Target discrimination of man-made objects using passive polarimetric signatures acquired in the visible and infrared spectral bands

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ABSTRACT

Surveillance operations and search and rescue missions regularly exploit electro-optic imaging systems to detect targets of interest in both the civilian and military communities. By incorporating the polarization of light as supplementary information to such electro-optic imaging systems, it is possible to increase their target discrimination capabilities, considering that man-made objects are known to depolarized light in different manner than natural backgrounds. As it is known that electro-magnetic radiation emitted and reflected from a smooth surface observed near a grazing angle becomes partially polarized in the visible and infrared wavelength bands, additional information about the shape, roughness, shading, and surface temperatures of difficult targets can be extracted by processing effectively such reflected/emitted polarized signatures. This paper presents a set of polarimetric image processing algorithms devised to extract meaningful information from a broad range of man-made objects. Passive polarimetric signatures are acquired in the visible, shortwave infrared, midwave infrared, and longwave infrared bands using a fully automated imaging system developed at DRDC Valcartier. A fusion algorithm is used to enable the discrimination of some objects lying in shadowed areas. Performance metrics, derived from the computed Stokes parameters, characterize the degree of polarization of man-made objects. Field experiments conducted during winter and summer time demonstrate: 1) the utility of the imaging system to collect polarized signatures of different objects in the visible and infrared spectral bands, and 2) the enhanced performance of target discrimination and fusion algorithms to exploit the polarized signatures of man-made objects against cluttered backgrounds.

Keywords: Polarimetric imaging, infrared bands, target discrimination, polarized light

1. INTRODUCTION

The detection and recognition of targets is typically achieved using electro-optic (EO) imaging systems deployed to attain selected operational objectives, according to a given civilian or military concept of operations. The spatial and spectral resolutions and the sensor imaging modalities employed are chosen according to the applications seek and the geospatial image products needed by the end users. In recent years, numerous EO sensor imaging systems using the polarized light as additional information to traditional spectral sensors have been developed in order to provide increased target detection and recognition capabilities. The rationale behind the design of such polarimetric imaging systems is the fact that it is possible to increase the target detection performance of some objects of interest of a given scene, considering the fact that they depolarize light in different manners than natural backgrounds. Indeed, electromagnetic (EM) radiation, when emitted and reflected from an object’s smooth surface observed near a grazing angle, becomes partially polarized in the visible and the infrared wavelength spectral bands. Consequently, such polarimetric imaging systems can be used for the characterization of different materials using the observation of the contrast levels that are undetectable in conventional intensity images. Building on the facts that polarimetric images are independent of the spatial non-uniformity of the illumination since they are normalized by the local total intensity, important and relevant target features that are not discernable in intensity images can thus be revealed by the analysis of the light backscattered from these targets of interest.

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This paper highlights a set of polarimetric image processing algorithms devised to extract meaningful information from a broad range of man-made objects. Passive polarimetric signatures are acquired concurrently in the visible, shortwave infrared, midwave infrared, and longwave infrared bands using a fully automated imaging system developed at DRDC Valcartier. A fusion algorithm is used to enable the discrimination of the objects lying in shadowed areas. Performance metrics, derived from the computed Stokes parameters, characterize the degree of polarization of man-made objects.

Field experiments conducted during winter and summer time demonstrate: 1) the utility of the imaging system to collect polarized signatures of different man-made objects in the visible through thermal spectral bands, and 2) the enhanced performance of target discrimination and fusion algorithms to exploit the polarized signatures of man-made objects against cluttered backgrounds.

### 2. PASSIVE POLARIMETRIC IMAGING SENSOR SUITE

Over the past few years, DRDC Valcartier has been involved in the development of active and passive polarimetric sensors for the discrimination of targets of interest for the military community. To this extent, a broadband passive polarimetric imaging system operating in the visible to thermal spectral band has been devised. The Visible Infrared Passive Spectral Polarimetric Imager for Contrast Enhancement (VIP SPICE) operates a suite of four cameras concomitantly in the visible (VIS), the shortwave infrared (SWIR), the midwave infrared (MWIR), and the longwave infrared (LWIR) bands.

A single belt linking a series of polarizers mounted in front of each camera is synchronously-rotated. Linear polarizers are oriented successively at 0, 45, 90, and 135 degrees and along specific time intervals. The four sensor suite is mounted on a motorized pan & tilt platform device. The calibration, data acquisition, and data processing are all fully automated. The computer controls the entire capture process: from aligning the pan & tilt toward the scene to the data acquisition. A GPS receiver and range finder provide accurate geolocation of the sensor suite and the targets, respectively. The capture process includes the calibration, the capture and the display of the images. Figure 1 illustrates the VIP SPICE sensor suite. More specifications about the operation of the cameras embedded in the passive polarimetric imaging sensor-suite and the acquisition and calibration processes are available.

![Figure 1. VIP SPICE sensor-suite. Four polarized cameras operating concomitantly in the visible (VIS), the shortwave infrared (SWIR), the midwave infrared (MWIR), and the longwave infrared (LWIR) bands.](image)
3. TARGET DISCRIMINATION USING CONTRAST ENHANCEMENT LEVELS

While the light originating from the sun is not polarized, polarization is an intrinsic property of light that can be used for target discrimination, since most of the light reflected or scattered from object surfaces is partially polarized. Consequently, the polarization state of the radiation emitted and reflected by such target surfaces can be characterized by the estimation of the polarization parameters. While the measured intensity of light is made of two parts, the polarized light can be described by three elements: the polarized light, the degree of polarization, and the phase of polarization. Following subsections describe the way these polarization parameters are computed using different metrics.

3.1 Performance metrics

It is well known that the polarized EM radiation is consequential of the interaction between the ensemble waves that are propagated in the same direction but with different amplitude and phase. Radiation backscattered by some targets, either partially, completely, circularly or elliptically polarized, can thus be modeled using the Stokes vector:

$$\mathbf{F} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} I \\ I \cos{2\psi} \cos{2\chi} \\ I \sin{2\psi} \cos{2\chi} \\ I \sin{2\chi} \end{bmatrix} = \begin{bmatrix} \langle A_x^2 + A_y^2 \rangle \\ \langle A_x^2 - A_y^2 \rangle \\ 2A_xA_y \cos{\gamma} \\ 2A_xA_y \sin{\gamma} \end{bmatrix} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}$$

where $I$ is the intensity of radiation whose geometrical parameters characterize the EM wave polarization: i.e. ellipticity angle $\chi$ and ellipse orientation angle $\psi$. $A_x$, $A_y$ are the amplitudes of the EM waves in mutually perpendicular directions, $A^2$ is the intensity, $\gamma$ is the phase angle between $A_x$ and $A_y$, and $\langle \rangle$ indicates time averaging. The Stokes parameters are all related by $I^2 = Q^2 + U^2 + V^2$, so only three of them are independent. $Q$ is the difference in radiant intensity between the orthogonal $x$ and $y$ directions used to specify $A_x$ and $A_y$. $I$ and $Q$ are computed by passing light waves through linear polarizers at 0 and 90 degrees respectively, while $U$ indicates the excess of radiation in the $+45$ degrees direction over that in the $+135$ degrees direction relative to the plane of vision. $V$, which was not considered nor computed during the following field experiments, is the circularly polarized component in the radiation. Figure 2 illustrates the polarization of the EM waves, where the electric $\mathbf{E}$ and magnetic $\mathbf{H}$ fields are orthogonally propagating along the energy propagation direction $\mathbf{k}$, forming a polarization ellipse by the projection of the electrical field trajectory in the transverse plan. Linear polarization states $S_1$ and $S_2$ are generated when $\chi = 0$.

![Figure 2](image-url)

Figure 2. Polarization of EM waves. 2(a) Magnetic $\mathbf{H}$ and electric $\mathbf{E}$ fields are positioned in orthogonal directions and contained within the transverse plan of the EM wave along the energy propagation direction $\mathbf{k}$. 2(b) Polarization ellipse formed by the projection of the electric field trajectory in the transverse plan during its propagation.
The total intensity of backscattered by the scene is represents by $S_0$, while the portion of the incident radiation polarized either parallel to or perpendicular to the axis as defined by $\psi = 0$. Finally, the backscattered light polarized along the axes $\psi = 45$ and $\psi = 135$ degrees is described by $S_2$. All these linear components of the Stokes vector are then used to compute additional metrics to discriminate polarized targets’ surface against the background of the scene. For instance, the degree of linear polarization (DoLP), derived from the degree of polarization (DoP), can be calculated using the linear information and normalizing it for the intensity. The orientation of the polarization angle ($\phi$), which is the orientation of the major axis of the polarization ellipse, represents the polarizer angle where the intensity should be the strongest. These metrics can be computed using the following equations:

$$DoP = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}$$  \hfill (1)

$$DoLP = \frac{\sqrt{S_1^2 + S_2^2}}{S_0}$$  \hfill (2)

$$\phi = \frac{1}{2} \tan^{-1} \left( \frac{S_2}{S_1} \right)$$  \hfill (3)

Color mapping is another way used to illustrate polarimetric information collected from a scene. It uses a single Red-Green-Blue (RGB) or Hue-Saturation-Lightness (HSL) version of the acquired image. Numerous alternatives of color map coding have been proposed over the years; Table 1 presents a few of the most common ones.

<table>
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<th>Authors</th>
<th>$H$</th>
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<tr>
<td>Bernard et al$^6$</td>
<td>$2 \phi$</td>
<td>DoP</td>
<td>1</td>
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<td>Breugnot$^7$</td>
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<td>Solomon$^4$</td>
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<td>Tyo et al$^{11}$</td>
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Figure 3 illustrates an example of the color map representation using Tyo et al method$^{11}$.
The Poincare sphere is another metric that can be used to visualize in three-dimensional space the polarimetric state changes of polarization of propagating electromagnetic waves emitted and reflected by specific objects of a scene. A single point within a unit sphere describes a polarization ellipse of ellipticity angle $\chi$ and ellipse orientation angle $\psi$ (fig.4). For a given state of polarization represented by a single point on the sphere, a continuous evolution of polarization can be modeled as a continuous path on the Poincare sphere, where the coordinates of the point are the three normalized Stokes parameters describing the state of polarization of a given target.

![Figure 4. The Poincare Sphere.](image)

3.2 Shadow enhancement

An algorithm has been developed for the detection of targets using spectral and polarimetric characteristics of the diffuse and specular reflected light acquired from the targets. The total intensity of the scene, the DoLP, and the polarization angle are all computed within a fusion framework in order to discriminate objects lying in shadow areas against cluttered backgrounds. This algorithm can be summarized as follows: 1) Polarimetric images are preprocessed (normalization and filtering), and then co-registered together; 2) the local minimum operator is computed using the total intensity, the DoLP, and the polarization angle; 3) the unique contribution of each polarized image is calculated, following an image adjustment process; and 4) fusion of the resulting images following the conversion HSV to RGB color maps. Details of the whole shadow enhancement algorithm is described extensively. Figure 5 illustrates computed results of a metallic aluminum plate in the visible band. Image is segmented from the natural backgrounds, even in different region areas (including the shadowed one).

![Figure 5. Shadow penetration target segmentation.](image)
4. SUMMER AND WINTER FIELD EXPERIMENTS

During the past few years, polarimetric signatures of different man-made objects have been collected during field trials conducted in summer and winter times. During these trials, the VIP SPICE sensor system successfully collected polarimetric signatures simultaneously in the VIS/SWIR/MWIR/LWIR spectral bands. Following subsections enumerate experimental results according to these winter and summer field collections.

4.1 Summer time experiments

Polarimetric signatures of targets of interest have been collected by the VIP SPICE sensor suite during deployments over the dry prairie grassland environment of Alberta, Canada. The sensor was mounted on a Genie boom lift to acquire target signatures from nadir to 45 degrees oblique views at different elevation levels.

Figure 6 illustrates polarimetric signatures of a road in the visible band in summer conditions. While only the main road is detectable in the original visible band (fig.6a), the processing of the polarimetric image using the DoLP metric enhances some trafficability features, thus providing the ability to identify a supplementary road near the spherical building (fig.6b).

![Figure 6](image)

(a)  
(b)

Figure 6. Tracks detection in the visible band. 6(a) Original image of a road in a summer environment. 6(b) Polarimetric image enables the detection of tracks on the road using the DoLP metric.

Other experiments were conducted in summer time in order to characterize the polarimetric signature properties of man-made objects in the visible to thermal bands. Figure 7 illustrates a set of wires of different materials (e.g. copper conductor, with/without insulation, etc.) as seen in the 400 – 700 nm band. Some type of wires are indiscernible wrt background (fig.7a), but clearly enhanced using the DoLP metric (fig.7b).

![Figure 7](image)

(a)  
(b)

Figure 7. Set of wires of different materials. 7(a) Original image (including some feature enhancement processing) acquired in the 400 – 700 nm band. 7(b) Computed DoLP image in the visible, where some types of wires are clearly enhanced against the natural background.
4.2 Winter time experiments

The VIP SPICE sensor suite has been deployed for the first time in a winter environment in January 2011. The objective of the field trial was to collect polarimetric signatures of various man-made objects cluttered in snow. Among the various objects used, we note: plates of different material (wood, glass, plexiglass, aluminum covered with military paint, etc.) and a variety of camouflage nets. Polarimetric signatures of each object have been acquired in the visible to thermal bands using the VIP SPICE sensor suite mounted aboard a Genie boom. The set up was similar to the previous one used during the summer experiments.

Figure 8a illustrates an image of the scene, as acquired by the SWIR camera of the VIP SPICE system mounted aboard the Genie boom. The set of objects used as surrogate of targets of interest laid out on the snow surface is not clearly discernable. However, using the DoLP metric, a clear plexiglass plate is easily detected (fig.8b). Ground-truth image of the plexiglass plate is showed (fig.8c).

During this winter field trial, many alternative events indirectly related to human activities have also been adequately detected using their polarimetric signatures. These events are mainly tracks on the snow made by pedestrians or vehicles. Figure 9a illustrates a road covered with snow, where the main centered track imperceptible in the visible band was adequately enhanced in the DoLP image (fig.9b).
Figure 9. Snow tracks in the visible. 9(a) $S_0$ image of a snow covered road. 9(b) Computed DoLP image of the road. The main track centered on the road is easily discernible (ellipse).

The VIP SPICE sensor suite has been deployed successfully in summer and winter environments. Using computed metrics in the visible, shortwave infrared, midwave infrared, and longwave infrared spectral bands, polarimetric signatures of man-made objects and other related signatures from human activities were collected simultaneously. These signatures were useful to enhance the detection of targets against their respective winter and summer backgrounds. A fusion algorithm was devised to enable the discrimination of objects lying in shadowed areas. Quantification of human-related activities can be evaluated using polarimetric signatures of tracks left in snow and sand.

5. CONCLUSION

This paper highlighted recent R&D activities conducted at DRDC Valcartier regarding the use of passive polarimetric images as a way to detect difficult man-made objects cluttered in complex environments.

VIP SPICE, a passive polarimetric imaging sensor suite operating in the visible through thermal infrared spectral bands, has been described. This sensor suite system was deployed successfully in summer and winter environments to automatically collect polarimetric signatures of interesting potential targets, simultaneously in the visible to longwave infrared spectral bands.

A set of polarimetric image processing algorithms has been devised to extract meaningful information from a broad range of man-made objects. A fusion algorithm was developed to enable the discrimination of objects lying in shadowed areas.

Using the computed Stokes parameters, performance metrics were derived to characterize the degree of polarization of man-made objects. Experimental results demonstrated that different kind of wires and plates of different materials that were not discernable in both the visible nor the shortwave infrared spectral were successfully discriminated from their respective background using the DoLP metric. Additionally, tracks left in snow and in sand were adequately enhanced using their polarimetric signatures in the visible band.

Polarimetric signatures of man-made objects and other human related activities can clearly be exploited by computation of adequate metrics using the polarimetric components of signatures acquired in the visible to thermal spectral bands.

Future work will involve additional experiments involving a wider range of targets deployed in complex environments, in order to improve further the understanding of the phenomenology associated with the use of passive polarimetric images. Specific metrics dealing with the specific behavior of the phenomenology associated with each spectral band will also be developed and tested accordingly.
REFERENCES


