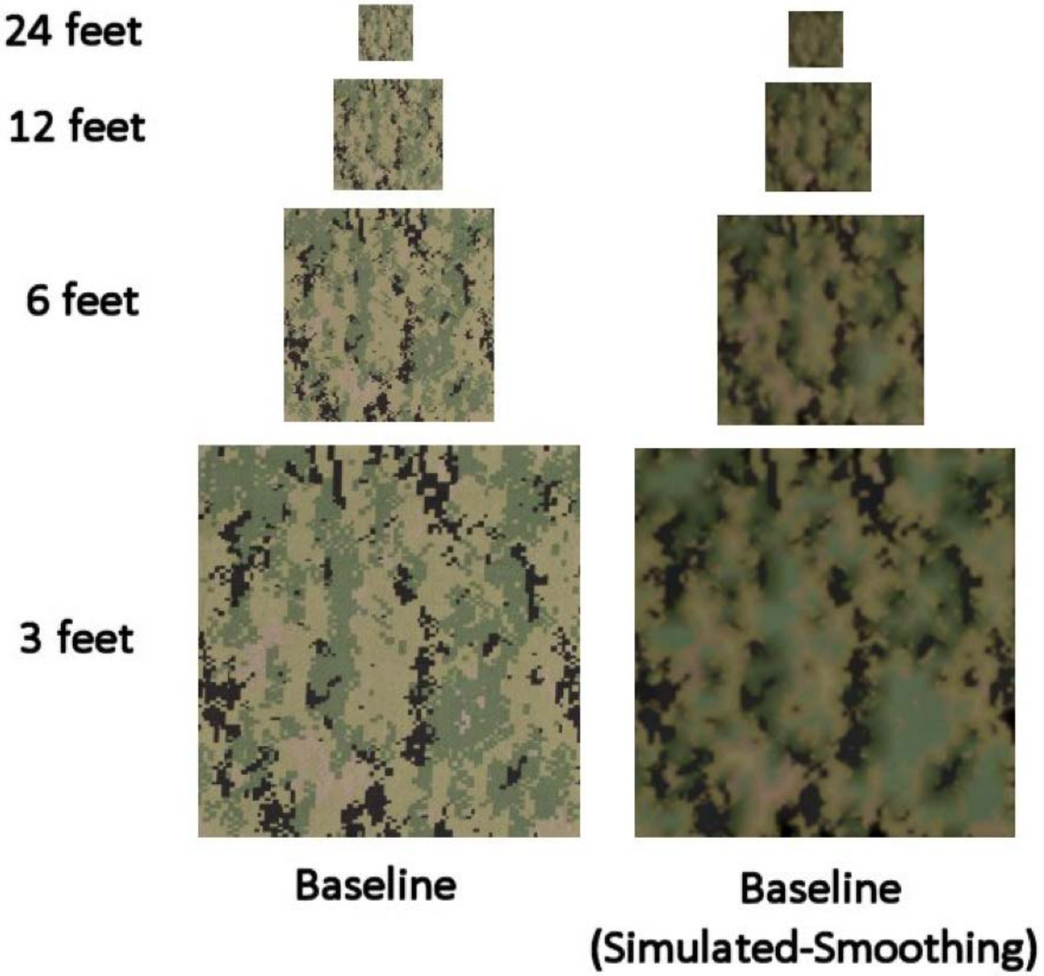


Figure 7. The baseline fabric at various distances in comparison with the simulated pattern smoothing of the same fabric. Note that 3 feet is considered the baseline distance.

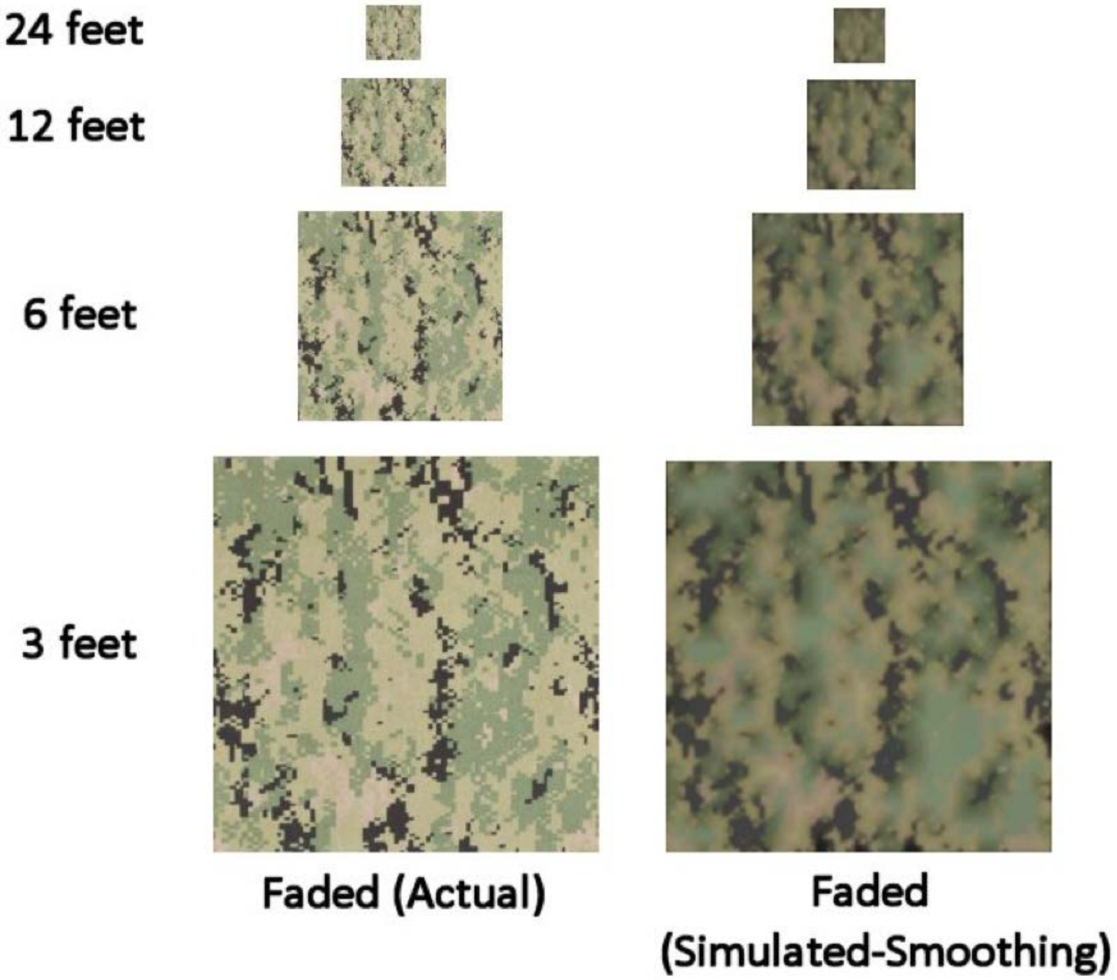


Figure 8. The degraded fabric at various distances in comparison with simulated pattern smoothing of the same fabric. Note that 3 feet is considered the baseline distance. Overall the results of the simulation are nearly identical to the actual images representing the degraded fabric. Additionally, the smoothing operations produces blurring which is consistent with what is observed when an object is viewed from a distance.

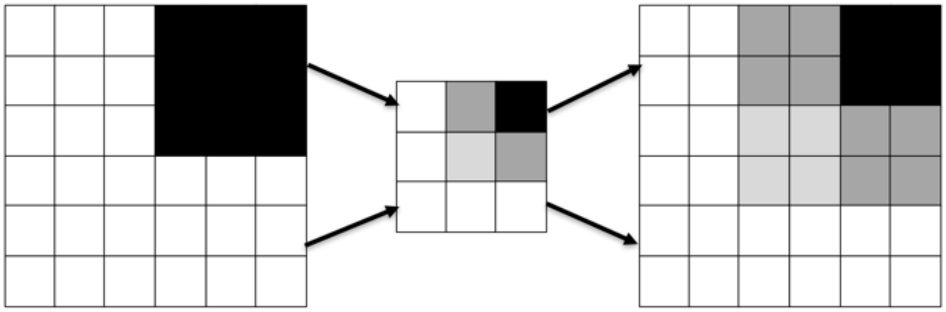


Figure 9. Schematic representation of image blurring by downscaling.

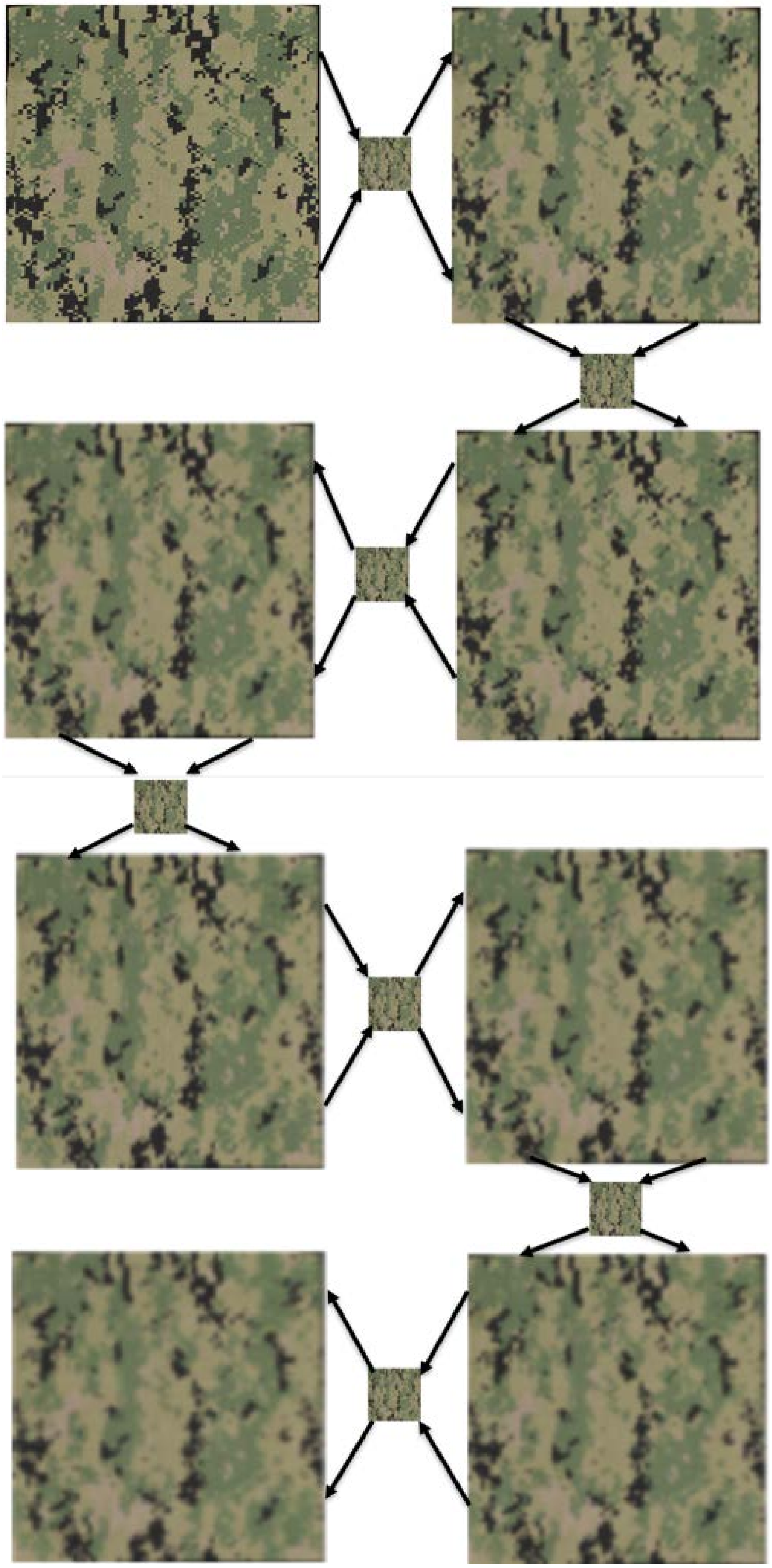


Figure 10. Simulated degradation of camouflage-fabric image by repeated application of image downscaling.

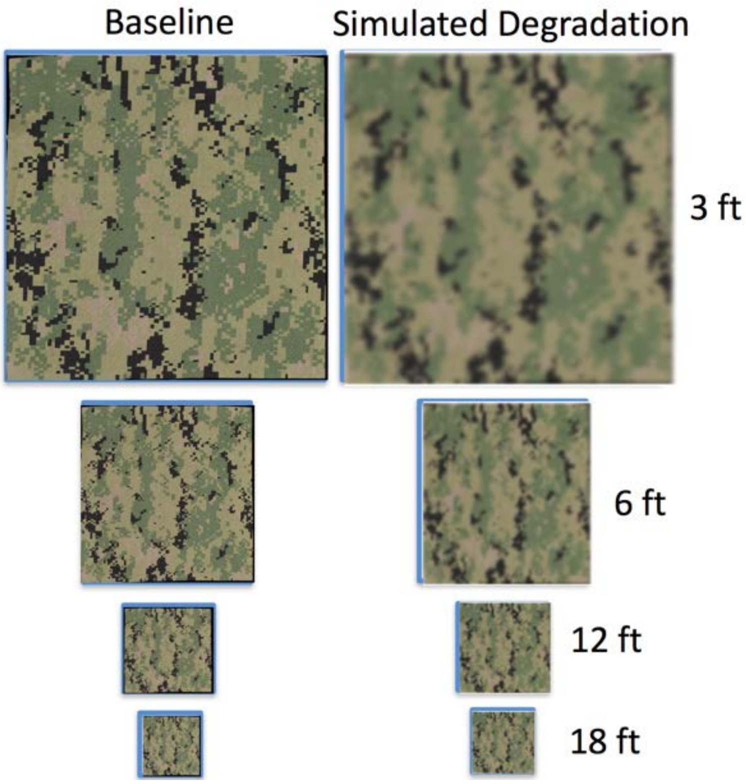


Figure 11. Comparisons of camouflage-fabric image and its simulated degradation as a function of distance.

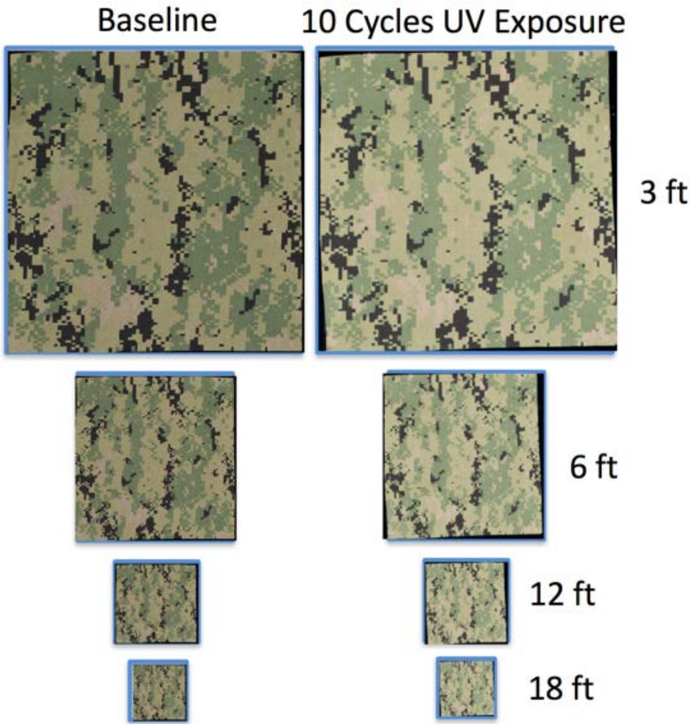


Figure 12. Comparisons of baseline and UV-exposed camouflage-fabric images as a function of distance.

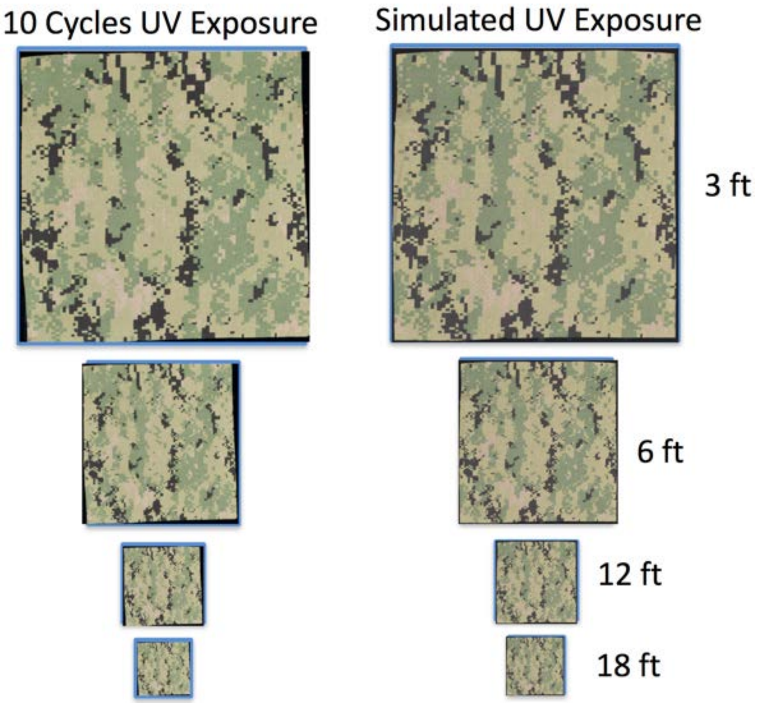


Figure 13. Comparisons of UV-exposed camouflage-fabric image and its simulation as a function of distance.

## Image processing algorithms

### Image Segmentation Process

There are five steps in the procedure to segment an image of a camouflage fabric into its individual colors. These five steps require the ImageJ software (Ref. 3), an open source image processing program that can display, edit, analyze, process and save images.

### Step 1: Apply smooth

This smooth function will slightly blur the image and replace the value of each pixel with the average values of its 3x3 pixel neighborhood. See below for a description of the computational process of the smooth function. The purpose of this function is to produce clear segmentation of the image.

### Step 2: Apply Color Threshold

This process will threshold the image based on the following color spaces:

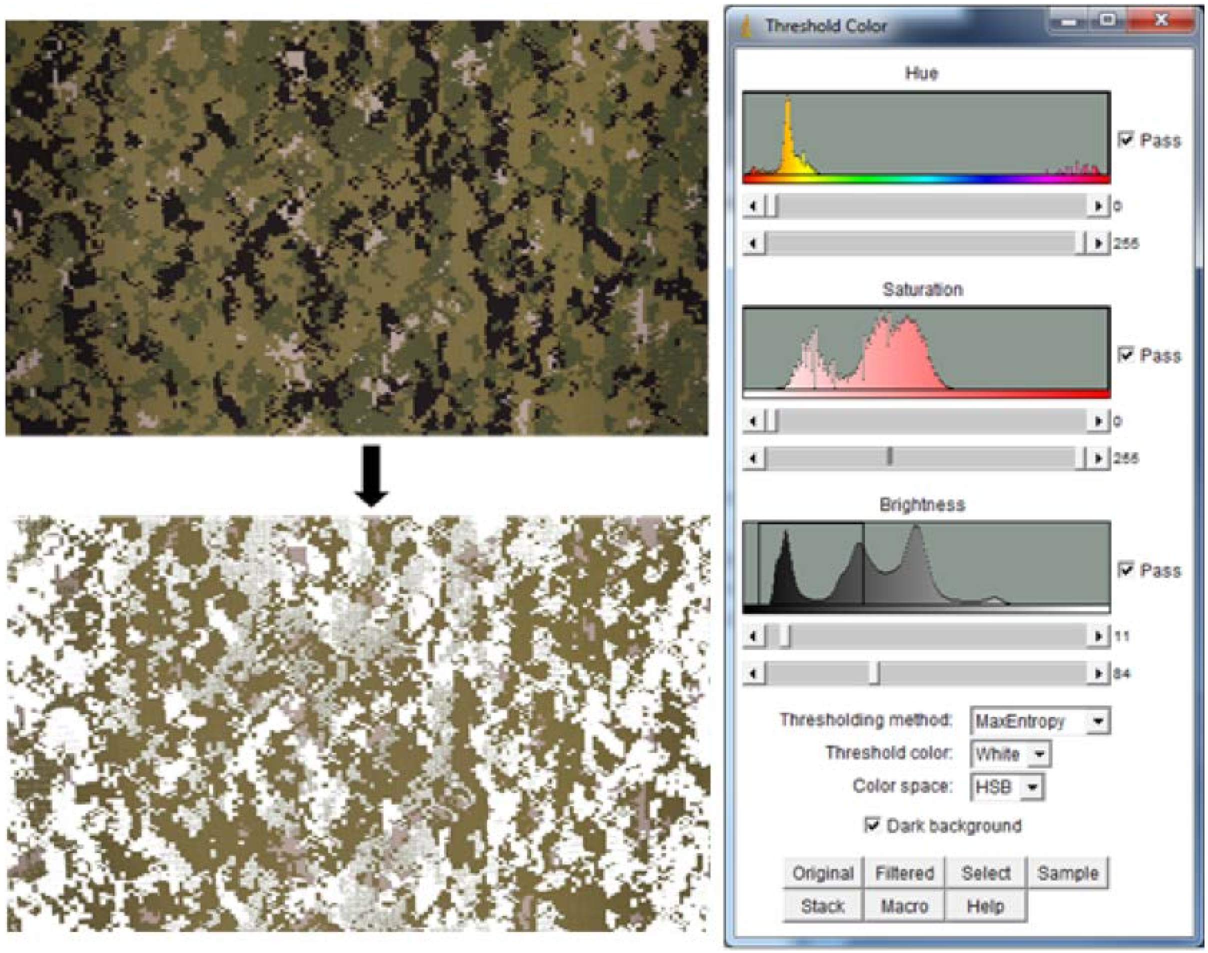
- Hue, Saturation and Brightness (HSB)
- Red, Green and Blue (RGB)
- CIE Lab
- YUV

The specific color space chosen is typically the HSB, though other color spaces can be chosen for color thresholding depending on the colors in the camouflage image. For the chosen color space, filters for each of the components of color (e.g. Hue, Saturation and Brightness) are set to certain ranges of color values manually via slider bars in order to segment out these specific colors (See Figs. (14, 15 and 16). Color values within each range are then thresholded and displayed.

Sixteen different color thresholding methods can be selected for this process. These available methods are:

1) Default - The original method of auto thresholding available in ImageJ, which is a variation of the IsoData algorithm.
2) Huang - Implements Huang's fuzzy thresholding method (Ref. 4).
3) Intermodes - This assumes a bimodal histogram. The histogram is iteratively smoothed using a running average of size 3, until there are only two local maxima: j and k. The threshold is then computed as $(j+k)/2$ (Ref. 5).
4) IsoData - The procedure divides the image into object and background by taking an initial threshold and then the averages of the pixels at or below the threshold and pixels above are computed. The threshold is incremented and the process is repeated until the threshold is larger than the composite average (Ref. 6).
5) Li - Implements Li's Minimum Cross Entropy thresholding method (Ref. 7).
6) Max Entropy - Implements Kapur-Sahoo-Wong (Maximum Entropy) thresholding method (Ref. 8).
7) Mean - Uses the mean of grey levels as the threshold (Ref. 8)
8) Min Error(I) - An iterative implementation of Kittler and Illingworth's Minimum Error thresholding (Ref. 9).
9) Minimum - Similarly to the Intermodes method, this assumes a bimodal histogram. The histogram is iteratively smoothed using a running average of size 3, until there are only two local maxima. The threshold t is such that $y*t-1 > y*t <= y*t+1$.
10) Moments – Uses Tsai's method and attempts to preserve the moments of the original image in the thresholded result (Ref. 10).
11) Otsu - Otsu's threshold clustering algorithm searches for the threshold that minimizes the intra-class variance, defined as a weighted sum of variances of the two classes (Ref. 11).
12) Percentile - Assumes the fraction of foreground pixels to be 0.5 (Ref. 8).
13) Renyi Entropy - Similar to the Max Entropy method, but uses Renyi's entropy instead (Ref. 8).
14) Shanbhag (see Ref. 12).
15) Triangle - The Triangle algorithm assumes a maximum peak (mode) near one end of the histogram and searches towards the other end. The algorithm will find on which side of the max peak the data goes the furthest and searches for the threshold within that range (Ref. 13).
16) Yen - Implements Yen's thresholding method from Ref. 14.

The choice of available color thresholding methods to pick is not unique and depends on the colors in the camouflage fabric, how these colors have been reduced due to environmental factors, and the type of illumination that the fabric exposed to. Finally, a threshold color type, must be chosen. Available color choices are red, white, black and B&W. The threshold color type chosen is usually white though other threshold colors can be chosen based on the desired color in the image of the camouflage fabric to be segmented.



Hue: ☑ Pass, 0, 255

Saturation: ☑ Pass, 0, 255

Brightness: ☑ Pass, 11, 84

Thresholding method: MaxEntropy

Threshold color: White

Color space: HSB

☑ Dark background

Figure 14. Segmentation of camouflage image using the Threshold Color function, where olive green is target.

### Step 3: Convert to 8-bit grey scale

This process will convert the camouflage image to an 8–bit grayscale. Here the number of colors is reduced to $2^8$. The purpose of this is to pave the way to segment the color as white over a black background.

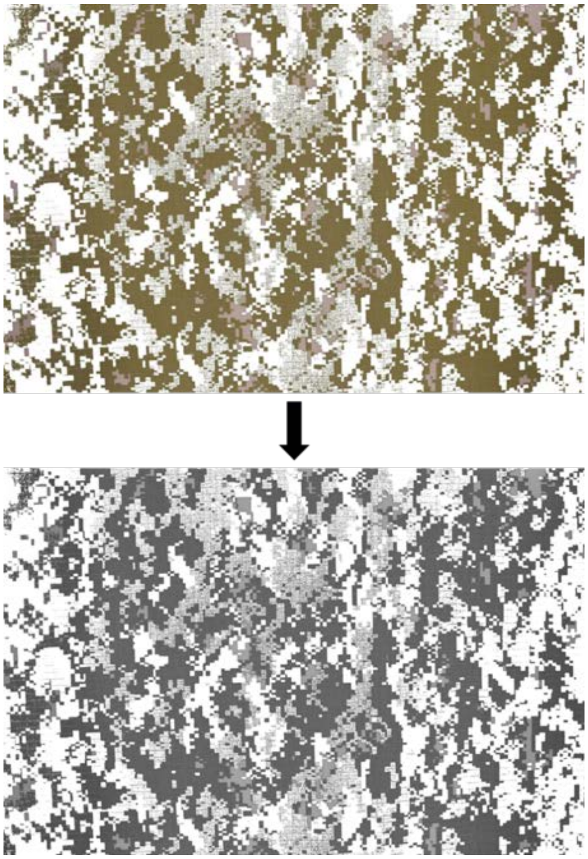


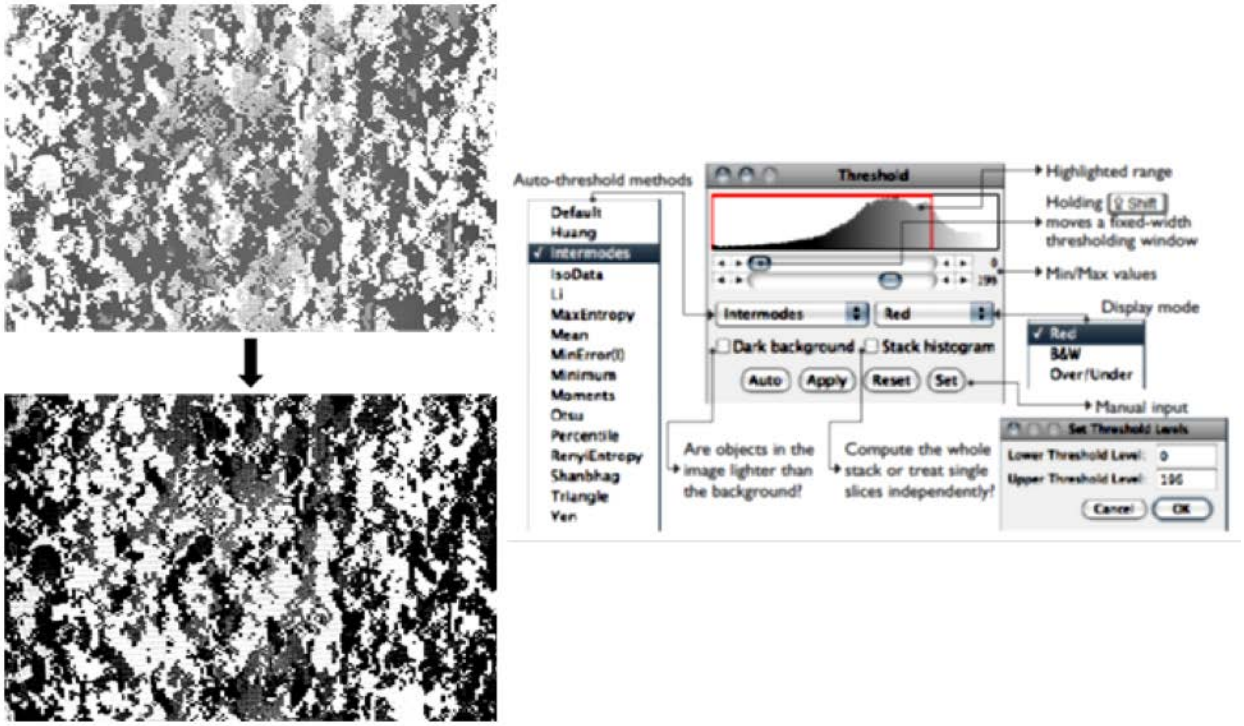
Figure 15. Conversion of image from threshold-based segmentation to that of 8-bit grey-scale (olive green is target).

**Step 4: Apply Threshold**

This process will segment a grey scale image into features of interest and background. Here the lower and upper threshold grey values can be interactively set via slider bars (see Fig. 16). A display mode must be selected as part of this thresholding process. The choices for a display mode are:

1) Red - Displays the thresholded values in red.
2) B & W - Features are displayed in black and background in white.
3) Over/Under - Displays pixels below the lower threshold value in blue, thresholded pixels in grayscale, and pixels above the upper threshold value in green.

The display mode that is chosen to segment an image of a camouflage fabric is B & W. The “Dark background” box may or may not be checked during the segmentation process. The purpose of this box is to reverse light features with dark features. The decision to check the “Dark background” box or not depends on whether or not the segmented color is in light or dark. Finally, a method for thresholding must be utilized. Available methods for thresholding are the same as given above under “Apply Color Threshold” and the choice of method to use is not unique but depends on the colors in the camouflage fabric, how these colors have been reduced due to environmental factors, and the type of illumination that the fabric exposed to.



Lower Threshold Level: 0
Upper Threshold Level: 196

Figure 16(a). Final Segmentation of olive green, whose pixels are assigned 1 (white) with background of 0 (black).

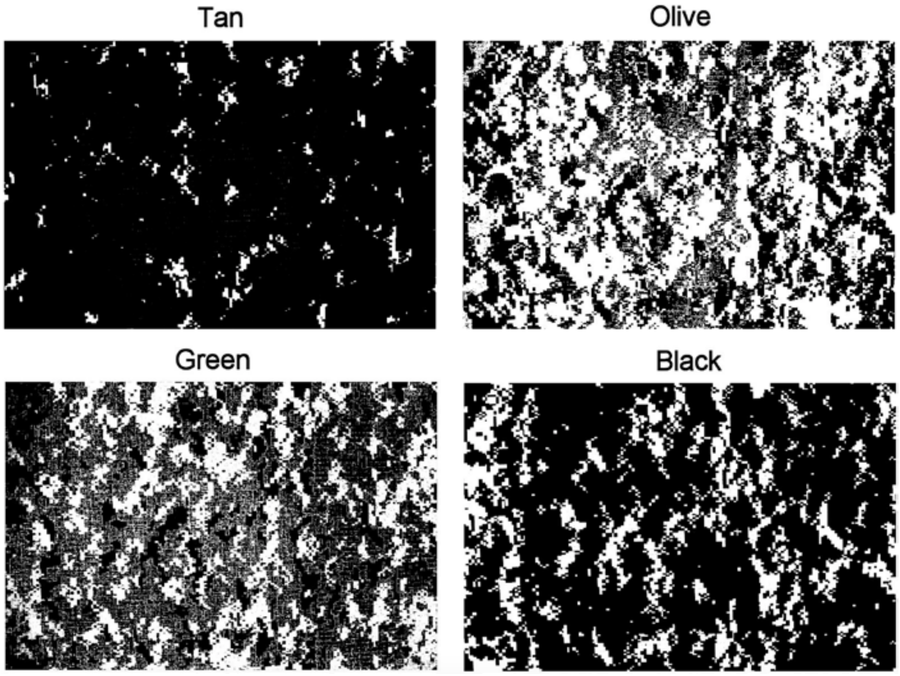


Figure 16(b). Segmentation of tan, olive green, green and black, whose pixels are assigned 1 (white) with background of 0 (black or grey).

### Step 5: Convert to Binary

This process will convert the image to black and white such that a black pixel has an 8-bit value of 255 and a white pixel has an 8-bit value of 0. This is the final step to segment out a particular color in a camouflage fabric as white over a black background.

### Point Spread Function

The point spread function is a process to simulate the appearance of a camouflage fabric when viewed from a distance by an observer and may be implemented by the following PSF operations in ImageJ. The first operation is to use the "smooth function" of ImageJ, where the image is blurred using a filtering algorithm. The filtering algorithm is the mean filter type, where each pixel is replaced with an average of its 3x3 neighborhood (Ref. 15). The "smooth function" may be applied to a segmented image successively.

The second operation involves the use of the "fast filter function," a plugin for ImageJ (Ref. 16), This function will perform an average over n x m pixels, where out-of-image pixels are replaced by nearest border pixel. The fast filter may be applied to a segmented image successively. The choice of which PSF operation to choose and how many times to apply that operation to the camouflage image, in order to simulate the effects that distance would have on the observation of the camouflage fabric, as seen by a viewing system, would depend on the distance of observation from the fabric. e.g., this would be the distance an observing detector would be from the camouflage object.

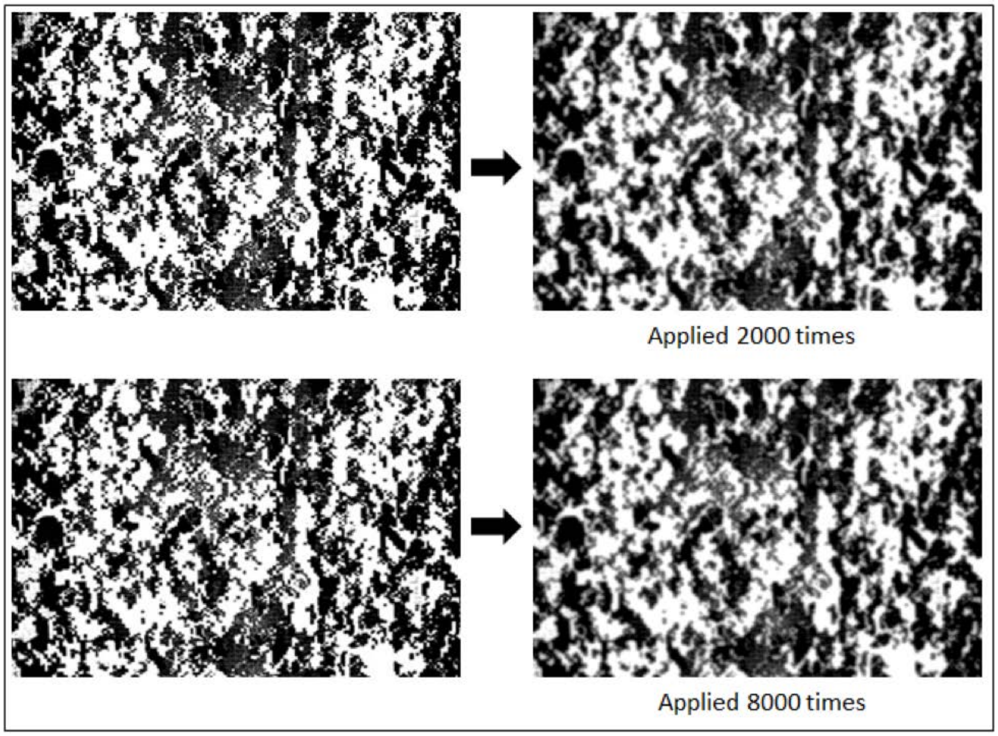
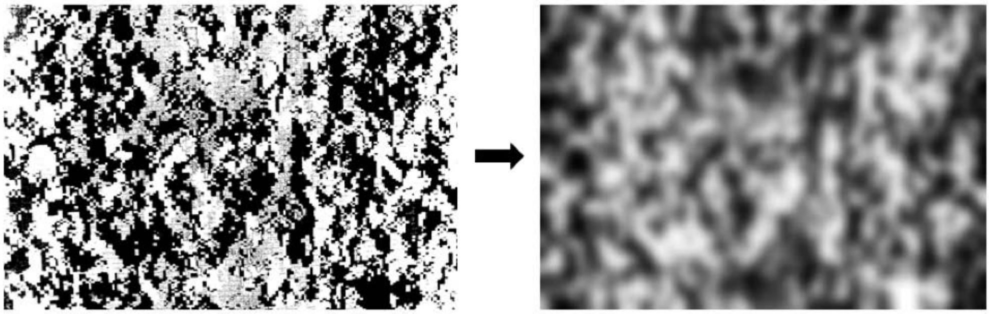
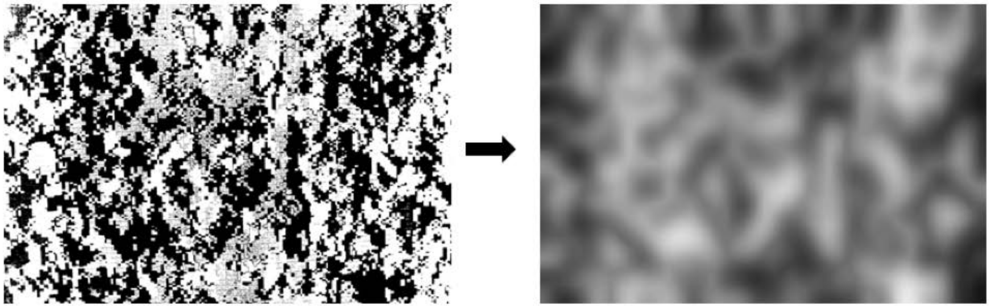


Figure 17. The smooth function applied to a segmented image (olive green) 2000 and 8000 consecutive times



Applied 250 times



Applied 1000 times

Figure 18. The fast filter function applied to a segmented image (olive green) 250 and 1000 consecutive times

As can be seen from the PSF functions, the fast filter has the greatest effect of reducing the resolution of the camouflage image, i.e., the effect of distance on the observation of the camouflage image is greatest with the use of the fast filter function.

**Smooth Filtering Algorithm**

The smooth filtering is a simple sliding-window spatial filter that replaces the center value in the window with the average (mean) of all the pixel values in the window. The window, or kernel, is usually square but can be any shape. An example of mean filtering of a single 3x3 window of values is shown below.

| unfiltered values | | |
|---|---|---|
| 5 | 3 | 6 |
| 2 | 1 | 9 |
| 8 | 4 | 7 |

5 + 3 + 6 + 2 + 1 + 9 + 8 + 4 + 7 = 45
45 / 9 = 5

| unfiltered values | | |
|---|---|---|
| * | * | * |
| * | 5 | * |
| * | * | * |

Center value (previously 1) is replaced by the mean of all nine values (5). The smooth filter in ImageJ only uses a 3x3 kernel. In order to use a larger kernel, the fast filtering process must be invoked.

**Fast Filtering Algorithm**

This algorithm is based on unidirectional filters (mean, min, max, median), i.e. filters that can be applied to rows or columns in an image. Filtering is applied to a rectangular (n)x(m) kernel area and is obtained by sequentially filtering rows and columns ("separable filters"). For each target (output) pixel, the simple operations (mean, min, max) are performed over a kernel given by a rectangle of width = 2xRadius+1 and height = 2yRadius+1. xRadius = 0 or yRadius=0 results in no filter operation in that direction, e.g., a "mean" filter with xRadius = 2 and yRadius = 2 results in averaging (or mean) over 5x5 pixels. For PSF modeling, both xRadius and yRadius of 5 was chosen and the mean over 11x11 pixels were computed by the process. The choice of what size kernel and filter to use (i.e. mean, min, max, median) is not unique and depends on the distance between observing detector and camouflage fabric.

**Smooth Filtering Macro Code**

```
for (i=0; i<N; i++)
{
run("Smooth", "");
}
```

Where N is the number of times to apply the smooth operation.

**Fast Filtering Macro Code**

```
for (i=0; i<N; i++)
{
run("Fast Filters", "link filter=mean x=J y=K preprocessing=none");
}
```

Where N is the number of times to apply the upscaling operation, and J and K are related to the pixel dimensions of the m x n rectangular area for which upscaling is applied to. Here m=2J+1 and n=2K+1 with m and n being the number of pixels.

## Conclusion

Modeling of apparent camouflage color and patterning as a function of camouflage-fabric conditions and environmental influences assists in predicting the viability of camouflage fabrics. This report presents various elements of a general framework for such modeling.

## Acknowledgement

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## References

[1] S. Ramsey, T. Mayo, A. Shabaev, S.G. Lambrakos, "Modeling Apparent Color for Visual Evaluation of Camouflage Fabrics, Proceedings of SPIE Volume 10395, Optics and Photonics for Information Processing XI, 103950I (2017). Doi: 10.1117/12.2272736.

[2] M. Petrou and C. Petrou, *Image Processing: The Fundamentals*, 2nd Ed., John Wiley and Sons, Ltd, United Kingdom, (2010).

[3] https://imagej.nih.gov/ij/

[4] L-K Huang and M-J.J. Wang, (1995), "Image thresholding by minimizing the measure of fuzziness", *Pattern Recognition* **28(1)**: 41-51

[5] J.M.S. Prewitt and M.L. Mendelsohn, (1966), "The analysis of cell images", Annals of the New York Academy of Sciences 128: 1035-1053

[6] T.W. Ridler and S. Calvard, (1978), "Picture thresholding using an iterative selection method", IEEE Transactions on Systems, Man and Cybernetics 8: 630-632

[7] C.H. Li and P.K.S. Tam, (1998), "An Iterative Algorithm for Minimum Cross Entropy Thresholding", Pattern Recognition Letters, 18(8), pp 771-776.

[8] J.N. Kapur, P.K. Sahoo and A.C.K. Wong, (1985), "A New Method for Gray-Level Picture Thresholding Using the Entropy of the Histogram", Graphical Models and Image Processing 29(3), pp 273-285.

[9] J. Kittler and J. Illingworth, (1986), "Minimum error thresholding", Pattern Recognition, 19, pp 41-47.

[10] W. Tsai, (1985), "Moment-preserving thresholding: a new approach", Computer Vision, Graphics, and Image Processing, 29, pp 377-39.

[11] N. Otsu, (1979), "A threshold selection method from gray-level histograms", IEEE Trans. Sys., Man., Cyber., 9, pp 62-66, doi:10.1109/TSMC.1979.4310076

[12] A.G. Shanbhag, (1994), "Utilization of information measure as a means of image thresholding", Graph. Models Image Process. (Academic Press, Inc.), 56 (5), pp 414--419, ISSN 1049-9652

[13] G.W. Zack, W.E. Rogers and S.A. Latt, (1977), "Automatic measurement of sister chromatid exchange frequency", J. Histochem. Cytochem. 25 (7): 741–53, PMID 70454

[14] J.C. Yen, F.J. Chang and S. Chang, (1995), "A New Criterion for Automatic Multilevel Thresholding", IEEE Trans. on Image Processing 4 (3): 370-378, ISSN 1057-7149, doi:10.1109/83.366472

[15] https://www.markschulze.net/java/meanmed.html

[16] http://imagejdocu.tudor.lu/doku.php?id=plugin:filter:fast_filters:start

# Appendix

| Baseline | L* | a* | b* |
|---|---|---|---|
| black.1st.control | 19.67 | 2.36 | 2.53 |
| black.2nd.control | 19.55 | 2.28 | 2.38 |
| black.3rd.control | 19.89 | 2.4 | 2.58 |
| olive.1st.control | 46.94 | -0.27 | 19.24 |
| olive.2nd.control | 48.66 | 0 | 18.41 |
| olive.3rd.control | 48.54 | -0.2 | 18.92 |
| green.1st.control | 39.98 | -5.71 | 13.25 |
| green.2nd.control | 40.23 | -5.32 | 12.33 |
| green.3rd.control | 40.18 | -5.46 | 13.44 |
| | | | |
| black.1st.milliken | 20.61 | 1.64 | 1.33 |
| black.2nd.milliken | 20.78 | 1.52 | 1.08 |
| black.3rd.milliken | 20.7 | 1.66 | 1.22 |
| olive.1st.milliken | 47.53 | -1.12 | 16.45 |
| olive.2nd.milliken | 46.36 | -1.65 | 17.98 |
| olive.3rd.milliken | 46.57 | -1.55 | 17.65 |
| green.1st.milliken | 39.24 | -5.7 | 13.15 |
| green.2nd.milliken | 39.04 | -4.82 | 12.76 |
| green.3rd.milliken | 38.19 | -5.78 | 12.92 |

| 1st cycle | L* | a* | b* |
|---|---|---|---|
| black.1st.control | 19.51 | 2.5 | 2.59 |
| black.2nd.control | 19.26 | 2.43 | 2.56 |
| black.3rd.control | 19.82 | 2.34 | 2.53 |
| olive.1st.control | 47.29 | 0.8 | 16.8 |
| olive.2nd.control | 48.25 | 0.49 | 16.71 |
| olive.3rd.control | 48.24 | 0.32 | 17.3 |
| green.1st.control | 39.73 | -4.78 | 9.6 |
| green.2nd.control | 39.6 | -4.46 | 10.18 |
| green.3rd.control | 39.49 | -4.35 | 10.94 |
| | | | |
| black.1st.milliken | 20.36 | 1.63 | 1.18 |
| black.2nd.milliken | 20.5 | 1.57 | 1.12 |
| black.3rd.milliken | 19.92 | 1.71 | 1.24 |
| olive.1st.milliken | 46.15 | -1.39 | 17.15 |
| olive.2nd.milliken | 46.23 | -1.84 | 18.65 |
| olive.3rd.milliken | 46.82 | -1.71 | 17.99 |
| green.1st.milliken | 38.48 | -5.41 | 12.96 |
| green.2nd.milliken | 39.25 | -5 | 12.88 |
| green.3rd.milliken | 38.48 | -5.27 | 12.77 |

| 2nd cycle | L* | a* | b* |
|---|---|---|---|
| black.1st.control | 19.58 | 2.5 | 2.52 |
| black.2nd.control | 19.78 | 2.49 | 2.47 |
| black.3rd.control | 19.97 | 2.42 | 2.49 |
| olive.1st.control | 49.73 | 0.77 | 15.12 |
| olive.2nd.control | 48.69 | 0.71 | 15.24 |
| olive.3rd.control | 48.05 | 0.72 | 15.24 |
| green.1st.control | 39.73 | -4.65 | 8.32 |
| green.2nd.control | 39.86 | -4.32 | 8.63 |
| green.3rd.control | 39.75 | -4.17 | 9.08 |
| | | | |
| black.1st.milliken | 20.37 | 1.71 | 1.33 |
| black.2nd.milliken | 20.49 | 1.62 | 1.07 |
| black.3rd.milliken | 20.24 | 1.71 | 1.23 |
| olive.1st.milliken | 46.31 | -1.48 | 17.5 |
| olive.2nd.milliken | 47.06 | -1.9 | 18.05 |
| olive.3rd.milliken | 46.47 | -1.47 | 17.12 |
| green.1st.milliken | 39.27 | -5.16 | 12.81 |
| green.2nd.milliken | 39.16 | -5.03 | 12.84 |
| green.3rd.milliken | 38.56 | -5.44 | 12.87 |

| 3rd cycle | L* | a* | b* |
|---|---|---|---|
| black.1st.control | 19.72 | 2.57 | 2.57 |
| black.2nd.control | 19.75 | 2.44 | 2.51 |
| black.3rd.control | 18.84 | 2.14 | 2.19 |
| olive.1st.control | 48.23 | 1.22 | 15.05 |
| olive.2nd.control | 49.64 | 0.58 | 14.29 |
| olive.3rd.control | 48.82 | 0.58 | 15.31 |
| green.1st.control | 39.47 | -4.68 | 7.4 |
| green.2nd.control | 40.62 | -4.29 | 7.99 |
| green.3rd.control | 40.35 | -4.24 | 8.13 |
| | | | |
| black.1st.milliken | 20.45 | 1.69 | 1.24 |
| black.2nd.milliken | 19.68 | 1.69 | 1.2 |
| black.3rd.milliken | 20.14 | 1.75 | 1.29 |
| olive.1st.milliken | 46.77 | -1.64 | 17.76 |
| olive.2nd.milliken | 46.2 | -1.65 | 17.67 |
| olive.3rd.milliken | 45.88 | -1.79 | 17.74 |
| green.1st.milliken | 39.73 | -5.32 | 13.02 |
| green.2nd.milliken | 38.98 | -4.96 | 12.87 |

| | | | |
|---|---|---|---|
| green.3rd.milliken | 38.96 | -5.12 | 12.77 |

| 4th cycle | L* | a* | b* |
|---|---|---|---|
| black.1st.control | 19.7 | 2.57 | 2.54 |
| black.2nd.control | 19.77 | 2.5 | 2.44 |
| black.3rd.control | 18.55 | 2.31 | 2.3 |
| olive.1st.control | 49.28 | 1.35 | 14.22 |
| olive.2nd.control | 49.5 | 0.91 | 14.04 |
| olive.3rd.control | 48.48 | 1.17 | 14.33 |
| green.1st.control | 39.79 | -4.68 | 6.71 |
| green.2nd.control | 40.91 | -4.32 | 7.2 |
| green.3rd.control | 40.59 | -4.25 | 7.48 |
| | | | |
| black.1st.milliken | 20.37 | 1.7 | 1.35 |
| black.2nd.milliken | 20.55 | 1.63 | 1.23 |
| black.3rd.milliken | 19.68 | 1.81 | 1.39 |
| olive.1st.milliken | 46.62 | -1.77 | 17.73 |
| olive.2nd.milliken | 46.15 | -1.44 | 17.16 |
| olive.3rd.milliken | 45.98 | -1.46 | 17.06 |
| green.1st.milliken | 38.35 | -5.33 | 12.85 |
| green.2nd.milliken | 38.43 | -4.88 | 12.76 |
| green.3rd.milliken | 38.26 | -5.31 | 12.76 |

| 5th cycle | L* | a* | b* |
|---|---|---|---|
| black.1st.control | 19.77 | 2.54 | 2.43 |
| black.2nd.control | 19.71 | 2.56 | 2.47 |
| black.3rd.control | 18.72 | 2.22 | 2.17 |
| olive.1st.control | 50.82 | 1.13 | 13.63 |
| olive.2nd.control | 49.87 | 0.92 | 13.85 |
| olive.3rd.control | 48.49 | 1.51 | 14.2 |
| green.1st.control | 40.16 | -4.72 | 6.31 |
| green.2nd.control | 41.81 | -4.33 | 6.84 |
| green.3rd.control | 41.17 | -4.28 | 7.09 |
| | | | |
| black.1st.milliken | 20.36 | 1.72 | 1.35 |
| black.2nd.milliken | 20.51 | 1.7 | 1.19 |
| black.3rd.milliken | 20.3 | 1.77 | 1.34 |
| olive.1st.milliken | 46.7 | -1.41 | 16.82 |
| olive.2nd.milliken | 46.23 | -1.73 | 17.78 |
| olive.3rd.milliken | 46.01 | -1.67 | 17.51 |

| | | | |
|---|---|---|---|
| green.1st.milliken | 38.86 | -5.26 | 12.72 |
| green.2nd.milliken | 38.26 | -5.04 | 12.91 |
| green.3rd.milliken | 38.27 | -5.42 | 12.75 |

| 6th cycle | L* | a* | b* |
|---|---|---|---|
| black.1st.control | 19.84 | 2.57 | 2.48 |
| black.2nd.control | 19.79 | 2.54 | 2.41 |
| black.3rd.control | 19.67 | 2.55 | 2.55 |
| olive.1st.control | 51.15 | 1.22 | 13.27 |
| olive.2nd.control | 48.78 | 0.68 | 14.63 |
| olive.3rd.control | 49.83 | 1.64 | 14.04 |
| green.1st.control | 40.39 | -4.79 | 6.02 |
| green.2nd.control | 41.98 | -4.35 | 6.49 |
| green.3rd.control | 41.13 | -4.4 | 6.91 |
| | | | |
| black.1st.milliken | 20.15 | 1.73 | 1.32 |
| black.2nd.milliken | 20.26 | 1.68 | 1.21 |
| black.3rd.milliken | 20.15 | 1.85 | 1.39 |
| olive.1st.milliken | 46.62 | -1.51 | 17.19 |
| olive.2nd.milliken | 46.11 | -1.37 | 16.65 |
| olive.3rd.milliken | 45.95 | -1.61 | 17.22 |
| green.1st.milliken | 39.15 | -5.36 | 12.62 |
| green.2nd.milliken | 38.43 | -4.88 | 12.71 |
| green.3rd.milliken | 37.5 | -5.51 | 12.77 |

| 7th cycle | L* | a* | b* |
|---|---|---|---|
| black.1st.control | 19.81 | 2.5 | 2.4 |
| black.2nd.control | 19.53 | 2.44 | 2.3 |
| black.3rd.control | 19.67 | 2.48 | 2.43 |
| olive.1st.control | 50.24 | 1.97 | 13.9 |
| olive.2nd.control | 49.46 | 0.86 | 14.16 |
| olive.3rd.control | 50.97 | 1.65 | 13.56 |
| green.1st.control | 41.07 | -4.59 | 6.58 |
| green.2nd.control | 42.14 | -4.44 | 6.42 |
| green.3rd.control | 40 | -4.25 | 8.42 |
| | | | |
| black.1st.milliken | 20.33 | 1.72 | 1.31 |
| black.2nd.milliken | 20.01 | 1.77 | 1.23 |
| black.3rd.milliken | 20.25 | 1.83 | 1.41 |
| olive.1st.milliken | 46.67 | -1.48 | 17.12 |

| | | | |
|---|---|---|---|
| olive.2nd.milliken | 45.77 | -1.67 | 17.68 |
| olive.3rd.milliken | 45.87 | -1.34 | 16.71 |
| green.1st.milliken | 38.79 | -5.46 | 12.86 |
| green.2nd.milliken | 38.32 | -4.9 | 12.71 |
| green.3rd.milliken | 38.64 | -5.37 | 12.76 |

| 8th cycle | L* | a* | b* |
|---|---|---|---|
| black.1st.control | 19.82 | 2.6 | 2.45 |
| black.2nd.control | 19.71 | 2.49 | 2.42 |
| black.3rd.control | 19.99 | 2.64 | 2.49 |
| olive.1st.control | 50.66 | 2.06 | 13.85 |
| olive.2nd.control | 51.35 | 1.24 | 13.17 |
| olive.3rd.control | 51.22 | 1.86 | 13.75 |
| green.1st.control | 40.58 | -4.88 | 5.69 |
| green.2nd.control | 42.2 | -4.45 | 6.31 |
| green.3rd.control | 40.3 | -4.26 | 8.15 |
| | | | |
| black.1st.milliken | 20.16 | 1.72 | 1.34 |
| black.2nd.milliken | 20.57 | 1.76 | 1.34 |
| black.3rd.milliken | 20.16 | 1.82 | 1.45 |
| olive.1st.milliken | 46.19 | -1.28 | 16.63 |
| olive.2nd.milliken | 45.41 | -1.4 | 16.84 |
| olive.3rd.milliken | 46.13 | -1.64 | 17.47 |
| green.1st.milliken | 38.84 | -5.08 | 12.8 |
| green.2nd.milliken | 37.99 | -4.93 | 12.42 |
| green.3rd.milliken | 37.66 | -5.36 | 12.59 |

| 9th cycle | L* | a* | b* |
|---|---|---|---|
| black.1st.control | 19.74 | 2.49 | 2.36 |
| black.2nd.control | 19.94 | 2.52 | 2.47 |
| black.3rd.control | 20.02 | 2.38 | 2.32 |
| olive.1st.control | 50.94 | 2.5 | 13.95 |
| olive.2nd.control | 52.26 | 2.11 | 13.5 |
| olive.3rd.control | 51.74 | 1.58 | 13.21 |
| green.1st.control | 42 | -4.74 | 5.71 |
| green.2nd.control | 42.25 | -4.42 | 6.44 |
| green.3rd.control | 42.87 | -4.4 | 6.19 |
| | | | |
| black.1st.milliken | 20.4 | 1.82 | 1.49 |
| black.2nd.milliken | 20.72 | 1.73 | 1.42 |
| black.3rd.milliken | 19.68 | 1.95 | 1.56 |
| olive.1st.milliken | 47.19 | -1.13 | 16.39 |

| | | | |
|---|---|---|---|
| olive.2nd.milliken | 45.3 | -1.89 | 17.65 |
| olive.3rd.milliken | 45.96 | -1.82 | 17.46 |
| green.1st.milliken | 38.93 | -5.35 | 12.66 |
| green.2nd.milliken | 38.63 | -4.85 | 12.41 |
| green.3rd.milliken | 38.15 | -5.19 | 12.57 |

| 10th cycle | L* | a* | b* |
|---|---|---|---|
| black.1st.control | 19.86 | 2.64 | 2.42 |
| black.2nd.control | 20.16 | 2.52 | 2.29 |
| black.3rd.control | 19.93 | 2.57 | 2.45 |
| olive.1st.control | 51.41 | 2.48 | 13.88 |
| olive.2nd.control | 51.34 | 1.57 | 13.31 |
| olive.3rd.control | 52.2 | 2.1 | 13.49 |
| green.1st.control | 42.25 | -4.64 | 5.5 |
| green.2nd.control | 43.19 | -4.21 | 5.93 |
| green.3rd.control | 42.17 | -4.3 | 6.22 |
| | | | |
| black.1st.milliken | 20.28 | 1.8 | 1.48 |
| black.2nd.milliken | 20.43 | 1.74 | 1.39 |
| black.3rd.milliken | 20 | 1.92 | 1.52 |
| olive.1st.milliken | 46.52 | -1.53 | 17.17 |
| olive.2nd.milliken | 45.45 | -1.47 | 17.12 |
| olive.3rd.milliken | 45.99 | -1.33 | 16.67 |
| green.1st.milliken | 38.84 | -5.29 | 12.47 |
| green.2nd.milliken | 38.66 | -4.79 | 12.47 |
| green.3rd.milliken | 37.67 | -5.34 | 12.42 |