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Initial results and field applications of a polarization imaging camera

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ABSTRACT

The SALSA linear Stokes polarization camera from Bossa Nova Technologies (520-550 nm) uses an electronically rotated polarization filter to measure four states of polarization nearly simultaneously. Some initial imagery results are presented. Preliminary analysis results indicate that the intensity and degree of linear polarization (DOLP) information can be used for image classification purposes. The DOLP images also show that the camera has a good ability to distinguish asphalt patches of different ages. These positive results and the relative simplicity of the camera system show the camera's potential for field applications.

Keywords: Polarization imaging, image classification, surface characterization

1. BACKGROUND

Polarimetric information is mostly uncorrelated with spectral or intensity information; whereas spectral content reveals material composition, polarization informs about "surface features, shape, shading, and roughness"¹. Remote sensing of polarization at optical wavelengths has only begun to be explored since the advent of imaging polarimetry in the 1970s^{1,2}. Polarimetric imaging thus has high potential for augmenting remote sensing capabilities in general and disturbed-surface detection in particular.

Light can be characterized by its intensity, spectrum, coherence, and polarization state¹. Linear polarization imagery is acquired by measuring light at multiple polarizations – typically linearly polarized at 0°, 45°, 90°, and 135°. Such data are then expressed by means of Stokes parameters, \bar{S} , with components commonly designated I , Q , U , and V , or alternatively s_0 , s_1 , s_2 and s_3 . Given the measured light intensities $I(\theta, \epsilon)$, where θ represents the angle of polarization with respect to the x-axis and $\epsilon = \varphi_2 - \varphi_1$, the Stokes vector is

$$\bar{S} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} I(0^\circ, 0) + I(90^\circ, 0) \\ I(0^\circ, 0) - I(90^\circ, 0) \\ I(45^\circ, 0) - I(-45^\circ, 0) \\ I(0^\circ, \pi/2) - I(-45^\circ, \pi/2) \end{bmatrix}.$$

The parameter I gives the total intensity. Q represents the difference in intensity accepted through polarizers oriented at 0° and 90° with respect to the x-axis. U has a similar interpretation for the 45° and -45° orientations. V represents the difference in circular polarizations in the right-handed and left-handed senses³. Circular polarization data is generally not measured.

The degree of linear polarization, or DOLP is calculated as follows¹:

$$DOLP = \sqrt{Q^2 + U^2} / I .$$

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2. THE CAMERA

The polarimetric imager used in this research is a division-of-time polarimeter. Lefaudeux et al. (2008) of Bossa Nova Technologies note that while past time-division polarimeters using mechanical rotation have been very slow and sensitive to scene motion, electrically driven elements such as birefringent ceramics and liquid crystals have now allowed for fast time-division polarimeters⁴. Their SALSA camera is such a device, employing fast programmable liquid crystal waveplates to detect four linear polarization states: 0, 45, 90, and -45 degrees. The wave plates alter the polarization state of the light passing through them and are able to switch between polarization states on a time scale of 100 microseconds.

This prototype camera is compact (4" x 4" x 6") and robust, and it employs a standard CCD (782 x 582 pixels) and standard F mount lenses (see Figure 1). It uses 12-bit digitization and can image at up to 35 frames per second in full resolution mode. The power supply is 15 V DC. Acquisition and image processing software run on a standard computer connected to the camera via IEEE-1394 FireWire and USB. The camera is integrated and calibrated with a green filter (520 – 550 nm)⁴.



Figure 1. The SALSA camera and its use in a field experiment⁴.

The polarized filtering system can be broken down into two components: a 45-degree polarization rotator and a 90-degree polarization rotator. The 45-degree polarization rotator is itself composed of two elements: a quarter-wave plate and a programmable quarter-wave plate. To detect horizontally or vertically polarized light, the programmable plate is oriented such that the light will pass through both of them with its polarization unaltered. Light polarized at 45 or -45 degrees will be converted to left-handed or right-handed circular polarization by the first plate, respectively, and the second plate is programmed such that these states will be converted to horizontal or vertical polarization, respectively.

The 90-degree polarization rotator consists of a half-wave programmable plate and a vertical polarizer. To acquire the various states, the plate is set to the appropriate state to convert the desired incoming light to vertical polarization to allow it to pass through the polarizer to be detected by a standard CCD camera. Each of the four polarization states listed above has a unique sequence of wave plate settings that allows that polarization state to be detected. This concept is best understood in a diagram; see Figure 2⁴.

The software interface for the camera provides real-time visualization as well as options to record the data in various formats. The visualization options include the Stokes parameters, DOLP, and angle-of-polarization displays, along with several other possible variations and combinations. All can be mathematically reconstructed from the basic data – arrays containing the three Stokes parameters I , Q , and U measured across the CCD⁴.

After calibration, the camera was shown to have excellent measurement; the standard deviation around a 100% DOLP measurement was 0.45%, which the manufacturer supposes can be further reduced by modifications. The standard deviation for measurements across other DOLP was 0.017%.

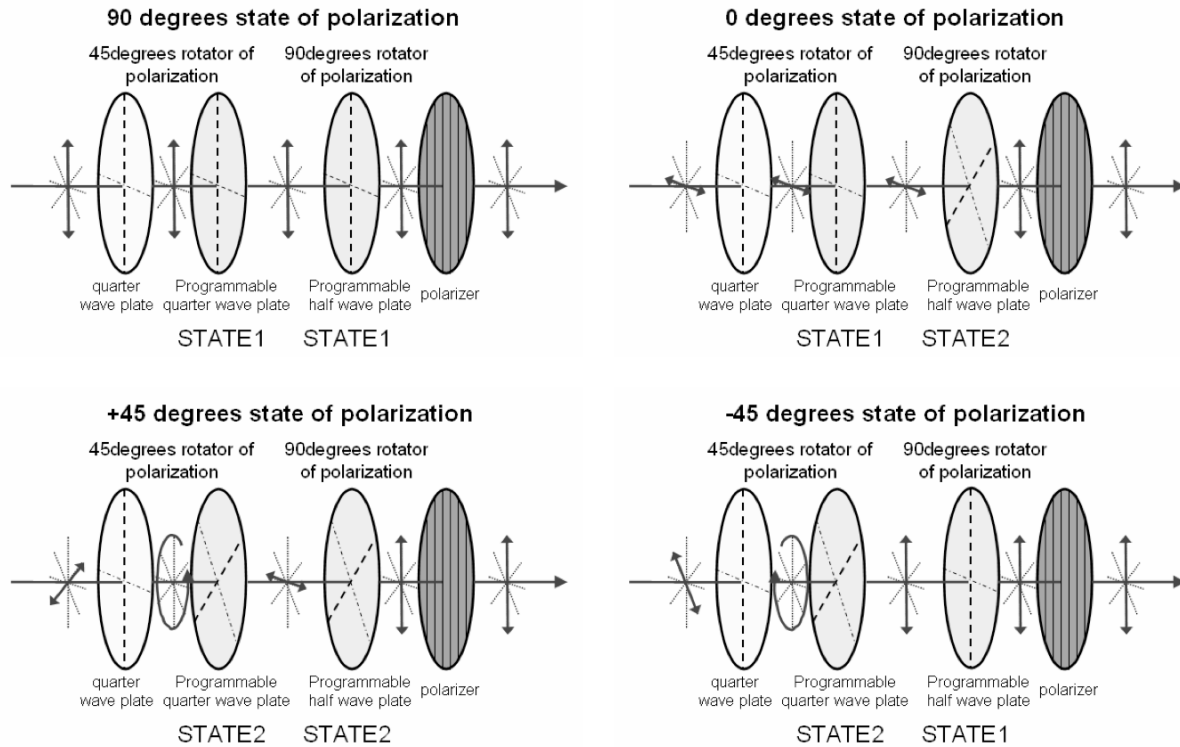


Figure 2. Polarization modulation in the SALSA camera⁴.

3. IMAGING RESULTS

Imaging focused on “natural” (i.e. outdoor, relatively uncontrolled) scenery and was limited to clear conditions, since the clear atmosphere and directionality of light favor polarization. Scenes were chosen to control the amount of textural contrast and materials in the images.

Two sets of images are reported: a panoramic view taken from the roof of Spanagel Hall on the Naval Postgraduate School campus, and images of paved areas with significant patching. In each case, exposure times were chosen to obtain enough data while minimizing oversaturation in the field of view.

3.1 Landscape Views

A panoramic image was created from a mosaic of four separate images acquired on 8 July 2009 between 2:10 and 2:15 pm. The sun was behind the camera, at an elevation of about 60° above the horizon. A 52 mm lens with the zoom set at infinity and an aperture of f/11 was used. Exposure time was set at 3 ms.



Figure 3. The Stokes image information from the panoramic scene collected from the roof of Spanagel Hall. From top to bottom, s_0 , s_1 , s_2 , and DOLP.



Figure 4. An RGB camera image showing approximately the same view as the polarimetric camera.



Figure 5. An RGB image with the s_0 image mapped to Red, DOLP mapped to Green, and s_1 mapped to Blue.

One of the basic questions we are investigating is the utility of polarimetric imagery for terrain classification and target identification. As a consequence, we are curious about the use of data such as these for classification purposes. We chose to look at this using the maximum likelihood classifier – a standard tool for spectral imaging. According to Richards (1999)⁵, maximum likelihood (ML) classification is the most widely used and often the most effective means of supervised classification in remote sensing. The classification is based upon the statistics of chosen regions of interest, which form the classes. The algorithm assumes that the statistics for each class are normally distributed in all bands and uses a Bayesian decision rule to calculate the probability that each pixel in an image belongs to a given class. The pixel is then assigned to the most likely class⁵.

Five regions of interest were chosen for use with the maximum likelihood supervised classifier.

Regions of Interest	
	Tree
	Shaded Tree
	Building
	Roof
	Window

The adjacent scatter plot shows s_0 versus DOLP for these regions of interest. While the regions are mostly well separated, the Umov effect, which states that the degree of linear polarization of an object is inversely proportional to the intensity of the object, is not as apparent as expected.

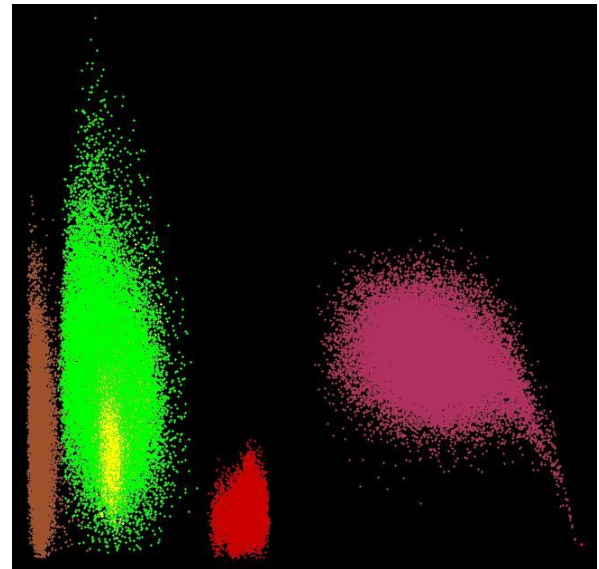


Figure 6. Scatter plot of s_0 versus DOLP for the five regions of interest.



Figure 7. The maximum likelihood image classification result for the panoramic scene.

The classification result above is a standard way of presenting this type of information. The image below is an attempt to present a combination of the maximum likelihood classification result and the s_0 (intensity) information. This image was created by transforming the maximum likelihood classification result from an RGB color space into an HLS color space. The s_0 band from the original polarimetric image was then treated as the Luminosity and combined with the Hue and Saturation values from the transformed classification result. This merged HLS image, containing both the image classification result and the original s_0 intensity information, was then transformed back into an RGB color space.



Figure 8. The maximum likelihood classification result combined with the s_0 intensity information from the panoramic scene collected from the roof of Spanagel Hall.

3.2 Disturbed Asphalt

To test the camera's ability to distinguish the polarimetric characteristics of asphalt of different ages, images were taken of a parking lot sites with significant asphalt patching. Intensity and DOLP images at various angles are shown in Figure 9. The difference between patches and the neighboring asphalt is visibly evident in both intensity and DOLP in most of the images. The general direction toward the Sun is indicated by an arrow in each image.

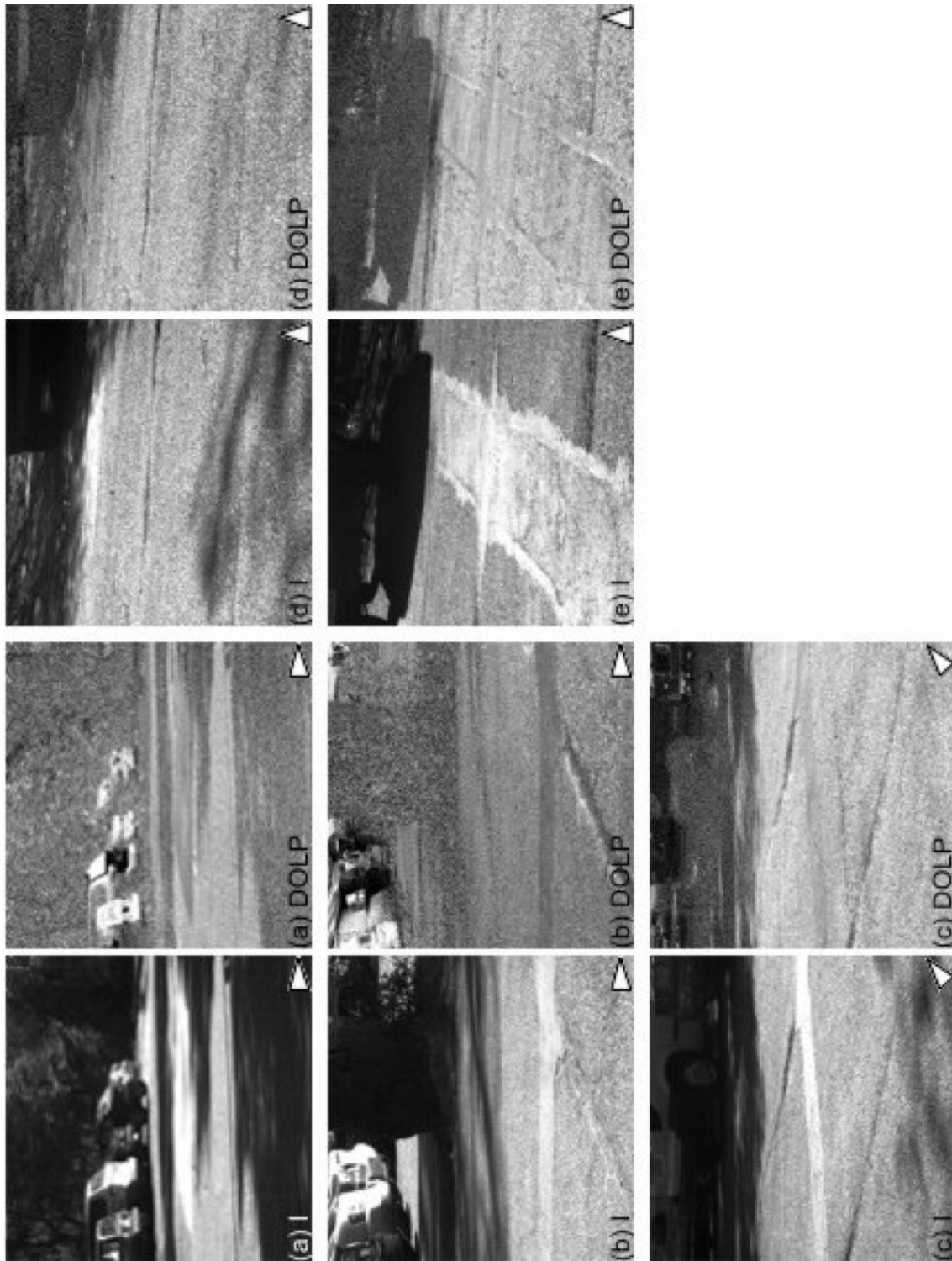


Figure 9. Images of a parking lot taken on 21 November 2008, 1320 – 1330, showing the visible distinction between new and old asphalt. The small triangle indicates the general direction of the sun when the image was taken.

A maximum likelihood analysis of the parking lot images was conducted using the maximum likelihood classifier included in the ENVI package. The analysis was performed twice – first using all four bands (I, Q, U, and DOLP), and then using only polarimetric bands (Q, U, and DOLP) to test the classifier without relying on intensity data.

The results of the maximum likelihood classification are shown in Figures 10 and 11. Figure 10 shows the classification result which is based on bands including intensity, and Figure 11 shows the result not including intensity information. Color-coding indicates areas classified as old asphalt and new patched asphalt. In both cases, the result is strikingly clear. A scatter plot of the DOLP for points in the two ROIs shows excellent separation. Purely polarization-based maximum likelihood classification is slightly less successful than that including intensity, but the result is still so sharp that it indicates that the maximum likelihood classifier may be able to find good separation even without large intensity differences.

Maximum Likelihood Classifier – I, Q, U, DOLP

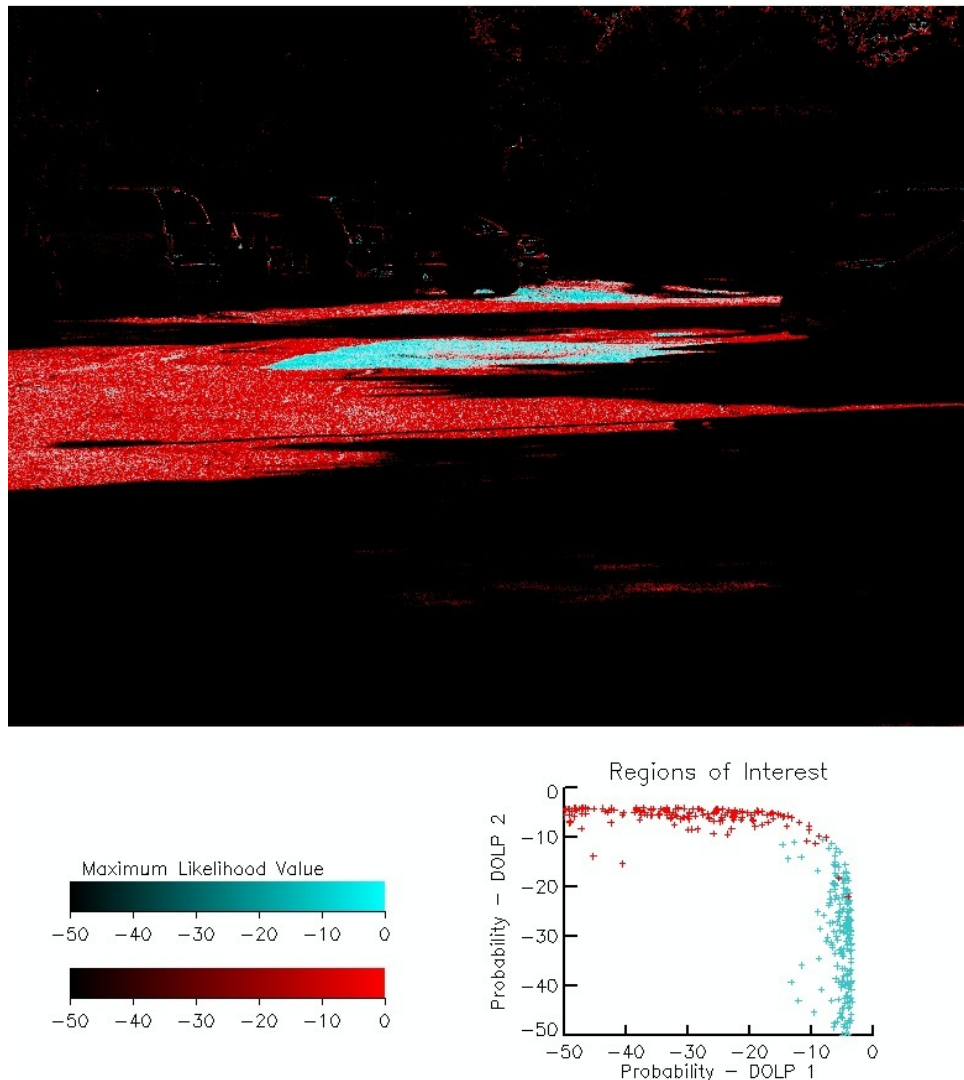


Figure 10. Maximum likelihood classification using I, Q, U and DOLP from the parking lot image, and scatter plot of the DOLP values for the old and new asphalt.

Maximum Likelihood Classifier – Q, U, DOLP

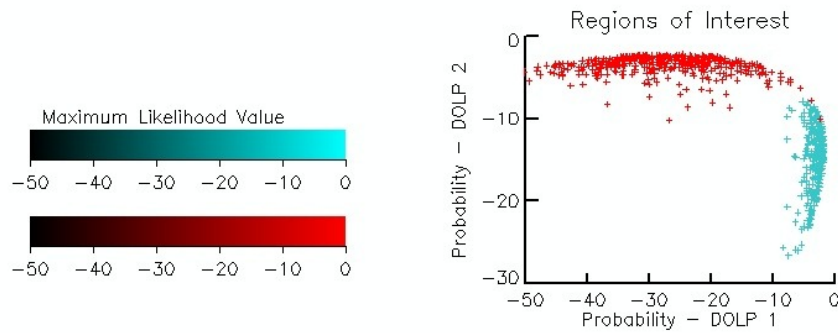


Figure 11. Maximum likelihood classification using Q, U and DOLP (but not intensity) from the parking lot image, and scatter plot of the DOLP values for the old and new asphalt.

5. CONCLUSIONS

There are many factors which affect the polarization signature of material, including the surface texture of the object being imaged, sensing geometry and illumination. Preliminary results indicate that polarization information may be useful for image classification purpose. Promising results were found in the case of distinguishing old from new asphalt. A maximum likelihood classifier can be used to distinguish these areas in a parking lot.

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