Colorimetric representations for use with polarization-difference imaging of objects in scattering media

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Received April 9, 1997; revised manuscript received September 8, 1997; accepted September 16, 1997

Polarization-difference imaging (PDI) has been shown to yield an improvement in the qualitative and quantitative detectability of objects in scattering media. In this investigation, PDI and conventional, polarization-blind imaging are combined to yield a novel representational scheme generally suitable for detection of targets having a low degree of linear polarization and specifically suitable for detection and discrimination of weakly polarizing targets in scattering media. This representational scheme meets several general criteria for optimization of the presentation of low-signal image information to human observers and takes specific advantage of the properties of the opponent-color coding used by the human visual system. © 1998 Optical Society of America [S0740-3232(98)01902-4]

OCIS codes: 110.0110, 330.1720, 290.0290, 230.5440.

1. INTRODUCTION

The polarization of light provides much useful information about scenes in optical imaging, information not available with conventional, polarization-blind imaging.[1–8] Imaging applications in which polarization information has been used in conjunction with intensity imaging include remote sensing,[1,2,4] microscopy,[3] machine vision,[5,6] and target detection in scattering media.[7,8] Although polarization information has been shown to be of considerable general utility, it remains unclear what approach is optimum for the collection of this information by an imaging system and what might be the optimum method of displaying the information to human observers for any particular imaging application.

In this investigation a strategy is described for representing polarization information when the observed degree of linear polarization is low, as is the case for the imaging of objects in a scattering environment.[8] In Section 2 two related mappings for representing polarization information in pseudocolor images are presented. In Section 3 several general criteria for a representational system are proposed, and the polarization → color transformations presented in Section 2 are evaluated with respect to these criteria. In Section 4 the novel polarization → color mappings presented here are compared with previously proposed transformations.[6,9] The new mappings are demonstrated to be more robust for presenting reliable information to human observers performing the task of detecting targets in a scattering medium and near the limits of visibility.

2. POLARIZATION → COLOR MAPPINGS

A number of different strategies for mapping polarization information into the parameters of a display system have been tested in different imaging applications. Simple gray-scale or monochromatic transformations have been employed by many researchers,[1,2,5,7] and simultaneous analysis of polarization information from different regions of the visible spectrum has been studied.[4] Techniques that map polarization parameters into colorimetric coordinates have also been formulated[9–11] and tested.[6,11,12]

Colorimetry dictates that all real lights are equivalent for the color-normal observer with specific mixtures of three suitable primaries—the three phosphors of a standard TV monitor are examples of such color-matching primaries. Thus colorimetry represents the entire range of experienced lights as a convex cone of a three-dimensional (3-D) vector space in which each point or vector is a particular set of values of the chosen primaries. A standard and familiar parameterization of this space is in terms of the parameters hue (H), saturation (S), and brightness (B), which serve to uniquely identify any particular vector.[13] For a color monitor at each pixel these parameters can vary as follows. B (brightness) is the pixel luminance and can vary over the operating range of the monitor. H is the angle in an equal-luminance plane of a vector originating in a central point chosen to represent gray, and it can vary from 0° to 360°. S represents the length of the H vector of a particular point in the equal-luminance plane relative to the maximal possible length of an H vector having the same orientation or angle; S can vary from 0 (indicating that the pixel lies at the gray point for the particular value of B) to 1 (indicating a pure color, formed on a monitor by a mixture of no more than two phosphors).

Bernard and Wehner[9] proposed a polarization mapping strategy that maps the three physical parameters intensity (I), degree of polarization (d), and angle of polarization (θ) of narrow-band light from a scene to colorimetric parameters as[6,12]

$$I \rightarrow B, \tag{1a}$$

$$d \rightarrow S, \tag{1b}$$

$$2\theta \rightarrow H. \tag{1c}$$

A notable feature of the Bernard–Wehner mapping strategy is that it takes the 3-D polarization information potentially available from the scene and maps it to the full 3-D color space. The mapping strategy proposed by Bernard and Wehner has been implemented by Wolff and colleagues in a polarization-sensitive imaging system that produces near-video-frame-rate images.[6,12]

The mapping of Bernard and Wehner is well suited for imaging scenes in normal atmospheric conditions under typical lighting.[6,12] However, the utility of directly mapping the angle of polarization to the colorimetric parameter H in strategies similar to that of Bernard and Wehner[2,10] has been questioned on the grounds that the estimated angle of polarization can fluctuate rapidly, both spatially and temporally, especially in images having a small percent polarization.[14] Such rapid fluctuations are expected in the images of scenes in scattering media near the limits of visibility. It is predictable (and demonstrated below) that as the percent polarization becomes small, such chromatic fluctuations appear in the representation. These fluctuations clearly compromise the information presented to the human visual system. This loss of potential information to the human viewer is unfortunate, since even images with an observed degree of linear polarization as low as 1% or less do contain valuable polarization information.[7,8] The representational strategy that we will now describe avoids the difficulties associated with mapping the angle of polarization directly into a hue parameter and is therefore arguably more useful when applied to imaging of scenes with low percent polarization.

Most polarization-sensitive imaging systems map information to a display coordinate that represents the degree of polarization. In contrast, polarization-difference imaging (PDI) represents the *difference* between images captured at orthogonal polarizations.[7,8] Polarization-difference (PD) information has been shown to aid in the detection of targets (and target features) in optically scattering media. In our previous work, PD images were

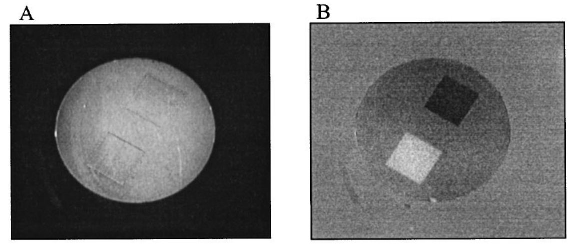

Fig. 1. Front-illuminated PS and PD images obtained at 1.4 attenuation lengths. The circular disk face is readily apparent in the PS image (A), but the scratched patches are only slightly visible and indistinguishable from each other. The scratched patches are distinct in the PD image (B), but the circular disk face is not clearly visible. The goal of colorimetric PDI is to incorporate the positive features of *both* A and B into a single image.

transformed only into gray-scale representations, and PD and polarization-blind, or polarization-sum (PS) (Ref. 15), images were analyzed separately. Although gray-scale representations have been useful, inspection of images such as those presented in Fig. 1 reveals that representing PS and PD images in separate gray-scale maps restricts the presentation of information about certain target features. To increase the total amount of information available to a human observer in a single image of a polarizing scene, the 3-D nature of human color vision should be exploited, as Bernard and Wehner proposed. Thus, in this investigation, a polarization → color mapping strategy is developed that enhances the visibility of target features to human observers by *combining* PS and PD images into a single image.

In our transformation the value of the PS intensity at any pixel is mapped into the colorimetric parameter B, as in the strategy proposed by Bernard and Wehner, and the PD magnitude is mapped into the parameter S. Thus we have

$${}_{\mathrm{PS}}I \equiv I_{\parallel} + I_{\perp} \rightarrow B, \tag{2}$$

$${}_{\mathrm{PD}}I \equiv I_{\parallel} - I_{\perp} \rightarrow S, \tag{3}$$

where ${}_{\mathrm{PS}}I$ and ${}_{\mathrm{PD}}I$ are the PS and PD intensities and $I_{\parallel}$ and $I_{\perp}$ are the intensities of the signal polarized parallel and perpendicular to the analyzer axis.[7,8] Because ${}_{\mathrm{PD}}I$ can be positive or negative and S is nonnegative, distinct hues must be used to identify the regions in the image having opposite signs. Net PD signal in the direction corresponding to one of the polarization axes (the $\parallel$ direction, positive values in the PD image) is represented as a particular value of H, and net PD signal in the orthogonal direction ($\perp$, the negative values in the PD image) is represented as the complementary or opponent value of H. This mapping strategy for PS and PD information is explicitly informed by the opponent-colors model of human color vision, which describes human color vision in terms of three orthogonal signals—an achromatic signal and two chromatic or opponent signals[16]—as discussed further in Subsection 3.A.

With the analyzer fixed, PDI utilizes only two images and thus subsamples the full 3-D polarization information available in the scene. In the framework just outlined, we map this two-dimensional (2-D) information onto a 2-D plane in the naturally 3-D colorimetric space[17];

thus we call the strategy two-parameter colorimetric PDI (2C-PDI). The choice of the pair of complementary hues defining the plane in color space onto which a particular PS/PD image pair is mapped represents a degree of freedom available for mapping additional information. At present, we use this degree of freedom to create a family of colorimetric representations of the scene. Specifically, the azimuthal setting of the rotatable polarization analyzer is mapped to H according to[18]

$$2\phi_0 \rightarrow (H, H + 180°), \tag{4}$$

where ϕ_0 is the azimuthal orientation of the analyzer axis measured with respect to vertical. Relations (2)–(4) together define the polarization → color mapping that we call 2C-PDI.

In certain applications 2C-PDI is not advantageous because of dominating features of the spatial distribution of ${}_{\mathrm{PS}}I$, such as large shadow regions in an image.[7,8] A one-parameter colorimetric mapping (1C-PDI) that presents PD information without PS information for such situations is given by relations (3) and (4) with B set to a constant determined by user preference (typically, $B \approx 0.75$, with 1.0 being the maximum brightness).

The images presented here were collected with experimental arrangements similar to those used previously.[7,8] The images were taken of a scene composed of a target suspended in the middle of a tank filled with a milk/water mixture that served as the scattering medium. The target was either a 3.8-cm-diameter aluminum disk or a 2.0-cm-diameter transparent Plexiglas sphere. Except for two 1.0-cm^2 patches, the surface of the disk was sandblasted, rendering it nearly Lambertian. The two patches on the disk were lightly scratched in orthogonal directions by using emery paper, and they reflected light partially polarized parallel to the direction of the scratches.[19] For the back-illuminated case when the dielectric sphere was used, the sphere partially polarized light through refraction; the local direction of the partial polarization was oriented in the plane defined by the local surface normal and the direction of observation. Images were captured by a CCD camera and digitized by an 8-bit analog-to-digital converter operating on a PC platform.[20] In this investigation the illuminating source(s) were in one of three configurations: (1) back illumination[7,8]: two tungsten filament slide projectors illuminated the tank from behind the target; (2) side illumination[8]: one projector illuminated the side of the tank so that the direction of illumination was orthogonal to the direction of view; and (3) front illumination: two light sources positioned near the camera illuminated the front of the tank. For back- and side-illumination experiments, a 30-cm × 30-cm × 15-cm (~13.5-l) rectangular glass tank was used, and for front-illumination experiments, a 44.5-cm-diameter × 25.8-cm (~40-l) circular clear Plexiglas tank was used. Orthogonal polarization components of the image-forming light were obtained with a fixed twisted nematic liquid-crystal cell operating in conjunction with a rotatable linear polarization analyzer and a narrow-band filter (10-nm FWHM at 610 nm) as described previously.[7] The colorimetric mappings were performed off line [with the MATLAB (version 4.2c) software package]. The strength of the scattering medium was measured in terms of attenuation lengths[21] of the medium between the target and the front face of the tank, i.e., the number of attenuation lengths through which the image-forming light must propagate.[8] Before implementing the mappings presented in this investigation, PS and PD images were scaled with an affine transformation[7,8] to ensure that the range of intensities was transformed to use the entire available dynamic range of the 8-bit color display. PD images were transformed symmetrically: Thus, if the intensity varied from −7 to 15 in a PD image (out of a possible ±255), then the mapped values were scaled according to ${}_{\mathrm{PD}}I = \pm 15 \rightarrow S = \pm 1$. PS images were transformed so that ${}_{\mathrm{PS}}I_{\min} \rightarrow B = 0$ and ${}_{\mathrm{PS}}I_{\max} \rightarrow B = 1$.

Figure 2 illustrates images implementing the 2C-PDI mapping. To obtain these images, the dielectric sphere was back illuminated; no milk was added to the water in the tank. The target was ~0.13 attenuation length from the front of the tank. In parts A, B, and C, the analyzer was set at angles of 0°, 36°, and 72° from the vertical, respectively. Saturated hues appear in the portions of the images where the polarization angle coincided with the PD axes, and unsaturated hues or polarization blind spots[9,17,22] appear where the axes of the ellipse of the polarized component of the radiation fall exactly midway between the two orthogonal PDI axes. The pair of opponent hues changes with analyzer angle according to relation (4), and thus different features of the target are highlighted chromatically. The properties of 1C- and 2C-

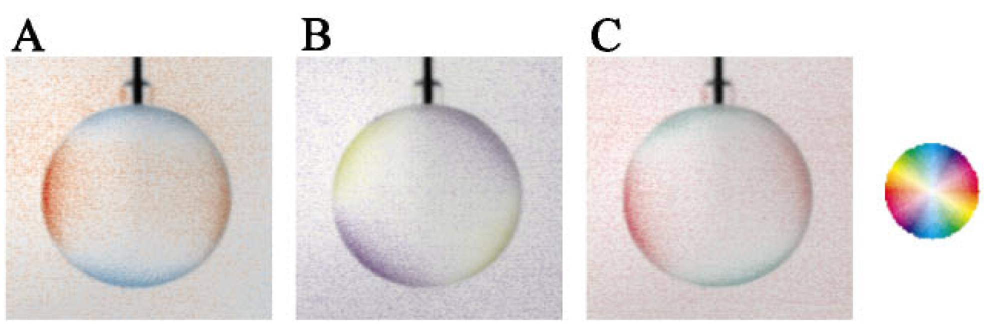

Fig. 2. 2C-PDI images of the back-illuminated dielectric sphere at an effective distance of 0.13 attenuation lengths. Images A, B, and C were obtained with the analyzer oriented at angles of 0°, 36°, and 72° with respect to the vertical, respectively. 2C-PDI highlights areas that are polarized parallel to the PDI axes and has blind spots where the light is polarized at 45° with respect to the PDI axes. The key at the right reveals how the colors in the images map into polarization direction; for example, red represents an excess of horizontal polarization and cyan represents an excess of vertical polarization.

PDI will now be examined in the light of these results and with respect to several generally useful criteria for a representational system.

3. CRITERIA FOR DESCRIBING POLARIZATION → COLOR MAPPINGS AS REPRESENTATIONAL SYSTEMS

To facilitate our analysis of colorimetric PDI, we propose four criteria that should be met by an effective representational system, i.e., a system that reliably presents optical information to a human observer. This list is not necessarily exhaustive; moreover, an effective system may require trade-offs in optimizing for the different criteria. Nonetheless, we propose that the following criteria be addressed in the design and the analysis of representational transformations like those discussed here: (1) orthogonal encoding, i.e., information should be presented with as little redundancy as possible; (2) computational simplicity, i.e., efficiency of implementation should be maximized; (3) anthropometric optimality, i.e., information should be presented in a way that maximizes usefulness to the human observer; and (4) ecological invariance, i.e., representations should remain qualitatively similar over natural variation of some significant environmental parameters. Below, each of these criteria is discussed in the specific context of the detection near the limits of visibility of targets in scattering media, and the extent to which colorimetric PDI meets these criteria is evaluated. To aid the analysis of each criterion, a comparison between human perception of chromatic stimuli and colorimetric PDI representation of polarization signals is made.

A. Orthogonal Encoding

To process information with a minimum amount of redundancy, it is useful to decorrelate the information in the various sensory channels. The human visual system receives information through three photoreceptors with different spectral sensitivity functions. However, there is abundant evidence that processing occurs through three neural channels[16] whose signals (at least for small inputs) are orthogonal linear combinations of the quantal capture rates of the cone photoreceptors of three spectral classes when these capture rates are considered as functionals operating on spectral energy distributions of visible light.[23] These three neural channels are referred to as the brightness or the achromatic channel (A) and two opponent-color channels, red/green (R/G), and blue/yellow (B/Y). The A channel is a positively weighted linear combination of the quantal capture rates of all three classes of cones, and the two opponent-color channels are positively *and* negatively weighted linear combinations of the cone capture rates. As shown by Buchsbaum and Gottschalk,[23] the resulting spectral sensitivity functions for the R/G and B/Y channels are mathematically orthogonal to each other and to the spectral sensitivity function of the A channel when integrated against a white spectrum in the visible range. Like the (A, R/G, B/Y) channels in the human visual system, the PS and PD signals are orthogonal when considered as functionals operating on the ensemble of potential polarization images.[22] The transformation defined by relation (2) maps the PS image onto the A channel, and though not obvious, relations (3) and (4) map the PD image onto a linear combination of the R/G and B/Y linear opponent channels. The latter follows because (1) $S = 0$ corresponds to the intensity-invariant gray point in the color diagram predicted by opponent-colors theory as the null space in the 3-D color cone of both R/G and B/Y channels and (2) any line in a constant-luminance plane that goes through $S = 0$ can be expressed as a linear combination of the two lines defined by pure R/G and pure B/Y channel activity in the constant-luminance plane. Thus, in the mappings that we propose, the orthogonality of PS and PD signals is preserved in their colorimetric representations.

B. Computational Efficiency

In a detection task, a definitive and typically rapid decision about the presence of a target is called for. Thus it is clearly advantageous for an organism to rapidly detect and correctly identify potential predators and prey. Examination of relations (2)–(4) shows that to implement 2C-PDI, only one addition operation and one subtraction operation are needed at each pixel. Furthermore, since 2C-PDI does not estimate the polarization state at each pixel, PDI requires only two images to be captured for each interval of time rather than the three images that would be necessary to characterize the state of polarization.[2,6,9,12] Using two measurements instead of three results in a 33% improvement in either spatial or temporal efficiency. This computational efficiency clearly comes at the cost of potential loss of information,[9,17,22] as demonstrated in Fig. 2 above and Figs. 3 and 4 below, since the scene has three potential dimensions or degrees of freedom of polarization information. However, in a detection task in which speed is desired, the extra degree of freedom is utilized off line in a judicious choice of the PD axes—for example, by choosing the PD axes in such a way that the signal from the targetless background is minimized,[8] as demonstrated in Fig. 4B below.

C. Anthropometric Optimality

It is desirable to have a representational system that utilizes as much of the available information as possible and presents this information in a form most useful to the human observer. When viewing a RGB display, an observer does not see the red, green, and blue phosphors as discrete, local features; rather, distinct hues are created by the human visual system from the various combinations of the quantal catch rates of the three cones from the R, G, and B phosphors. Rather than taking advantage of all potentially available spectral information, the human visual system makes a limited 3-D representation of the local spectral distribution that nonetheless preserves a great deal of the useful information.[24]

Like the human visual system representation of spectral information, 2C-PDI does not represent all potentially available polarization information. Rather, PDI *per se* represents information useful for identifying target features in specific conditions; in particular, it provides a robust representation of objects in scattering media near the limits of visibility.[8] Increasing scatterer concentration decreases the reliability of the estimate of polariza-

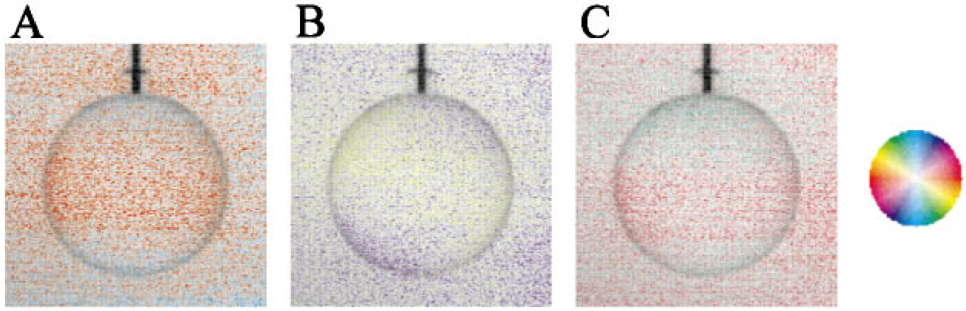

Fig. 3. 2C-PDI images of the back-illuminated dielectric sphere at an effective distance of 2.5 attenuation lengths. These images, although somewhat degraded, have the same qualitative form as that of the corresponding images in Fig. 2.

tion parameters, especially the angle of polarization, resulting in random fluctuations of the colorimetric parameters in the images as shown in detail in the figures below. Because the angle of polarization is not estimated in PDI, uncertainty in the angle of polarization implicitly present in ${}_{\mathrm{PD}}I(x, y)$ is mapped into the color parameter S, which the human visual system can process in a way that allows hue information to remain useful in identifying low-spatial-frequency targets and target features. Strategies like the one proposed by Bernard and Wehner[9] and implemented by Wolff and Mancini[6] and Wolff[12] that estimate the angle of polarization at each pixel position and map this estimate directly to H necessarily yield locally fluctuating hues when the uncertainty in the polarization angle is high. In Subsection 3.D and in Section 4, it is demonstrated that colorimetric PDI generates target images that retain their qualitative properties over variation in the degree of scattering in the medium, and it is also demonstrated that under the same conditions images generated with the mapping of Bernard and Wehner do not retain the same qualitative features. The mapping strategy of Bernard and Wehner and of Wolff, which maps the angle of polarization into hue, may nonetheless be optimal under other conditions, e.g., when polarization signals are larger.

D. Ecological Invariance

The human visual system has the ability to create a stable color representation of a given object over a wide range of illumination conditions.[25] For example, a white sheet of paper appears white under both artificial and natural lighting, even though the spectral content and the absolute intensity of the two sources can be quite different. Likewise, the perceived hues of targets are quite stable despite variations in illuminants. Ideally, a polarization imaging system designed for the detection of targets in scattering media should generate representations that are qualitatively invariant across changes in scatterer concentration, direction and intensity of the illumination, and maximum degree of polarization. Below, the 1C- and 2C-PDI representations are shown to be reasonably invariant as each of these environmental conditions is altered.

1. Scatterer Density/Effective Distance to Target

Although the clarity of the image of a scene is expected to degrade as the scatterer density is increased, the images should remain qualitatively similar. Comparison of Figs. 2 and 3 reveals how images obtained with the use of 2C-PDI degrade as scatterer concentration is increased. Figure 2 shows 2C-PDI images of the back-illuminated transparent dielectric sphere when viewed at a distance of ~0.13 attenuation length with various analyzer settings. In Fig. 3 2C-PDI images of the same sphere obtained at ~2.5 attenuation lengths with the same analyzer settings are presented. The sharpness of the images has degraded, but the qualitative features seen in Fig. 2 are preserved in Fig. 3.

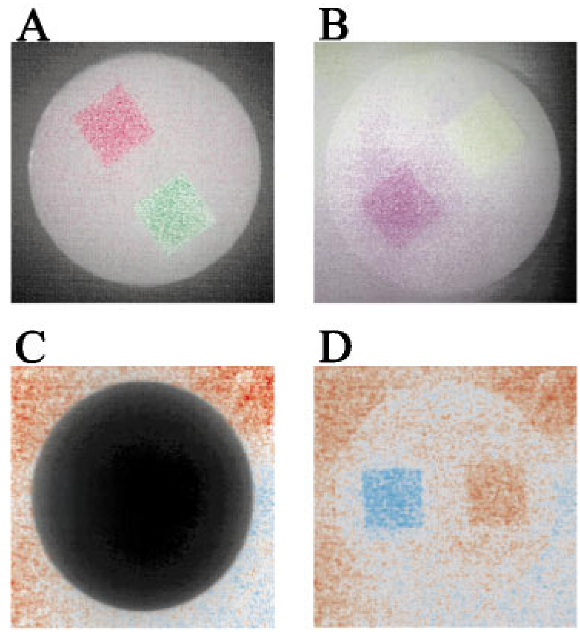

Fig. 4. Colorimetric PDI of the aluminum disk under (A) front-, (B) side-, and (C) and (D) back-illuminated conditions. Image C is obtained by using 2C-PDI, and image D is obtained by using 1C-PDI. Images A, B, and D demonstrate that, with the use of 1C- and 2C-PDI in conjunction, colorimetric PDI is extremely robust over varying illumination direction.

2. Direction of Illumination/Viewing Angle

Changing the direction of illumination can introduce significant background polarization,[8,26,27] and an effective polarization imaging system should be able to minimize the apparent effects of backgrounds so that targets that produce small polarization signals can be reliably detected.[8] Images obtained with three different cases of direction of illumination are presented in Fig. 4. Figure 4A shows the metallic target front-illuminated and viewed at a distance of ~3.0 attenuation lengths, Fig. 4B shows the metallic target side-illuminated and viewed at a distance of ~4.1 attenuation lengths, and Figs. 4C and 4D show back-illuminated images viewed at a distance of ~1.5 attenuation lengths. The 2C-PDI images for the front- and side-illuminated images (Figs. 4A and 4B) are almost identical in form, with a change in hue that is due to a rotation of the analyzer (63° in Fig. 4A, 45° in Fig. 4B). 2C-PDI rejects the vertically polarized background in the side-illuminated image by setting the analyzer to 45°,[8] and the two patches are presented with a separation of 180° of hue. For the back-illuminated case, the shadow of the disk does not allow the 2C-PDI image in Fig. 4C to display the polarization information effectively, but switching to 1C-PDI yields the image in Fig. 4D with many of the same features as those of the front- and side-illuminated images. Figure 4 demonstrates that by using 1C- and 2C-PDI in conjunction, one obtains consistent representations over variation in both the direction of illumination and the scatterer concentration, thereby satisfying qualitatively the criteria of anthropometric optimality and ecological invariance.

3. *Maximum Percent Polarization*

In some applications it is important to distinguish between targets having different degrees of polarization.[5] In a detection application, a system is designed for the rapid identification of targets with respect to the background. Because our primary concern is with detection, the PS and PD information is amplified by using an affine transformation as described in Section 1.[7,8] By means of this amplification algorithm, colorimetric PDI takes advantage of the common mode rejection/differential mode amplification feature inherent in PD images[8] to preserve the qualitative features of the image as the maximum percent polarization decreases.

4. *Effects of Rotating the Analyzer and/or the Viewing Angle*

Colorimetric PDI images obtained with the PDI axes oriented parallel to the scratches have been presented above, but the effects of rotating the analyzer in colorimetric PDI have not been addressed. Nonideal selection of analyzer angle does not necessarily render images unintelligible. For the front-illuminated case shown in Fig. 4, analyzer settings between 36° and 81° show qualitatively the same effects as those in Fig. 4A, but to a lesser degree and with a slightly different set of hues. The background polarization in the side-illuminated case reduces the usable range of analyzer settings, but the effects seen in Fig. 4B are apparent at analyzer settings between 36° and 54°.[17]

Because polarization is inherently a vector quantity, the information is not necessarily invariant under rotation of the target, as is demonstrated in Fig. 4. Any rotation of the target about the viewing direction will introduce, at the very least, a corresponding rotation in the observed angle of polarization corresponding to any particular location on the target. Any representational scheme that maps direction of polarization into a hue that is chosen based on the measured angle of polarization in the reference frame of the observer will possess the feature that the presented hues will vary as the target is rotated. For the colorimetric PDI mappings presented here, the hues will remain constant, so long as the analyzer is not rotated, but the representations of the features of the target that are highlighted will change accordingly.

An issue that has not been addressed is that of neglecting spectral information. Underwater, and in scattering media in general, there is typically a narrow window of frequencies in which light propagates with significantly lower attenuation than in other frequency regions.[27] Because there is such a narrow range of frequencies available, replacing spectral information with polarization information may result in an increase in the detectability of targets in the final image.

4. MAPPING THE STATE OF POLARIZATION

Mapping strategies that utilize the state of polarization—like that proposed by Bernard and Wehner[9] and implemented by Wolff and Mancini[6] and Wolff[12] work well under low-scattering atmospheric conditions when polarization signals are relatively large. However, such strategies lead to images that do not retain their qualitative features as scattering degrades the polarization in-

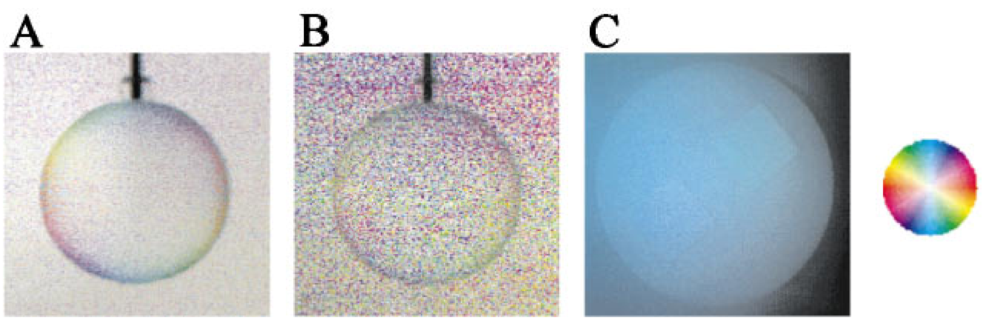

Fig. 5. Problems with mapping the state of polarization. Image A presents the dielectric sphere back-illuminated at an effective distance of 0.13 attenuation length with use of the mapping of Bernard and Wehner.[9] This image clearly indicates the direction of polarization around the edge of the image of the sphere. Image B presents an image of the same sphere as in image A but obtained at 2.5 attenuation lengths. The scatterers have introduced an uncertainty into the measured angle of polarization, resulting in a variation in hue in the image. Image C presents a side-illuminated view of the metallic target obtained at 4.1 attenuation lengths. The partially vertically polarized background dominates the image, so that the patches are separated by 36° of hue rather than 180° of hue, as was the case in Fig. 4B. The polarization parameters have been amplified in the creation of these images by using an affine transformation, as was done for colorimetric PDI in Figs. 2–4.

formation. Figure 5 demonstrates two problems that occur when mapping the state of polarization for a target detection task in scattering media. Figures 5A and 5B show images of the dielectric sphere created with the mapping of Bernard and Wehner at effective distances of ~0.13 and ~2.5 attenuation lengths, respectively. The increase in the concentration of scatterers causes the percent polarization in target regions of the image to decrease. Estimation of the polarization angle θ becomes unreliable, and the value of H fluctuates randomly on a pixel-by-pixel basis, as was predicted by Halaijan and Hallock.[14] Images in which the hue varies in a spatially rapid manner are not suited for observation by the chromatic pathways in the human visual system, since the R/G and B/Y pathways are relatively insensitive to high-spatial-frequency signals[28] like those present in Fig. 5B. Figures 5A and 5B demonstrate that the mapping strategy proposed by Bernard and Wehner[9] does not achieve ecological invariance for these experiments in this scattering medium. In contrast, by performing the above-mentioned dimensionality reduction, colorimetric PDI maps the uncertainty in θ into S (saturation), thereby preserving the qualitative features of the image (Figs. 2 and 3).

Figure 5C is a side-illuminated image of the metallic target created with the mapping of Bernard and Wehner. The partially vertically polarized background described above dominates this image, and the scratched patches do not appear as clearly as in the 2C-PDI image in Fig. 4B. The values of H for the patches in Fig. 5C differ by only 36° instead of 180°. For the side-illumination configuration in a scattering medium, transformations that map θ directly into H do not result in a representation that is anthropometrically optimal for a target detection task.

5. CONCLUSION

In summary, two variants of a novel strategy for mapping the polarization information captured by a PDI system onto colorimetric coordinates have been presented. These two mappings can generate images that retain their qualitative features to human observers over a wide range of environmental conditions in the task of detecting targets in scattering media. Four criteria have been proposed for an optical polarization representational system, and colorimetric PDI has been shown to satisfy qualitatively each of the criteria.

ACKNOWLEDGMENTS

We are grateful to M. P. Rowe for the development of the image processing system used in these experiments and for useful discussions during all phases of the work. We also thank F. Letterio and M. Suplick for invaluable assistance in the construction of the apparatus and the targets. This work was supported by the U.S. Department of the Navy, Office of Naval Research, through grant N00014-93-1-0935, and in part by the University of Pennsylvania Research Foundation. J. S. Tyo was supported by a National Science Foundation Graduate Research Fellowship and a U.S. Air Force Institute of Technology Sponsored Fellowship.

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REFERENCES AND NOTES

1. J. Halaijan and H. Hallock, "Principles and techniques of polarimetric mapping," in *Proceedings of the Eighth International Symposium on Remote Sensing of Environment* (Environmental Research Institute of Michigan, Ann Arbor, Mich., 1972), Vol. 1, pp. 523–540.
2. R. Walraven, "Polarization imagery," in *Optical Polarimetry: Instrumentation and Applications*, R. M. A. Azzam and D. L. Coffeen, eds., Proc. SPIE **112**, 164–167 (1977).
3. W. Mickols, I. Tinoco, J. E. Katz, M. F. Maestre, and C. Bustamante, "Imaging differential polarization microscope with electronic readout," Rev. Sci. Instrum. **12**, 2228–2236 (1985).
4. W. G. Egan, W. R. Johnson, and V. S. Whitehead, "Terrestrial polarization imagery obtained from the Space Shuttle: characterization and interpretation," Appl. Opt. **30**, 435–442 (1991).
5. L. B. Wolff and T. E. Boult, "Constraining object features using a polarization reflectance model," IEEE Trans. Pattern. Anal. Mach. Intell. **13**, 635–657 (1991).
6. L. B. Wolff and T. A. Mancini, "Liquid crystal polarization camera," in *Proceedings of the IEEE Workshop on Applications of Computer Vision* (IEEE, New York, 1992), pp. 120–127.
7. M. P. Rowe, E. N. Pugh, Jr., J. S. Tyo, and N. Engheta, "Polarization-difference imaging: a biologically inspired technique for imaging in scattering media," Opt. Lett. **20**, 608–610 (1995).
8. J. S. Tyo, M. P. Rowe, E. N. Pugh, Jr., and N. Engheta, "Target detection in optically scattering media using polarization-difference imaging," Appl. Opt. **35**, 1855–1870 (1996).
9. G. D. Bernard and R. Wehner, "Functional similarities between polarization vision and color vision," Vision Res. **17**, 1019–1028 (1977).
10. J. E. Solomon, "Polarization imaging," Appl. Opt. **20**, 1537–1544 (1981).
11. G. F. J. Garlick, C. A. Steigman, and W. E. Lamb, "Differential optical polarization detectors," U.S. patent 3,992,571 (November 16, 1976).
12. L. B. Wolff, "Polarization camera for computer vision with a beam splitter," J. Opt. Soc. Am. A **11**, 2935–2945 (1994).
13. J. Pokorny, S. K. Shevell, and V. C. Smith, "Color appearance and colour constancy," in *The Perception of Colour*, Vol. 6 of *Vision and Visual Dysfunction*, P. Gouras, ed. (CRC Press, Boca Raton, Fla., 1991), pp. 43–61.
14. J. Halaijan and H. Hallock, "Polarization imaging and mapping," Appl. Opt. **22**, 964–966 (1983).
15. A PS image, as defined in relation (2), is formed by adding the intensities captured through two orthogonal polarizers. As shown previously,[7,8] PS images are insensitive to the choice of orthogonal axes and are thus polarization blind.
16. L. M. Hurvich and D. Jameson, "Perceived color, induction effects, and opponent-response mechanisms," J. Gen. Physiol. **43** (No. 6) (Suppl.) 63–80 (1960).
17. J. S. Tyo, "Polarization difference imaging: a means for seeing through scattering media", Ph.D. dissertation (University of Pennsylvania, Philadelphia, 1997), Chaps. 7 and 8.
18. The actual mapping of analyzer angle into hue is dependent upon the choice of color space. In our mapping we use the (R,G,B) space of MATLAB, where pure red corresponds to $H = 0, S = 1$, and $B = 1$.
19. E. R. Méndez, A. G. Navarrette, and R. E. Luna, "Statistics of the polarization properties of one-dimensional randomly rough surfaces," J. Opt. Soc. Am. A **12**, 2507–2516 (1995).
20. The narrow-band filter is needed to eliminate wavelengths of light outside the operating wave band of the twisted nematic liquid-crystal cell[8]. Because of the filter, the re-

ceived signal was low. To compensate for this, 128 images were added into a 16-bit accumulator, and the resulting sum was divided by a number less than 128 to use as much of the dynamic range as possible. The divisor ranged from as small as 8 in some back-illuminated images (providingan amplification factor of 16) to as large as 32 for some front-illuminated images.
21. An attenuation length is equivalent to the mean free path of photons in the scattering medium.
22. J. S. Tyo, "Optimum linear combination strategy for an N-channel polarization-sensitive imaging or vision system," J. Opt. Soc. Am. A **15**, 359–366 (1998).
23. G. Buchsbaum and A. Gottschalk, "Trichromacy, opponent colours coding and optimum colour information transmission in the retina," Proc. R. Soc. London, Ser. B **220**, 89–113 (1983).
24. P. Lennie and M. D'Zmura, "Mechanisms of color vision," Crit. Rev. Neurobiol. **3**, 333–400 (1988).
25. D. H. Brainard, B. A. Wandell, and E.-J. Chichilnisky, "Color constancy: from physics to appearance," Curr. Dir. Psychol. Sci. **2** (October), 164–170 (1993).
26. T. H. Waterman, "Polarization sensitivity," in *Comparative Physiology and Evolution of Vision in Invertebrates B: Invertebrate Visual Centers and Behavior*, H. Atrum, ed. (Springer-Verlag, Berlin, 1981), Vol. VII/6B.
27. S. Q. Duntley, "Light in the sea," J. Opt. Soc. Am. **53**, 214–233 (1963).
28. K. T. Mullen, "The contrast sensitivity of human colour vision to red–green and blue–yellow chromatic gratings," J. Physiol. (London) **359**, 381–400 (1985).