

Extraction of surface normal and index of refraction using a pair of passive infrared polarimetric sensors

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Abstract

This paper summarizes a method for extracting 3D information and indices of refraction from a scene by means of a pair of polarimetric passive imaging sensors. Each sensor provides the Stokes vector at each sensor pixel location, from which, degree and angle of linear polarization are computed. Angle of linear polarization provides the azimuth angle of the surface normal vector. Two cases are considered. For the special case when the two sensors have a common azimuth plane the index of refraction can be found analytically in terms of the degrees of polarization and the angle between the lines of sight from the two sensors, from which the depression angle of the surface normal can be computed. For the second and more general case the surface normal is estimated from the cross-product of the azimuth vectors from the two sensors and the inner product of the line of sight vectors and surface normal. Once the depression angles are estimated the index of refraction can be computed.

Results of the application of this approach on simulated infrared polarimetric data are provided.

1. Introduction

Determination of 3D information from passive sensors has been a subject of interest in the remote sensing and optical information processing communities for the past several decades. It is known that 3D imaging can be achieved by determining orientation angles of surface normals at every points in the scene. Some of the known methods of determining these normals includes shape from shading, stereo imaging, and, more recently, use of reflectance polarization diversity operating in the visible to infrared range of the electromagnetic spectrum [1, 2, 3, 4, 5, 6, 7, 8]. Even though attempts at extracting surface orientations for reflectance polarization for limited sensor placement geometries has been reported [2, 4], the work being reported here

is novel in its use of emittance (important for passive sensors) polarization for general sensor placement geometries.

2. Polarization Diverse Sensing

The polarization of a plane wave describes the locus of the tip of the electric vector as a function of time in the plane perpendicular to the propagation direction. This locus generally moves in an ellipse. The sense of rotation or handedness is denoted right-handed (or left-handed) when rotation is as a right-handed (or left-handed) screw in the propagation direction. One way in which the state of polarization can be written is as a Stokes vector [8], where this vector is defined as:

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{bmatrix} = \begin{bmatrix} a^2 \\ a^2 \cos(2\chi) \cos(2\psi) \\ a^2 \cos(2\chi) \sin(2\psi) \\ a^2 \sin(2\chi) \end{bmatrix} \quad (1)$$

where a is the signal intensity, χ is the ellipticity angle of the polarization ellipse, and ψ is the angle of linear polarization (sometimes called the azimuth angle). State of polarization can also be represented in terms of just two parameters: degree of linear polarization r , and ψ , where

$$r = \frac{\sqrt{S_2^2 + S_3^2}}{S_1} \quad (2)$$

$$\psi = \frac{1}{2} \tan^{-1} \left(\frac{S_3}{S_2} \right) \quad (3)$$

3. Refraction Polarization and Fresnel Equations

Thermal polarization can be viewed as a special case of refraction polarization where electromagnetic waves emanating from within an object refract at the surface-air boundary and then are observed by an infrared sensor.

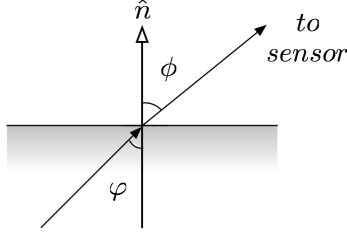


Figure 1. Emergent EM wave refracts at surface-air boundary

As observed by Fresnel, an unpolarized electromagnetic wave incident on its surface-air boundary both reflects and refracts. The refracted wave is polarized in a direction perpendicular to the plane of incidence and the reflected wave is polarized in a direction parallel to the plane of incidence. These two components are related by the Fresnel equations:

$$I_{\parallel} = \frac{\sin(2\phi)\sin(2\varphi)}{\sin^2(\phi + \varphi)\cos^2(\phi - \varphi)} \quad (4)$$

$$I_{\perp} = \frac{\sin(2\phi)\sin(2\varphi)}{\sin^2(\phi + \varphi)} \quad (5)$$

where φ is the angle of incidence and ϕ is the angle between the surface normal and the line of sight of the sensor (see Fig. 1). It has been shown [3] that the degree of linear polarization r is related to the above parallel and perpendicular components by

$$r = \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}} \quad (6)$$

By making use of the Snell's law we can eliminate φ , leading to the following solutions for ϕ in terms of degree of linear polarization r and the index of refraction n of the surface material (where n is in general a complex number): [7]:

$$\phi_{\pm} = \sin^{-1} \left(\frac{\frac{1-r}{1+r} - 1}{\pm \frac{2}{n} \left(\frac{1-r}{1+r} \right)^{\frac{1}{2}} - \frac{1}{n^2} - 1} \right)^{\frac{1}{2}} \quad (7)$$

The imaginary part of n is called extinction coefficient, and indicates the amount of absorption loss when the electromagnetic wave propagates through the material. This value is typically larger than 1 for a transparent material. The range of r is from 0 to 1.

In order to specify the index of refraction of the surface material one needs to specify the degree of polarization r and the depression angle ϕ . r can be determined from the Stokes vector given by the sensor and ϕ can be determined from the sensor-target geometry discussed in the next section.

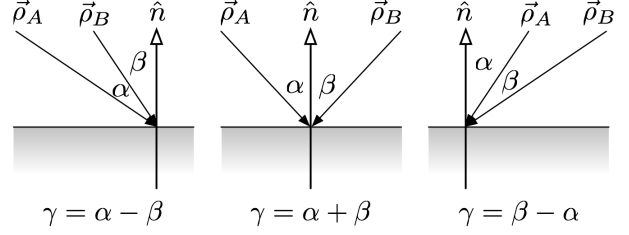


Figure 2. Special two-sensor geometry showing the three possible combinations of depression angles

4. Estimating Index of Refraction from an Image Pair

Consider a point O on the target. A line connecting O to an observer A , is the line of sight ($\vec{\rho}_A$) for that observer. Assume that this line forms a depression angle $\phi = \alpha$ with the surface normal at O . Similarly the angle of line sight $\vec{\rho}_B$ of another observer B forms an angle β with the surface normal at O . Label ψ_A as the azimuth angle of the plane of incidence for observer A , and ψ_B for observer B . Labeling the angle between these two lines of sight as γ .

There exists a special case where the surface normal \hat{n} lies in the plane defined by the two observers A and B and the surface point O . In this case

$$\gamma = \begin{cases} \alpha - \beta \\ \alpha + \beta \\ -\alpha + \beta \end{cases} \quad (8)$$

where the three cases arise from the three possible relative orientations of the two observers relative to the normal in the plane (see Fig. 2).

In principle one can define α in terms of γ ,

$$\gamma = \cos^{-1} \left(\frac{\vec{\rho}_A \cdot \vec{\rho}_B}{|\vec{\rho}_A| |\vec{\rho}_B|} \right) \quad (9)$$

and the degrees of linear polarization for both observers (r_A and r_B). From Eqn. (7) one can find α and β :

$$\begin{aligned} \alpha &= \cos^{-1} \left(\frac{k_A^2 + x^2 \mp 2xk_A}{1 + x^2 \mp 2xk_A} \right)^{\frac{1}{2}} \\ \beta &= \cos^{-1} \left(\frac{k_B^2 + x^2 \mp 2xk_B}{1 + x^2 \mp 2xk_B} \right)^{\frac{1}{2}} \end{aligned} \quad (10)$$

where $x = \frac{1}{n}$ and $k_i^2 = \left(\frac{1-r_i}{1+r_i} \right)^{\frac{1}{2}}$ for $i = A, B$. Summing both forms of Eqn. (10) according to the appropriate form of Eqn. (8) and taking γ as defined in Eqn. (9) gives a relation for the index of refraction of the surface in terms of the two lines of sight and the two degrees of linear polarization. The surface normal can be easily defined by reconstructing either of the depression angles α, β the index is found.

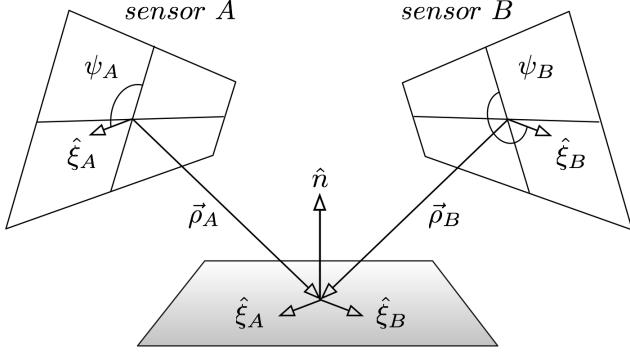


Figure 3. General two-sensor geometry showing surface normal and azimuth vectors

For a more general sensor placement (see Fig. 3) one needs to construct azimuth vectors from the two sensors ($\hat{\xi}_A$ and $\hat{\xi}_B$). An azimuth vector is defined as a unit vector perpendicular to the plane that contains surface normal and line of sight. This vector then lies in the plane of the surface of the target at point O such that if one takes the cross-product of two such vectors (as defined by two observers) one can reconstruct the surface normal. The individual azimuth vectors as represented in the image plane of the sensor, are defined by the azimuth angle ψ rotated from the image's vertical axis. In this notation, the special case from above corresponds to when the two azimuth vectors are parallel and cannot be used to define a unique normal vector.

$$\hat{n} = \hat{\xi}_A \times \hat{\xi}_B \quad (11)$$

The components of the azimuth vectors can be written in terms of the polar angles (θ_i, ϕ_i) that define the line of sight $\vec{\rho}_i$, and the azimuth angle ψ_i as

$$\xi_i = \begin{pmatrix} \sin\theta_i \sin\psi_i - \cos\theta_i \cos\phi_i \cos\psi_i \\ -\cos\theta_i \sin\psi_i - \sin\theta_i \cos\phi_i \cos\psi_i \\ \sin\phi_i \cos\psi_i \end{pmatrix} \quad (12)$$

where $i = A, B$. From the normal vector \hat{n} and either of the lines of sight one can easily compute the appropriate depression angle using a dot-product

$$\begin{aligned} \alpha &= \cos^{-1} \left(\frac{\vec{\rho}_A \cdot \hat{n}}{|\vec{\rho}_A| |\hat{n}|} \right) \\ \beta &= \cos^{-1} \left(\frac{\vec{\rho}_B \cdot \hat{n}}{|\vec{\rho}_B| |\hat{n}|} \right) \end{aligned} \quad (13)$$

Using Eqn. (10) one can then solve for the index of refraction for the surface in terms of the two lines of sight, the two degrees of linear polarization, and the two azimuth angles.

5. Simulation and Experimental Results

Using a physics based infrared modeling tool we generated polarimetric images of a tactical scene. In this scene,

several aircraft hangars are connected by runways and the target is parked on the grass. In some images the target was a M35 truck; in other images a T72 tank was used.

For the polarimetric sensors, we assumed we are using off-the-shelf components. We included the characteristics of the Santa Barbara Focal plane SBF-119 640x512 InSb focal plane array. We also included the characteristics of a 400 mm lens. Among the simplifying assumptions made in this scenario are: (i) All surfaces have the same temperature 24 C. (ii) Only two surface materials exist: grass which emits unpolarized light, and glossy paint, which emits polarized light with characteristics described by Fresnel equations. [We use a complex index of refraction of $1.5 + i 0.15$, which is representative of paint in the wavelength range, 3-5 microns.] (iii) No sun is present. The range from sensor to target varies from 1 to 12 km. At 1 km the target and a hangar are well resolved. At 12 km the target subtends only 4 pixels.

By making use of two sensors one can obtain more direct estimates of the indices of refraction and depression angles of objects' surface normals. In this case the images of a scene are captured by two sensors placed at two different geographical positions. First the Stokes vectors for the two different views of the scene were computed at each pixel. Then the two images were registered to establish correspondence among pixels associated with the same points in the scene. This is a critical stage in the process. Any error in this step will contribute directly to the errors in the following computations. Figs. 4 and 5 show the degree of linear polarization, azimuth and depression angles of the surface normals for the objects (a M35 truck) in the scene as sensed by the two sensors. Figs. 6 and 7 similarly show the degree of linear polarization, azimuth and depression angles of the surface normals for the objects (a T72 tank) in the scene as sensed by the two sensors. It can be seen that horizontal surfaces such as top of the vehicles and runways correspond to large depression values. Whereas side-looking surfaces such as side of the vehicles and hangars correspond to large azimuth angle values.

6. Summary and Conclusions

This paper summarizes a method for extracting 3D information and indices of refraction from a scene by means of a pair of polarimetric passive imaging sensors. Each sensor provides the degree and angle of linear polarization. Angle of linear polarization provides the azimuth angle of the surface normal vector. Two cases are considered. For the special case when the two sensors have a common azimuth plane the index of refraction can be found analytically in terms of the degrees of polarization and the angle γ between the lines of sight from the two sensors, from which the depression angles of the surface normal can be computed. For the second and more general case the surface

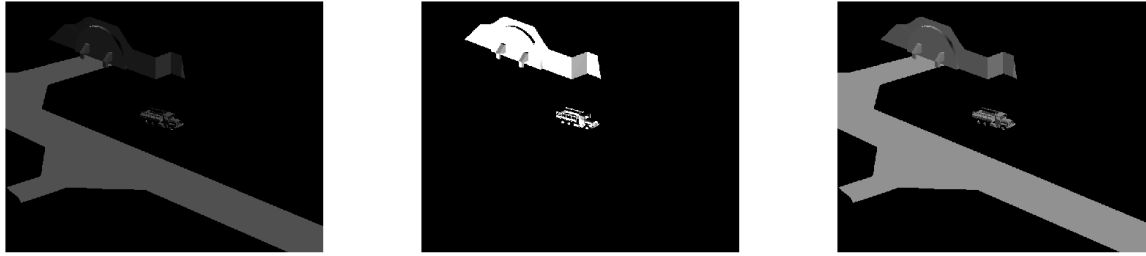


Figure 4. Degree of linear polarization, azimuth and depression angles of the surface normals at sensor position 1 for a scene containing an M35 truck

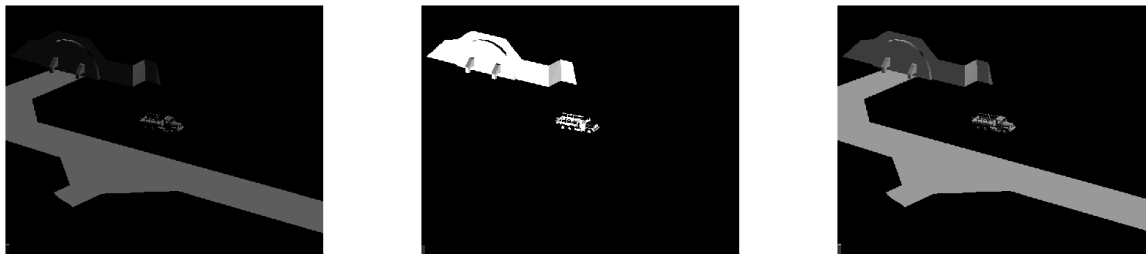


Figure 5. Degree of linear polarization, azimuth and depression angles of the surface normals at sensor position 2 for a scene containing an M35 truck

normal is estimated from the cross-product of the azimuth vectors from the two sensors and the depression angle from the dot-product of the line of sight vectors and surface normal. Once the depression angles are estimated the index of refraction can be computed. The method is applied on simulated polarimetric infrared imagery. The results are significant because by use of two passive polarimetric imaging sensors positioned at different (but with overlapping fields of views) geographical positions one can obtain both 3D geometrical shape information and indices of the refractions of the objects in the scene.

References

- [1] L. B. Wolff, T. E. B. Boulton, "Constraining Object Features Using a Polarization Reflectance Model," *IEEE Transaction on Pattern Analysis and Machine Intelligence*, Vol.13, No. 7, July 1991.
- [2] M. Saito, Y. Sato, K. Ikeuchi, H. Kashiwagi, "Measurement of surface Orientations of Transparent Objects Using Polarization in Highlight," *Journal of Optical Society of America, A*, Vol. 16, No. 9, 1999.
- [3] M. Born, and E. Wolf, *Principles of Optics*, Cambridge Press, 1998.
- [4] D. Miyazaki, M. Kagesawa, and K. Ikeuchi, "Transparent Surface Modeling from a Pair of Polarization Images," *IEEE Transaction on Pattern Analysis and Machine Intelligence*, Vol. 26, No. 1, January 2004.
- [5] F. A. Sadjadi, C. S. Chun, "Passive Polarimetric IR Target Classification," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-37, No. 3, July 2001.
- [6] F. A. Sadjadi and C. S. Chun, "Automatic detection of small objects from their infrared state-of-polarization vectors," *Optics Letters*, Vol. 28, 531-533, April 2003.
- [7] F. A. Sadjadi, "Passive 3D imaging using polarimetric diversity," *Optics Letters*, Optical Society of America Publication, Vol. 32, No. 3, February 2007.
- [8] S. Huard, *Polarization of Light*, John Wiley & Sons, New York, 1996.

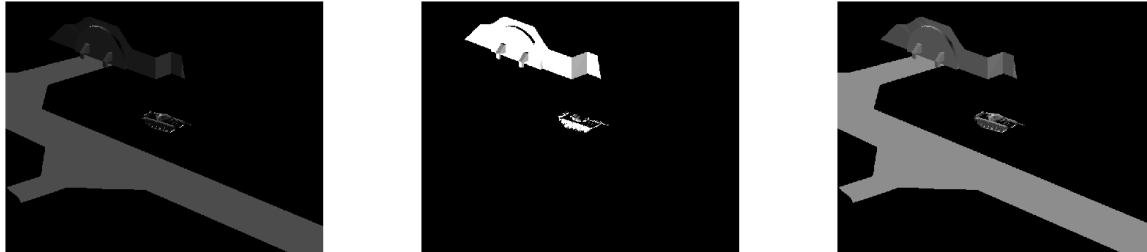


Figure 6. Degree of linear polarization, azimuth and depression angles of the surface normals at sensor position 1 for a scene containing an T72 tank

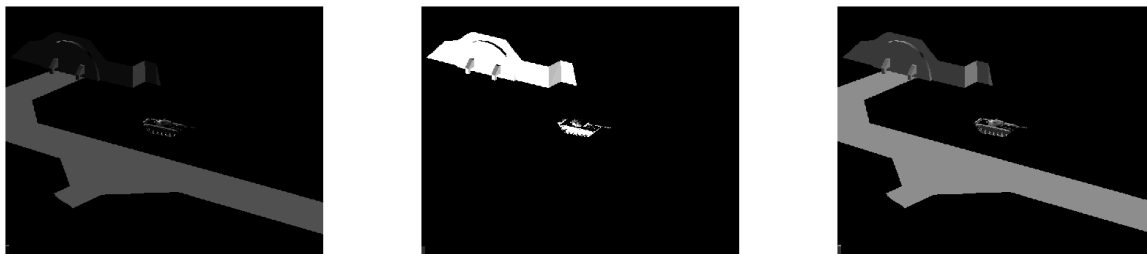


Figure 7. Degree of linear polarization, azimuth and depression angles of the surface normals at sensor position 2 for a scene containing an T72 tank