Stereo Videopolarimetry: Measuring and Visualizing Polarization Patterns in Three Dimensions

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Because the human eye is practically blind to the polarization of light, biologists dealing with polarization vision of animals, or engineers designing robots using polarization-sensitive computer vision to enhance contrast in the optical environment need a technique to image the spatial distribution of polarized light in the visual environment. Recently, different kinds of imaging polarimetry were developed to measure the polarization patterns of objects and natural scenes in a single, two-dimensional, wide field of view. As a further development of this technique, we report here on the realization of the addition of depth to scenes imaging the distribution of polarized light: One kind of stereo videopolarimetry was designed to measure and visualize in three dimensions the polarization patterns in nature and to mimic the ability of animal-eyes to receive visual information from a binocular field of view. We demonstrate the power of stereo videopolarimetry on an applied problem representing (in parallel view stereo format) a three-dimensional object, a car with a shiny bodywork and also having strong reflection polarization. The technical difficulties and hitches of stereo videopolarimetry as well as the importance of the distance of observation, the role of the angle of view, the influence of the color of the object, and the possibility to state differences between metallized and non-metallized paints are discussed.

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Introduction

The visual system of many animal species is able to perceive the polarization of light, which is used for different purposes: e.g., for orientation[1] or habitat finding.[2–4] Several different point source polarimeters have been designed to measure the polarization characteristics of light.[5–7] These sophisticated optical devices can analyze with a high accuracy the optical parameters—brightness, degree of polarization, direction of polarization—of a light beam coming from a given direction. They are, however, of little use in the analysis of natural scenes and give little insight into the information content of the polarization of the visual world, which is inaccessible for the human eye being practically blind to polarization.

The need to receive polarized optical information pixel-by-pixel from a wide field of view has resulted in the rapid development of imaging polarimetry in the last decade. Recently, this technique was used for different measurements in computer vision,[8] in atmospheric remote sensing,[9–18] and in biology.[19–25] This technique can measure and visualize the spatial distribution of polarized light only in two dimensions. Thus, it cannot mimic one of the fundamental features of animal and human eyes, stereo vision, that is, the ability to combine visual information from two eyes in their binocular field of view.

The aim of this work is to report on the realization of stereo videopolarimetry, which is an application and a further development of the technique of videopolarimetry. The essence of stereo videopolarimetry is the addition of depth to scenes imaging the distribution of polarized light. Stereo videopolarimetry is actually nothing more than the match-making of two different methods, namely, stereoscopic imagery and imaging polarimetry (in this work videopolarimetry). The former technique is more than one century old,[26,27] and is well-known and wide-spread not only in science, but also in art, education, photography and entertainment.[28,29] On the other hand, imaging polarimetry (e.g., videopolarimetry) is a younger, but already well-established technique, which was developed to measure and visualize the spatial distribution of the degree and angle of polarization of light originating from objects and visual environments.

In this work we demonstrate the power of stereo videopolarimetry on an applied problem representing (in parallel view stereo format) a three-dimensional object, a car with a shiny bodywork and also having strong reflection polarization. The technical difficulties and hitches of stereo videopolarimetry as well as the importance of the distance of observation, the role of the angle of view, the influence of the color of the object, and the possibility to state differences between metallized and non-metallized paints are discussed. Using this technique, any polarization pattern in the nature can be measured and visualized in three dimensions. This method is applicable to both scientific and educational purposes in spite of the fact that there is no information that any animal visual system uses polarization as an input of binocular fusion, or stereopsis.

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Materials and Methods

To take a stereo videopolarimetric recording one first films the selected scene with a video camera recorder through a rotating linear polarization filter of high optical quality (without optical distortions) in front of the objective lens (Fig. 1A). To avoid any translation or rotation, the camera must be set up on a tripod. The camera should remain level in the roll plane and parallel in the yaw plane, but can have a constant down-angle in the pitch plane required by the object being filmed. Prior to recording, the focus, aperture, shutter speed and gain are manually selected. The initial alignment of the transmission axis (direction of polarization) of the filter is arbitrary, e.g. vertical. After a few seconds, it is turned twice at 45°, for example. The actual direction of the filter (0°,45°,90°) is spoken into the built-in microphone during recording. Using a single CCD video camera recorder r a wide spectral sensitivity and a proper series of color filters in front of the objective lens, the videopolarimetric recording can be performed as a function of the wavelength of light.

To simulate the distance between the two eyes, we need to take a second videopolarimetric recording of the investigated scene from another, properly selected direction of view (Fig. 1A). After taking the first recording the video camera is translated horizontally (from left to right, or right to left) a certain distance—about *t*/50, where *t* is the distance of the subject to be recorded[28,29]—to take the second recording. In the case of Fig. 2 the camera was typically moved by 6 centimeters between the two images. (This baseline corresponds with the average distance between the two human eyes but exceeds the ocular separation in several animal having polarization vision.) After moving the camera the videopolarimetric recording of the scene must be repeated as described above.

Because the stereo pairs are taken subsequently (rather than simultaneously), there is one very important consideration that must be taken into account when taking recordings with a single camera: any movement of any object or change in illumination during the two subsequent recordings will ruin the polarization pattern as well as the stereo effect. This problem can be partially overcome by using two cameras simultaneously. However, the problem of light change or subject movement even exists for both a single monocular image and stereo pairs, because the three polarization images take some time to capture. This means one must be aware of all movements or illumination changes in the scene during recording.

In order to obtain a stereo effect of high quality one has to follow the general guidelines of stereo imagery.[28,29] It is very important that both video recordings must be taken at the same focus, aperture, shutter speed and gain. One has to pay attention to the common distance restriction of stereo recording: the distance from the camera to the nearest object in the scene must not be too small. Objects closer than a certain limit will produce too much disparity in the stereo images, and will make these images difficult and uncomfortable to view.

After taking the stereo videopolarimetric recordings, their evaluation is performed with a personal computer. The recorded scenes are digitized with 8-bit (true color) frame by frame using a frame grabber (Screen Machine II, FAST Multimedia AG, Munich, Germany) in the computer connected to a, Hi8 video recorder (Figure 1B). For all three orientations $\varphi = 0°$, 45° and 90° of the polarizer (Hama, mounted dichroic sheet polarizer) 25 digitized frames are averaged in order to filter the inevitable small noise of the video signal. After the calibration of the camera/frame grabber combination for response versus intensity coding, from these three averaged video pictures, the modulation of the brightness I is obtained as a function of φ. A sinusoid $I = A \sin[2(\varphi - \alpha) + \pi/4] + B$ is fitted to this brightness modulation for each pixel of the picture in order to determine $I_{max} = B + A$, $I_{min} = B - A$ and the angle of polarization α, that is the angular position of I_{max} (Fig. 1C). From these parameters the total light intensity, $I = (I_{max} + I_{min})/2 = B$, and the degree of linear polarization $\delta = (I_{max} - I_{min})/(I_{max} + I_{min}) = A/B$ are calculated for every point in the image. Finally, two-dimensional color- or gray-coded maps of I, δ and α are produced with pixel resolution (Fig. 1D) in the red (650 nm), green (550 nm) and blue (450 nm) spectral ranges, in which the three color-sensitive CCD-chips of the used camera (CCD-VX1E Sony video Hi8 video camera) have the maximal sensitivity. Hence, the red, green and blue spectral ranges were obtained by using a digital image processing program belonging to the frame grabber to digitally separate the color channels in the digitized images.

After this evaluation procedure is performed, the color- or gray-coded stereo pairs are displayed on the computer screen or printed out. Because the camera was slightly shifted during the recording, there is some image loss when comparing the stereo pair: there is some additional image information on the right side of the right image, that does not appear in the left image, and vice versa. These additional regions must be eliminated by a proper mounting; they must be trimmed or cropped off of each image to obtain a common stereo window.

Because the stereo images of the same scene are taken from slightly different viewpoints, they are visually combined in our mind producing a three-dimensional image. The general principle is to restrict the viewing of the right image to the right eye and the left image to the left eye". The most common viewing method is known as parallel, or free, or wall-eye viewing, and is reached the most conveniently with the help of proper stereoscopic viewing lenses or prisms. Without such devices, one can use simply the palm of the hand or a sheet of paper.[29] The palm of the hand or the sheet must be held vertically in front of one's nose, parallel to the symmetry plane of the head. By selecting properly the distance of our eyes from the stereo pair, one can arrange that the left eye looks at, and only at, the left image, and the right eve looks at the right image, then in the mind a third image is produced in the center: the three-dimensional image.

Results

In this work the stereo images are presented in free-view (or wall-eye, or parallel) format. Figure 2 shows the stereo pairs of the reflection-polarization patterns of a car with a shiny bodywork. In the first row of Fig. 2 the common stereo pair of the color picture of the car is seen. This stereo pair comprises actually all visual information (the three-dimensional distribution of the brightness and color) that is available for the human eye from a given direction of view. The second and third rows in Fig. 2 show the stereo pairs of the pattern of the degree and the angle of polarization, respectively. This polarization information would be available for a binocular polarization-sensitive visual system. We should, however, mention that although there are many animals with polarization-sensitive eyes,[30] there are none that

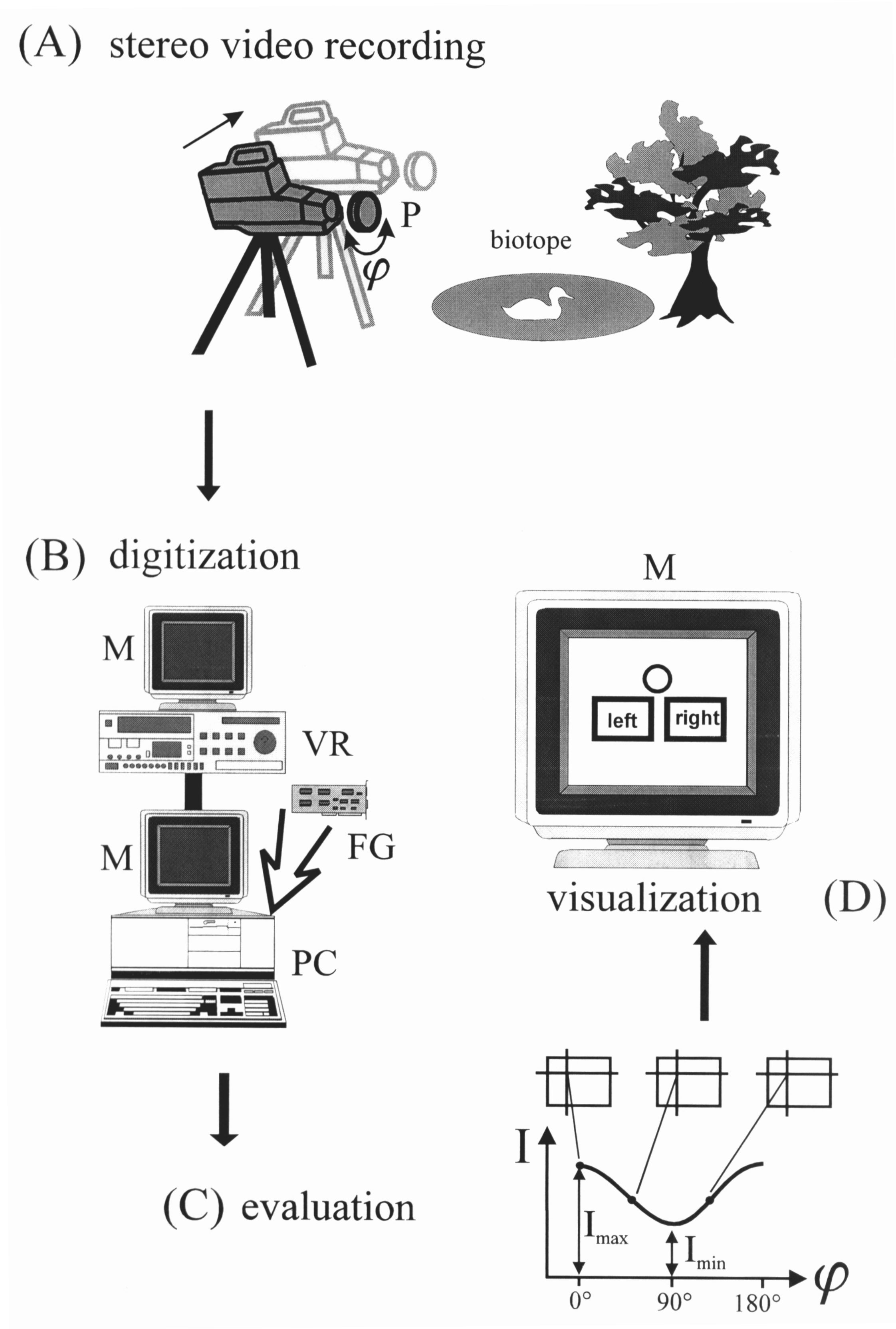

Figure 1. Schematic representation of the technique of rotating-analyzer stereo videopolarimetry. (A) Recording with a video camera mounted with a rotating linear polarization filter in front of the objective lens. (B) Digitizing the recorded pictures using a frame grabber in a personal computer connected directly to the video camera recorder or to a video recorder. (C) Evaluating the brightness (or light intensity) I, the degree of polarization δ and the angle of polarization a on the basis of the brightness modulation from pixel to pixel of the recorded scene. (D) Visualizing the patterns of 1, δ and α on the computer screen. P: rotatable linear polarization filter, φ: angle of rotation of the polarizer, M: monitor, VR: video recorder, FG: frame grabber, PC: personal computer.

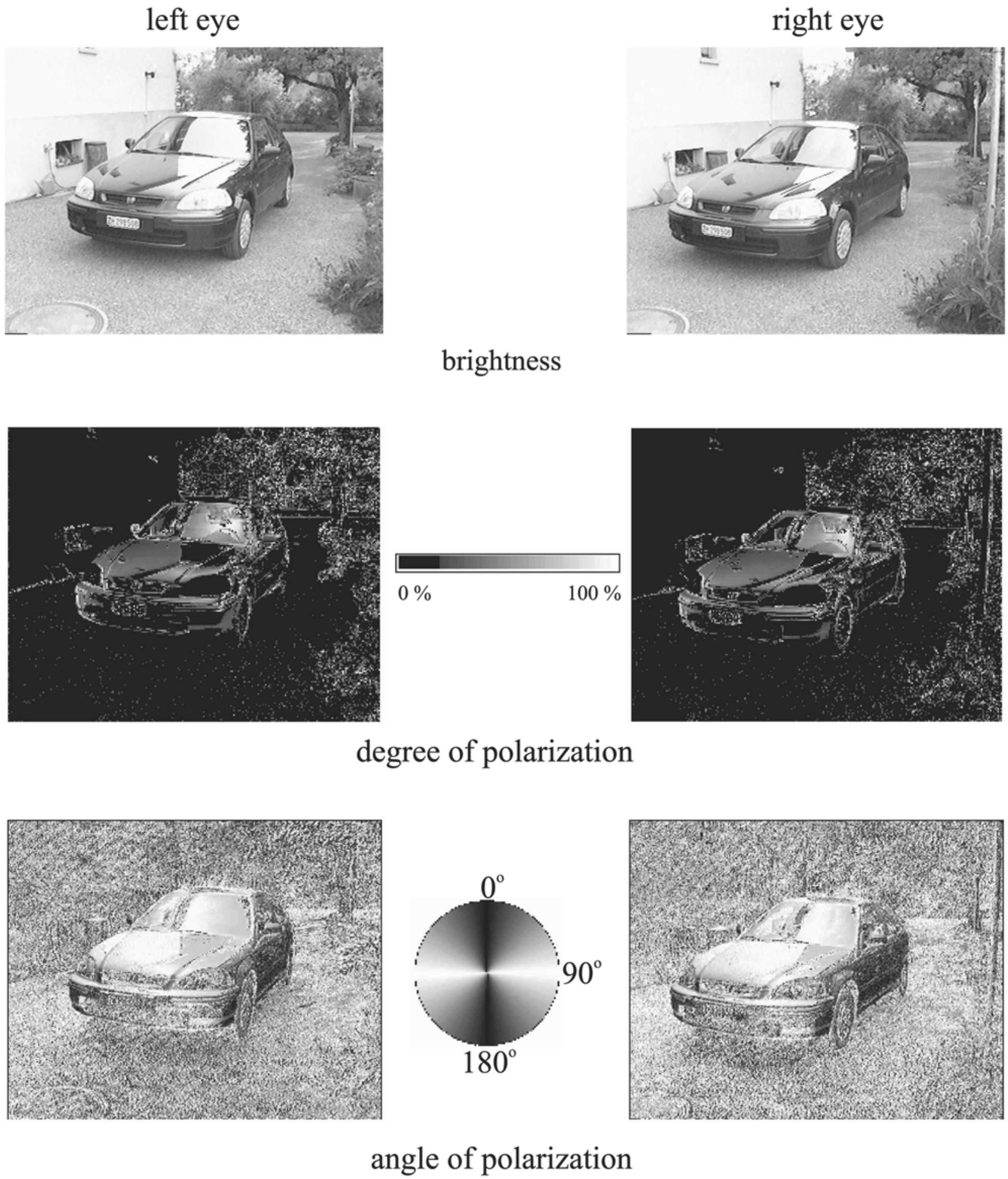

Figure 2 (Color to be posted on the IS&T website as supplemental material). The reflection- polarization characteristics of a car with a shiny bodywork represented in parallel view stereo format and the corresponding color palettes encoding the numerical values of the degree of polarization δ and angle of polarization α. *First row:* Stereo pair of the color picture of the car as an observer can see through a video camera. *Second row:* Stereo pair of the degree of polarization pattern of the car measured through the green channel (550 nm) of the videopolarimeter. *Third row***:** Stereo pair of the pattern of the angle of polarization of the car measured from the vertical and through the green channel. *Fourth row:* Stereo pair for the distribution of the brightness and the degree of polarization of the car in the green spectral range. The higher the value of δ, the deeper is the red hue. The higher the value of 1, the lighter is the brightness. If $I < 20\% = I_{threshold}$, then δ is not represented by red color. We used $I_{threshold}$, else due to the inevitable small noise of δ at low brightness values erratic deep red patches or pixels would be resulted in on the picture. *Fifth row:* Stereo pair for the distribution of brightness and angle of polarization of the car in the green spectral range. The higher the value of I, the brighter the colors. The same $I_{threshold}$ is used again as in row 4 to remove the noise of the angle of polarization at low light intensities.

are known to use polarization binocularly, that is, in the sense of stereopsis.

We can see that in some regions of the scene, the degree and angle of polarization changes strongly from point to point, which results in a rather erratic false-color distribution in these regions in rows 2 and 3 of Fig. 2. The consequence of this is that the false colors of a given pixel on the stereo pair in rows 2 and 3 can be frequently different; thus, the three-dimensional image cannot be developed, or at least the stereo effect is considerably reduced, because the mind of the observer is not able to (or can hardly) discover the corresponding pixels in the stereo pair.

To eliminate or at least minimize this problem, we can use the false-color combination of the stereo pair of the color picture and the polarization patterns of the investigated scene. Rows 4 and 5 in the color version of Fig. 2 (posted on the IS&T Website as supplemental material) show the stereo combination of the brightness distribution of the car [measured in the green (550 nm) spectral range] with the degree and the angle of polarization, respectively. In these combined stereo pairs the fight intensity is coded by the brightness and the polarization information is displayed by the color. Such a combined stereo representation of the reflection-polarization characteristics of the car as shown in rows 4 and 5 of the color version of Fig. 2 makes it possible for a spectacular stereo videopolarimetric image to be formed in the mind of the observer.

Discussion

The stereo videopolarimetric patterns presented in this work demonstrate the power of this combined technique and its possible application for scientific purposes, that is, to measure and visualize the reflection–polarization characteristics of natural scenes and objects in three dimensions. This is important for the students of the polarization vision of animals, because only sporadic information is available in the literature about the polarization features of natural biotopes. Using videopolarimetry, one can gather conveniently and easily a huge amount of polarized light information from any desired habitat. After performing stereo videopolarimetric recordings in the field, the polarization patterns of these biotopes can be spectacularly visualized in three-dimensional format.

The human visual system extracts spatial information from the two, slightly different images perceived by the right and left eye on the basis of retinal disparities. Our mind is not adapted, however, to reconstruct cyclopean (3D) images from false-color stereo pairs encoding the spatial distribution of polarization of light originating from the optical environment. This is the reason why the 3D image is so difficulty formed when viewing the fully false-color stereo pairs of the degree (row 2 in Fig. 2) or angle (row 3 in Fig. 2) of polarization. Thus, our mind needs some help to produce the 3D image of a. polarized scene. The function of the stereo pair of the brightness distribution of the scene (in a given spectral range) in rows 4 and 5 of the color version of Fig. 2 is to construct a “visual skeleton”, on the basis of which the stereo image can be formed. This skeleton is then filled with the polarization information (either the degree or the angle of polarization) that is coded by color shades. This trick ensures that the polarization patterns of objects and biotopes can be visualized in three dimensions.

As far, as we know, there is no evidence of binocular polarization channels in any visual system, just as there is no combination of color binocularly in animal or human vision (stereo vision is achromatic and polarization-blind). Thus for this reason we admit that stereo videopolarimetry is nothing else as a, useful technique to visualize for a human observer how polarized light varies with distance in a scene.

Attractiveness of the Bodywork of Cars to Certain Insects

We selected a car with a shiny bodywork to demonstrate the power of stereo videopolarimetry, not only because a car is a typical and common three-dimensional object, but also because its bodywork is usually so strongly polarized (see row 2 in Fig. 2), that it can attract water-seeking polarotactic insects with polarization-sensitive visual system. Many insects associated with water find their aquatic habitat on the basis of the strongly and horizontally polarized light reflected from the water surface.[2,3] There are many observations[31–33] that insects associated with water are deceived by and attracted to shiny car-bodies of cars. Recently, it was demonstrated[34,35] that the eggs laid by certain Brasilian dragonflies onto certain coach-works produce strong sulfonic acids above 70°C that destroy the clear-coat. These acids originate from proteins of the egg-shell (chorion) as products of chemical reactions that can proceed in the eggs of most insects. The temperature of car-bodies can often rise above 70°C in sunshine. Then eggs laid onto the car surface can damage the resin like acid rain. Dragonflies too, find the water by polarotaxis,[23,36] like many other insects associated with water.

On the basis of Fig. 2 it is clear that the reason why polarotactic insects are deceived by and attracted to cars is that due to the shiny clear-coat the bodywork of cars possesses such regions (the windscreen and the hood, for instance) from which strongly and horizontally polarized light is reflected.[37] These regions are very attractive to water-seeking insects, because they mimic a water surface to the insect’s visual system. We have also observed that polarotactic insects land and oviposite onto the glittering horizontal parts (e.g., hood, top) of the coach-work, because they mistake them for water. Although beyond the polarization the role of colors in the attractiveness of car-bodies to insects is not cleared up yet, also the color of the paintwork may strongly influence the behavior of insects.

This phenomenon was largely ignored till now in site of the fact that for all car-owners one of the most important properties of the new automobile is its spotless shiny clear-coat demonstrating that the vehicle is brand new. The longer the clear-coat retains its glitter, the more satisfied is the customer. Thus, the manufacturer has interest in elucidating all environmental factors that damage the automotive clear-coats and in developing preventions and defenses from them. The car-body can suffer damage from many environmental factors that can dull the paintwork and clear-coat. One of these factors is the attraction of certain insects swarming in large numbers towards the shiny car-bodies and laying often their eggs onto the coach-work.

Influence of the Angle of View and the Distance of Observation on the Reflection Polarization

The angle of view strongly, influences the reflection-polarization characteristics of a given object. The direction of polarization of fight reflected from a non-metallic (dielectric) object usually follows the curvature of its surface, because the reflected light becomes partially linear polarized parallel to any dielectric reflector in such a way, that the plane of oscillation is perpendicular to the plane of reflection determined by the incident and reflected rays and the normal vector of the surface at the point of reflection. The degree of polarization of reflected light depends on the angle of reflection; at smooth surfaces there is a characteristic angle of reflection, the so-called Brewster angle,[37] at which the reflected light is maximally polarized. Thus, changing the direction of view, the plane of reflection changes too with respect to the local normal vector of the observed surface, the consequence of which is the change of both the degree and angle of polarization. This is the reason for the fact that there may be considerable differences between certain corresponding regions of the right and left polarization patterns of the stereo pairs obtained by stereo videopolarimetry as mentioned at the end of the **Results** section.

The distance of observation influences the reflection-polarization characteristics of an object measured by stereo videopolarimetry indirectly through the angle of view: The smaller the distance of observation, the greater is the viewing angle difference between the two pictures of the stereo pair, which results in larger reflection-polarization differences too. Due to the latter the stereo effect is more or less reduced, as we have seen at the end of the **Results** section.

Influence of Color

The surface roughness as well as the color of the bodywork strongly influences the reflection polarization characteristics of a car. Because rough surfaces reflect light diffusely, which reduces polarization, the rougher the bodywork, the lower the degree of polarization of reflected light. The darker the bodywork in a given spectral range, the higher is the degree of polarization of reflected light. The reason for this is the following: The surface of the transparent clear-coat of the car body reflects more or less partially linear polarized light depending on the incident angle, but almost independently of the wavelength, and the direction of polarization of this reflected light is parallel to the surface. The color of' the bodywork arises from the selective absorption and diffuse scattering of light in the paint layer below the transparent clear-coat. The diffuse light emanating from this paint layer is originally unpolarized, but it becomes partially polarized after transmission and refraction at the surface of the clear-coat. The direction of polarization of the paint-scattered light is perpendicular to the clear-coat surface because of refraction polarization.[37] Hence, the net degree and direction of polarization of a coach-work are determined by the superposition of the clear-coat-reflected and the sub-clear-coat scattered (paint-scattered) light. If the former dominates, then the direction of polarization is parallel to the clear-coat surface. Otherwise it is perpendicular to the surface. In those spectral regions where the (paint-scattered) light has a considerable contribution to the net polarization, the net degree of polarization of the returned light is reduced or even abolished.

Hence, the light reflected from cars with shiny, smooth clear-coat and red paintwork, for example, is less polarized in the red spectral range and the degree of polarization of reflected light is highest in the blue (and ultraviolet) range of the spectrum (if the paint layer absorbs ultraviolet light). The considerably reduced amount of paint-scattered light for the shorter wavelengths causes the red bodywork to be dark and strongly polarized in the blue (and ultraviolet) region of the spectrum. For longer wavelengths (green and especially red) the amount of light emanating from the red paint below the transparent clear-coat is greater, thus, the net degree of polarization is reduced in the red (and green) spectral range. This is the reason for the general rule that in a given spectral region the darker objects polarize light to a higher degree if the illuminating light is unpolarized and white (like the sunlight).

Many insects do not perceive red light, but perceive ultraviolet light; their color sensitivity is shifted towards the shorter wavelengths in comparison with the human color sensitivity. Thus, due to the above-mentioned reasons red cars, for instance, are highly attractive to water-seeking polarotactic red-blind insects, because of the high degree of polarization of reflected light in the blue and ultraviolet spectral ranges.

Differences between Metallized and Non-Metallized Paints

Whether is it possible to state differences between metallized and non-metallized paints of car bodies on the basis of reflection polarization? The reflection-polarization characteristics of pure metal surfaces (which induce circular or elliptic polarization of the reflected light if the incident light is linearly polarized) considerably differ from those of dielectric (non-metallic) surfaces (which do not alter the linearity of the polarization of the incident light after reflection). This is thoroughly discussed by Azzam and Bashara,[6] Collett[7] and Können,[37] for instance. These differences are the basis of the polarimetric discrimination between metal and dielectric surfaces.[38] In spite of this optical phenomenon, the metallized paints of the car-bodies influence the polarization of reflected fight like non-metallized paints because of the transparent non-metallic clear-coat. However, the reflectivity of metallized paints is high in a relatively wide spectral range, in which the degree of polarization of reflected light is considerably reduced, as we have already seen above. Hence, the bodywork of cars with metallized paint will possess low degrees of polarization in the wide region of the spectrum, where the metal particles reflect light efficiently.

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References

1. R. Wehner, The hymenopteran skylight compass: matched filtering and parallel coding, *J. Experimental Bio.* **146,** 63 (1989).
2. R. Schwind, Polarization vision in water insects and insects living on a moist substrate, *J. Comparative Physiol.* **169,** 531 (1991).
3. R. Schwind, Spectral regions in which aquatic insects see reflected polarized light, *J. Comparative Physiol. A* **177,** 439 (1995).
4. G. Horváth, Reflection-polarization patterns at flat water surfaces and their relevance for insect polarization vision, *J. Theoretical Biol.* **175,** 27 (1995).
5. K. L. Coulson, *Polarization and Intensity of Light in the Atmosphere*, A. Deepak Publishing, Hampton, Virginia, 1988.
6. R. M. A. Azzam and N. M. Bashara, Ellipsometry and Polarized Light, North-Holland, Amsterdam, 1989.
7. E. Collett, Polarized Light. Fundamentals and Applications, M. Dekker Inc., New York, 1994.
8. L. B. Wolff, Polarization camera technology, *Proceedings of the DARPA Image Understanding Workshop* 1031–1036 (1993).
9. R. L. Walraven, Polarization imagery, *Opt. Eng.* **20,** 14 (1981).
10. T. Prosch, D. Hennings and E. Raschke, Video Polarimetry: A new imaging technique in atmospheric science, *Appl. Opt.* **22,** 1360 (1983).

11. W. G. Egan, Proposed design of an imaging spectropolarimeter/photometer for remote sensing of earth resources, *Opt. Eng.* **25,** 1155 (1986).
12. P. Y. Deschamps, F. M. Bréon, M. Leroy, A. Podaire, A. Bricaud, J. C. Buriez, and G. Séze, The POLDER mission: Instrument characteristics and scientific objectives, *IEEE Transactions of Geosciences and Remote Sensing* **32,** 598 (1994).
13. J. A. North and M. J. Duggin, Stokes vector imaging of the polarized sky-dome, *Appl. Opt.* **36,** 723 (1997).
14. K. J. Voss and Y. Liu, Polarized radiance distribution measurements of skylight, I. System description and characterization, *Appl. Opt.* **36,** 6083 (1997).
15. G. Horvith, J. Gál, I. Pomozi and R. Wehner, Polarization portrait of the Arago point: Video-polarimetric imaging of the neutral points of skylight polarization, *Naturwiss.* **85,** 333 (1998).
16. J. Gál, G. Horváth and V. B. Meyer-Rochow, Measurement of the reflection-polarization pattern of the flat water surface under a clear sky at sunset, *Remote Sensing of Environment* (in press) (2001).
17. J. Gál, G. Horváth, V. B. Meyer-Rochow, and R. Wehner, Polarization patterns of the summer sky and its neutral points measured by full-sky imaging polarimetry in Finnish Lapland north of the Arctic Circle, *Proc. Roy. Soc. London A* (in press) (2001).
18. I. Pomozi, J. Gál, G. Horváth and R. Wehner, Fine structure of the celestial polarization pattern and its temporal change during the total solar eclipse of 11 August 1999, *Remote Sensing of Environment* (in press) (2001).
19. N. Shashar, T. W. Cronin, G. Johnson, and L. B. Wolff, Portable imaging polarized light analyzer, *Proc. SPIE* **2426,** 28 (1995).
20. G. Horwith and J. Zeil, Kuwait oil lakes as insect traps, *Nature* **379,** 303 (1996).
21. G. Horvith and D. Varjú, Polarization pattern of freshwater habitats recorded by video polarimetry in red, green and blue spectral ranges and its relevance for water detection by aquatic insects, *J. Exp. Bio.* **200,** 1155 (1997).
22. G. Horváth, J. Gál and R. Wehner, Why are water-seeking insects not attracted by mirages? The polarization pattern of mirages, *Naturwiss* **84,** 300 (1997).
23. G. Horváth, B. Bernáth and G. Molnár, Dragonflies find crude oil visually more attractive than water: Multiple choice experiments on dragonfly polarotaxis, *Naturwiss* **85,** 292 (1998).
24. G. Kriska, G. Horváth and S. Andrikovics, Why do mayflies lay their eggs en masse on dry asphalt roads? Water-imitating polarized light reflected from asphalt attracts Ephemeroptera *J. Exp. Bio.* **201**, 2273 (1998).
25. B. Bernáth, G. Szedenics, G. Kriska, and G. Horváth, Visual ecological impact of “shiny black anthropogenic products” on aquatic insects: oil reservoirs and plastic sheets as polarized traps for insects associated with water, *Archives of Nature Conservation and Landscape Research* (in press) (2001).
26. F. Drouin, The Stereoscope and Stereoscopic Photography, (London, 1894), a facsimile of the 1894 2nd ed., Reel 3-D Enterprises Historical 3-D Reprint Series, USA, 1995.
27. T. Brown, Stereoscopic Phenomena of Light and Sight (London, 1903), a facsimile of the 1903 edition, Reel 3-D Enterprises Historical 3-D Reprint Series, USA, 1994.
28. F. G. Waack, Stereo Photography, Germany, 1985.
29. D. Burder and P. Whitehouse, Photographing in 3-D, Stereoscopic Society, England, 1992.
30. T. H. Waterman, Polarization sensitivity, Handbook of Sensory Physiology VII/6B, Comparative Physiology and Evolution of Vision Invertebrates B: Invertebrate Visual Centers and Behavior, vol. I, H. Autrum, Ed., Sringer, Berlin, 1981, pp. 281–469.
31. C. H. Fernando, The colonization of small freshwater habitats by aquatic insects. 1. General discussion, methods and colonization in the aquatic Coleoptera, *Ceylon J. Sci.* (*Biological Sciences*) **1**(2), 116 (1958).
32. E. J. Popham, The migration of aquatic bugs with special reference to the Corixidae (Hemiptera Heteroptera), *Archives of Hydrobiology*, **60,** 450 (1964).
33. J. A. L. Watson, Oviposition by exophytic dragonflies on vehicles, *Notul. Odonatol.* **3**, 137 (1992).
34. C. V. Stevani, J. S. Porto, D. J. Trindade, and E. J. H. Bechara, Automotive clearcoat damage due to oviposition of dragonflies, *J. Appl. Poly. Sci.* **75,** 1632 (2000).
35. C. V. Stevani, D. L. A. de Faria, J. S. Porto, D. J. Trindade, and E. J. H. Bechara, Mechanism of automotive clearcoat damage by dragonfly eggs investigated by surface enhanced Raman scattering, *Polymer Degradation and Stability* **68,** 61 (2000).
36. H. Wildermuth, Dragonflies recognize the water of rendezvous and oviposition sites by horizontally polarized light: a behavioral field test, *Naturwiss.* **85,** 297 (1998).
37. G. P. Können, *Polarized Light in Nature*, Cambridge University Press, Cambridge, 1985.
38. L. B. Wolff and T. E. Boult, Constraining object features using a polarization reflectance model, *IEEE Trans. on Pattern Analysis and Machine Intelligence* **13,** 635 (1991).