Robust Materials Classification Based on Multispectral Polarimetric BRDF Imagery

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ABSTRACT

When light is reflected from object surface, its spectral characteristics will be affected by surface’s elemental composition, while its polarimetric characteristics will be determined by the surface’s orientation, roughness and conductance. Multispectral polarimetric imaging technique records both the spectral and polarimetric characteristics of the light, and adds dimensions to the spatial intensity typically acquired and it also could provide unique and discriminatory information which may argument material classification techniques. But for the sake of non-Lambert of object surface, the spectral and polarimetric characteristics will change along with the illumination angle and observation angle. If BRDF is ignored during the material classification, misclassification is inevitable. To get a feature that is robust material classification to non-Lambert surface, a new classification methods based on multispectral polarimetric BRDF characteristics is proposed in this paper. Support Vector Machine method is adopted to classify targets in clutter grass environments. The train sets are obtained in the sunny, while the test sets are got from three different weather and detected conditions, at last the classification results based on multispectral polarimetric BRDF features are compared with other two results based on spectral information, and multispectral polarimetric information under sunny, cloudy and dark conditions respectively. The experimental results present that the method based on multispectral polarimetric BRDF features performs the most robust, and the classification precision also surpasses the other two. When imaging objects under the dark weather, it’s difficult to distinguish different materials using spectral features as the grays between backgrounds and targets in each different wavelength would be very close, but the method proposed in this paper would efficiently solve this problem.

Keywords: multispectral polarimetric BRDF, robust material classification, feature selection, SVM

1. INTRODUCTION

Several limitations were suffered when utilizing imaging systems only based on measurements of light intensity that are inherently related to ignoring the polarization nature of reflected light. These restrictions become critical especially in the situations when imaging in bad illumination condition or when high reflection peaks of objects happens. Multispectral polarimetric imaging technique, which combines spectral imaging and polarization sensing, is potentially a powerful tool to be added to existing imaging techniques. Lots of information could be extracted from a scene by multispectral polarimetric imaging technique, including spatial information, spectral information, and polarization information. Exploiting the polarization of light has been shown to be a useful and powerful technique. There is an increasing evidence that imaging the polarization properties of inhomogeneous objects provides a rich set of information about the local nature of the target.

However, the intensity, spectral, and polarization information obtained from targets reflections depend on various of factors including the radiant intense of source (typically the Sun in passive systems) and the non-Lambert characteristics. When imaging the same objects under different measurement geometry, or various solar radiant intense, the information obtained would have a high dynamic. Therefore, the classification methods would not work well. It is desirable to utilize feature vectors that describe an object but that are invariant to the various imaging conditions commonly encountered, and the non-Lambert characteristics of targets should be considered as well. In this work, we demonstrate that the multispectral polarimetric BRDF feature is relatively invariant to the solar radiant intense and takes consideration of non-Lambert characteristics, thus making it a potentially useful feature vector for material classification. Using sun as the light source, and under various weather and
detected conditions, groups of images are obtained at four polarization directions during the outdoor experiments, at their spectrum wavelength from 400 to 720nm with interval of 10nm, then multispectral polarimetric BRDF imagery of targets was derived from a group of images contain both calibration white-board and targets. Image the calibration white-board and targets under the same conditions at different polarization directions respectively, and then be divided by the targets radiance value using white-board radiance value as standard, and finally the polarimetric BRDF of targets were derived. During the division progress, the effect of the different radiance value of targets in different weather conditions was well normalized and eliminated. So the multispectral polarimetric BRDF of certain material in various radiant intense would keep relatively unchanged, and moreover, the shape, edge, texture of the targets could also be enhanced to some extent. The multispectral polarimetric BRDF of objects are firstly calculated from images sampled, and it would contain up to 5 parameters, including 2 derived elements, and then 3 elements, rather than 5, are selected as feature for classification after carefully analysis of the images and curves. The experimental results present that the method based on multispectral polarimetric BRDF features performs the most robust, and it would work efficient even when imaging under dark weather condition.

The organization of this paper is listed as follows. In the second section, we give background knowledge of polarimetric BRDF and its outdoor measurement methods. In the third section, we discuss the feature analysis and the setups of classification methods. In addition, the evaluation of classification results in two ways is illustrated in this section as well. In the final section, we have the conclusions and discuss the perspective of multispectral polarimetric information in application.

2. BACKGROUND

2.1 Polarimetric BRDF

A bidirectional reflectance distribution function (BRDF)\(^8\) characterizes optical scattering from surface reflections. Figure 1 illustrates the geometry required to specify the BRDF. \(\theta_i, \phi_i\) are the incident zenith and azimuth angles, respectively; \(\theta_r, \phi_r\) are the reflected zenith (or the reflection angle) and azimuth angles, respectively. The BRDF is given by

\[
f(\theta_i, \phi_i, \theta_r, \phi_r, \lambda) = \frac{dL_r(\theta_r, \phi_r)}{dE_i(\theta_i, \phi_i)} \text{sr}^{-1}
\]  \hspace{1cm} (1)

where \(\lambda\) denotes the wavelength, \(L_r\) is the radiance leaving the surface with units of watts per square meter per steradian\([w/(m^2\text{sr})]\) and \(E_i\) is the irradiance incident on the surface with units of watts per square meter \((w/m^2)\). The BRDF has units of inverse steradians \((\text{sr}^{-1})\). Because most materials have azimuthal or rotational symmetry about the surface normal, the azimuthal angle can be expressed as a difference \(\phi = \phi_r - \phi_i\), which reduces the number of degrees of freedom by 1.
The polarimetric BRDF is a generalization of the scalar BRDF and is capable of modeling polarization effects. The polarimetric BRDF can be formally written as

\[ dL_r(\theta_r, \phi_r) = F(\theta_i, \phi_i, \theta_r, \phi_r, \lambda) dE_i(\theta_i, \phi_i) \]  

where \( F \) is the polarimetric BRDF Muller matrix, \( L_r \) is the reflected Stokes vector, and \( E_i \) is the incident Stokes vector. The Muller-Stokes of the Eq. 2 would be this:

\[
\begin{bmatrix}
  L_0 \\
  L_1 \\
  L_2 \\
\end{bmatrix} =
\begin{bmatrix}
  f_{00} & f_{01} & f_{02} \\
  f_{10} & f_{11} & f_{12} \\
  f_{20} & f_{21} & f_{22} \\
\end{bmatrix}
\begin{bmatrix}
  E_0 \\
  E_1 \\
  E_2 \\
\end{bmatrix}
\]  

\[ (3) \]

2.2 Multispectral polarimetric BRDF and outdoor measurement

Experimental measurement is conducted outdoor with the solar as the illumination. The real equipment is illustrated in Figure 2 (left), while 2 (right) is corresponding to the light travels and the imaging procedure of experiment.

![Figure 2. Experimental equipment (left); Illustration of multispectral polarimetric imaging system (right)](image)

Reflected light from observed targets is first captured by the polarizer, which is rotated at 0, 45, 90, 135 respectively, then the light travels through the optical lens to the LCTF, where the spectrum of the light produces, and finally the spectral images at different polarization direction are formed by High Quality CCD. The captured light is partial polarized, and can be represented in the Stokes form by ignoring the eclipse part, \([I, Q, U]\). The multispectral polarimetric information is well represented by \([I, P, \theta]\), where \( P \) and \( \theta \) can be got in the following:

\[ P(\lambda) = \frac{\sqrt{Q^2 + U^2}}{I} \]  

\[ \theta(\lambda) = \tan^{-1}\frac{U}{Q} \]  

\[ (4) \]

\[ (5) \]

The illumination source can be assumed to be unpolarized. The Stokes vector with respect to incident denotes as \([1,0,0]^T\), and the Stokes vector can be substituted by its’ first element \(E_s\). So the 4×4 Muller matrix can be reduced to 1-column matrix, and only 3 elements can be obtained in our outdoor experiment. The total energy (\(L_t\)) of the detector received is the sum of the following three components:

1. direct solar reflections from the targets; we have \(L_r = kF_s E_s\), where \(k\) is a value related to solar angle and the condition of atmosphere, and here is assumed to only depend on the solar angle;
2. target-reflected downwelled radiance from the skydome, \(L_s\);
3. upwelled atmosphere radiance resulting from solar scatter along the target-to-detector path, \(L_{rs}\), which is usually assumed to be none as the sensor receives little this kind of light.

Substitute \(E_s\) with its first element \(E_s\), we can derive the following equation:

\[
\begin{bmatrix}
  f_{00} \\
  f_{10} \\
  f_{20} \\
\end{bmatrix}_{(\lambda)} = \frac{L_t - L_s - L_{rs}}{kE_s}
\]  

\[ (6) \]
We use the calibrate white board, the \( f_r \) of which is known and remain unchanged with the angle of view, to derive the value of the radiance of solar, \( E_s \), as it is impossible to get this value directly. As for the calibrate board, we could get:

\[
\begin{bmatrix}
    f_{00,ref} \\
    f_{10,ref} \\
    f_{20,ref}
\end{bmatrix}_{(\lambda)} = \frac{L_t,ref - L_s,ref}{kE_s}
\]

Where \( k \) is related to the condition of the atmosphere. Then it would follow the Eq.7, which represents the value of:

\[
kE_s = \frac{L_t,ref - L_s,ref}{f_{00,ref}}
\]

Substitute (8) to (6), and we could derive the following (9):

\[
\begin{bmatrix}
    f_{00} \\
    f_{10} \\
    f_{20}
\end{bmatrix}_{(\lambda)} = \frac{L_t - L_s}{E} = \frac{f_{00,ref} \ast (L_t - L_s)}{L_t,ref - L_s,ref}
\]

We have the degree of polarization(DoP)and angle of polarization(AoP):

\[
DoP(\lambda) = \sqrt{f_{10}^2 + f_{20}^2} \\
AoP(\lambda) = \tan^{-1}\left(\frac{f_{20}}{f_{10}}\right)
\]

3. FEATURE ANALYSIS AND SELECTION

The multispectral polarimetric BRDF we concern contains three elements, \( f_{00}, f_{10}, f_{20} \) respectively, and two derived elements, \( DoP, AoP \) respectively. These five elements are all depend on wavelength and are overly redundant and complement. The dimension of features would be higher if all of them were used as selection features, and therefore the performance of classification algorithm would be affected a lot. Attempted to obtain proper features for classification, the imagery of five elements and curves are analyzed in advance.

Figure 3. Original image; 4 white color but different materials were placed in the cement; 1,2,3,4 represent the Al, plastic, paper, and tile, respectively

Figure 4. Imagery of five elements; From left to right represent the imagery of \( f_{00}, f_{10}, f_{20}, DoP, \) and \( AoP \) at 560nm respectively
Figure 5. Curves of five elements; From left to right represent the curves of $f_{00}$, $f_{10}$, $f_{20}$, DoP, and AoP with the dependence of wavelength respectively.

As illustrated in Fig.3, the four similar color objects are placed in the cement background, and the original image is one of groups of images sampled with its wavelength value of 560nm at 0 degree polarization direction. The $f_{00}$ imagery of four objects is hard to distinguish as all four objects have near reflectance ratio, while $f_{10}$, $f_{20}$ imagery contains more information about the edges, and the surfaces’ roughness. Compared with $f_{10}$ and $f_{20}$, in the imagery of DoP and AoP, the edges and the differences among objects are enhanced further. As we can see, the texture of background is also well enhanced in the DoP imagery (see Fig.4).

Fig.5 shows the curves of five elements depend on wavelength. The regions of one specific object are randomly selected twice. The curves of two regions may be slightly different since the surface is not the ideal azimuth symmetrical, and the illumination and reflectance angles for regions are also slightly different, and this dynamic ensures us to select more robust features.

We have the following conclusions: 1. Slight difference exists for the same materials but different selected regions, and evident difference performs for the different materials expect for $f_{10}$ element; 2. The multispectral characteristics of objects help to increase the classification accuracy. If only the parameters of 500 nm are available, the misclassification is inevitable. With wavelength from 480 nm to 700nm, it becomes more easily to distinguish objects. Multispectral $f_{00}$ element represents the reflectance radio and it is the most robust and institute feature. Multispectral $f_{10}$ element for different regions of one specific material has a high dynamic, and it is unsuitable for classification. Although multispectral $f_{20}$ element could also show the differences, it only serves as redundant information for $f_{00}$, and it could not supply extra useful information for classification. As for Multispectral DoP and AoP elements, they perform stable and could supply extra and complement information for $f_{00}$, and therefore these three elements are selected as features.

4. CLASSIFICATION RESULTS

As for the advantages of SVMs dealing with insufficient train samples and better classification performance, classification approach based on SVMs would be used.

![Flow chart of classification based on multispectral polarimetric BRDF imagery using SVM](Figure 6)

Figure 6. Flow chart of classification based on multispectral polarimetric BRDF imagery using SVM.
Several scenes contain different targets and backgrounds are designed for classification using multispectral polarimetric imaging system. A scene with four different materials in clutter grass background is selected in this paper. As demonstrate in Fig.7(11), these four materials are white tile, white plastic, board, and green painted board, respectively. All results of classification in this study use the same train samples from sun weather condition, while the test samples are under sun, cloudy, and dark respectively. The performance of classification using multispectral polarimetric BRDF features is compared to other two features both in quality (Figures7∼8) and quantity(Tables1∼3).

Figure 7. 11,21,31 represent the original images at 560nm under sunny, cloudy and dark respectively; 12,22,32 represent the results based on multispectral information under sunny, cloudy and dark respectively; 13,23,33 represent the results based on multispectral polarimetric information under sunny, cloudy and dark respectively; 14,24,34 represent the results based on multispectral polarimetric BRDF information under sunny, cloudy and dark respectively.

The results of classification under sunny perform the best as the train and test sets are both obtained under the sun as well, followed with cloudy and dark weather. All three results based on three different selected features in the sunny condition are pleased, and misclassification only happens in very small regions near edges.

When imaging under the cloudy weather, the radiance that detector received is changeable and relatively weak result in the average intense is low and difficult to distinguish. Fig.7(22) shows the result of classification using multispectral characteristics. Though the grass background is almost classified well, misclassification happens in a large scale, and only three materials rather than four are detected. White plastic is misclassified to board completely. The similar case is happened when using the multispectral polarimetric information as features (see Fig.7(23)). White tile and board are both misclassified to background, and plastic is misclassified to tile as well. Though materials’ polarimetric information is introduced, the results of classification are enhanced limited. The results of classification based on multispectral polarimetric information (see Fig.7(24)) are enhanced to a great deal comparing to the other two features, and different targets and grass were distinguishable besides the region near edges of white tile is misclassified to white plastic.

Fig.7(32) shows the results of classification based on multispectral information under the dark weather, and the results are worse than the above two cases overall (Fig.7(12,22)). Though only a small region of grass background between white tile and plastic is misclassified, green painted board is misclassified to board completely. The central region of white tile is misclassified to plastic, while the central region of plastic is misclassified to white tile alternatively. In the case of dark weather, the results of classification based on multispectral polarimetric (see Fig.7(33)) are improved to some extent as polarimetric information is introduced. Misclassification case happens in the edges of white tile, and the central of plastic, and the green painted board. Though the grass background and green painted board are almost misclassified each other, the results of classification based
multispectral BRDF information (see Fig. 7(34)) are best among the three selected features. Misclassification case only happens the edges of materials.

Table 1. Accuracy of classification using SVM based on multispectral feature

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<th>Accuracy of classification using SVM</th>
<th>Total</th>
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<tbody>
<tr>
<td></td>
<td>tile</td>
<td>plastic</td>
</tr>
<tr>
<td>sunny</td>
<td>0.9993</td>
<td>0.9931</td>
</tr>
<tr>
<td>cloudy</td>
<td>0</td>
<td>0.0008</td>
</tr>
<tr>
<td>dark</td>
<td>0.062</td>
<td>0.0014</td>
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Table 2. Accuracy of classification using SVM based on multispectral polarimatic feature

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<th>Accuracy of classification using SVM</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>tile</td>
<td>plastic</td>
</tr>
<tr>
<td>sunny</td>
<td>0.9971</td>
<td>0.9950</td>
</tr>
<tr>
<td>cloudy</td>
<td>0.0572</td>
<td>0.80319</td>
</tr>
<tr>
<td>dark</td>
<td>0.9029</td>
<td>0.37375</td>
</tr>
</tbody>
</table>

Table 3. Accuracy of classification using SVM based on multispectral polarimetric BRDF feature

<table>
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<tr>
<th></th>
<th>Accuracy of classification using SVM</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>tile</td>
<td>plastic</td>
</tr>
<tr>
<td>sunny</td>
<td>1</td>
<td>0.96583</td>
</tr>
<tr>
<td>cloudy</td>
<td>0.73517</td>
<td>0.99176</td>
</tr>
<tr>
<td>dark</td>
<td>0.9798</td>
<td>0.85634</td>
</tr>
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</table>

The accuracy of classification is evaluated by the common confusion matrix. Kappa value\(^\text{11}\) is used to evaluate the total accuracy of classification since it considers the misclassification points as well. Table 1, 2 and 3 show the accuracy of classification in three imaging conditions respectively. The values of Kappa in the sunny are all large, with 99.71\% as the largest value. The smallest value of Kappa (32.79\%) is happened in the dark without considering the polarimetric characteristics. Although the value of Kappa related with the classification results based on the multispectral polarimetric BRDF decreases with the weather condition, from 93.64\% under the sunny to 79.02\% under the dark, it outperforms the results of classification based on the other two characteristics to a great extent.

The experimental scene where places several black colored materials and black cloth is designed to prove the robust performance of multispectral BRDF features under the dark weather condition. We could see from the figure, it is impossible to distinguish any kind of the targets in the intense-only image since it is taken under relative low intense solar illumination and resulting the intense between targets and background is almost the

![Figure 8. Original image at 560nm (Left); Results based on multispectral (Middle); Results based on multispectral BRDF (Right)](http://proceedings.spiedigitallibrary.org/ on 02/19/2014 Terms of Use: http://spiedl.org/terms)
same (see Fig. 8) (Left). The results of classification based on multispectral characteristics (see Fig. 8) (Middle) are unsatisfiable and misclassification is happened, and only 3 targets rather than 5 could been seen. Black painted Al is completely misclassified as the black cloth background, and black painted board is misclassified as the sand paper as well. From the results of classification based on multispectral polarimetric BRDF (see Fig. 8 (Right)), we could see five different targets and background. Misclassification only happens in some regions of sandpaper and background. Though the intense among the studied targets and background is close when imaging under the dark weather condition, classification based on multispectral polarimetric BRDF would work efficiently.

5. CONCLUSION AND PERSPECTIVE

Materials classification under different weather conditions is studied in this paper. The polarimetric information is introduced and the results are improved to different extent under different weather conditions. A method of classification based on the multispectral polarimetric BRDF which is robust to the various weather conditions is proposed under detailed feature analysis. The proposed method is tested on two scenes, one of which is grass background while the other is man-made black cloth. The results of classification are showed in both quality and quantity. Results show the introduced polarimetric information would enhance the accuracy of classification, and moreover, this information introduced have lots of characteristics that traditional imaging technology could not capture and it would play more and more important role in the filed of remote sensing and pattern recognition in the future.

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