Characterization of material reflectance variation through measurement and simulation

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ABSTRACT

The characterization of material reflectance properties is important in the analysis of hyperspectral and polarization imagery as well as accurate simulation of such images. This paper merges the results of empirical reflectance property (spectral pBRDF) measurements with detailed model based simulations. The empirical data are collected with a laboratory spectroradiometer as well as an RIT-developed spectro-polarimetric imaging goniometer. The modeling uses an adaptation of RIT’s Digital Imaging and Remote Sensing Image Generation (DIRSIG) model to capture the radiative transfer in rough surfaces with micron-scale features. Measurements and model results for several man-made materials under various conditions are presented.

Keywords: spectral reflectance, material variability, polarized spectral bidirectional reflectance distribution function

1. INTRODUCTION

The characterization of material reflectance properties is important in the analysis of hyperspectral and polarization imagery in material/object detection and identification applications, as well as in the accurate physics-based forward simulation of such images. While significant efforts have been put forth for the measurement of reflectance properties of man-made materials, much has been done in the laboratory under ideal conditions. Real imagery, however, typically is of objects observed under less ideal conditions. Therefore, it remains an open topic to more fully understand the variation in reflectance properties of materials as observed in the real world.

This paper reports on work performed to merge the results of empirical reflectance property (spectral polarized bidirectional reflectance distribution function – spectral pBRDF) measurements of materials with detailed physical model based simulations with a goal of validating the modeling and allowing it to be used to extend the measurements to additional arbitrary conditions. The instrumentation used to collect the empirical data includes a commercial laboratory spectroradiometer as well as an RIT-developed spectro-polarimetric imaging goniometer. Characterization of the instruments and their associated limitations are discussed. The modeling is performed using an adaptation of RIT’s Digital Imaging and Remote Sensing Image Generation (DIRSIG) model to capture the radiative transfer occurring on rough surfaces with micron-scale features. Measurements and model results for several man-made materials observed under various conditions (e.g., dirty, wet) are presented. The validated model results will be used to extend the material reflectance characterization to more arbitrary conditions and to provide insights into ways to capture the variability using statistical models.

2. SPECTRAL MEASUREMENTS OF FABRIC SAMPLES

2.1 Fabric samples and weathering procedures

Four fabric samples made of Suraline gabardine 100% polyester were investigated. The samples were measured in three different states: pristine, weathered and dirty. Multiple 3” x 3” samples were prepared in each of the states. The pristine samples were as provided by the vendor. The weathering occurred through placement on the roof of a building for four days and exposed to sun, clouds, and normal aerosols. No precipitation occurred during the exposure period. Figure 1 shows the samples on the roof.

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The dirty samples were prepared by rubbing each sample in a box of poor quality soil until well covered. Samples were lightly shaken out to release excess soil and prevent dust from contaminating the measurement equipment. Figure 2 shows the box of soil and the dirty samples.

Figure 1. Fabric samples as placed on the roof for weathering.

2.2 Spectral measurements and results

Diffuse hemispheric reflectance measurements were made using a Cary 500 spectrophotometer. Figures 3 through 6 show comparisons of the reflectances for the various fabrics in the pristine, weathered and dirty states.

Among all the samples, the change in the reflectance was most apparent in the spectra of the light cream (white) fabric. The increase in impurities, from pristine to dirty, reduced the magnitude of the reflectance, but also exhibited a smoothing effect on the curve at wavelengths under 1000 nm. Though less apparent, the color features of the blue and green fabric in the visible also appear to lose distinction, especially in the dirty samples. The shortwave infrared (SWIR) region of all the samples was relatively unaffected, maintaining features related to the material properties of the fabric.
Figure 3. Reflectance spectra of light cream sample. As expected, this sample demonstrated the greatest change in reflectance spectra. The VIS-NIR section of the spectrum became more 'smooth', losing the distinctive small dip at 450 nm – 500nm.

Figure 4. Reflectance spectra of khaki sample. The khaki sample demonstrated a similar 'smoothing' trend in the VIS and NIR. Notice that the local minimums do not change, but the maximum values are reduced as impurities are added.
Figure 5. Reflectance spectra of green sample. An interesting increase in reflectance of the dirty green fabric can be seen in the VIS.

Figure 6. Reflectance spectra of blue sample. The dirty blue fabric shows an increase in reflectance between 500 nm and 700 nm. Also worthy of notice is the small spectral shift in the VIS.
3. POLARIZED BRDF MEASUREMENTS OF FABRIC SAMPLES

3.1 Polarized BRDF measurement equipment

The bidirectional reflectance distribution function (BRDF) measurements made for this effort were acquired using an image-based spectro-polarimetric goniometer. This research instrument was custom integrated using commercial off the shelf components. The sensor package consists of a GC780 gigabit Ethernet CCD camera from Prosilica with a 35mm compact fixed focal length lens from Edmund Optics. This CCD array captures imagery monochromatically with a resolution of 782x582 and a pixel pitch of 8.3 μm square. The lens was chosen to allow for an angular FOV of 5.29° that will meet the acceptance angle specification of 7.5° for the liquid crystal tunable filter (LCTF). The LCTF is a 35mm VariSpec© from Cambridge Research & Instrumentation, Inc. (CRi) which allows for a very fast (5 ms) adjustment of the 7 nm bandpass from 400 – 720 nm. The filter also acts as a linear polarizer and is attached to a rotation stage which allows for Stokes parameters to be generated from imagery.

The sensor package is attached to a rotation stage with allows for the camera optical axis to be positioned and source illumination to be moved relative to the sample surface normal. Figure 7 shows a diagram of the layout of the machine. This axis configuration can be used to generate any measurement geometry (θ_i, θ_s, Δφ) which allows for isotropic samples to be measured automatically. For non-isotropic samples, the principle plane can be sampled, and the test sample can be manually rotated to explore different azimuthal effects.

![Diagram of BRDF measurement system](https://via.placeholder.com/150)

Figure 7. Layout of BRDF measurement system. The light source and camera system can be automatically placed at different zenith and azimuth locations relative to sample surface.

The light source is an 850 W tungsten filament light bulb driven with a stable DC power supply, which is monitored using the amount of voltage across a calibrated resistive shunt. The entire system is controlled using a custom graphical user interface (GUI) written in Labview. This GUI facilitates the synchronizing of camera exposures, stage positions, and filter wavelengths, as well as optimizing the order of stage positions to minimize the travel time.

3.2 Comparison between BRDF measurement system and Cary 500

The first experiment performed was to compare the reflectance measurements obtained using the Cary 500 spectrophotometer to the BRDF machine measurements using a Labsphere DRA-CA-5500 Diffuse Reflectance accessory. The Cary 500 uses a standard 8° illumination and 0° view geometry with an integrating sphere thus generating diffuse hemispherical reflectance values. In order to compare this measurement to the BRDF machine, the source/sample geometry was set to 10° illumination and 0° view angles. This geometry was chosen to be close to the
Cary geometry, while still avoiding the blind spot on the BRDF machine created by the sensor head obscuring the light source. Since the LCTF acts as a linear polarizer, each location was collected at four polarization angles. This allows for the Modified Pickering Method to be used to generate the Stokes vector for each sample geometry\(^1\).

The region of interest (ROI) used to obtain image pixels for each sample location is warped depending on the image distortions created by the tilt and rotation of the sample surface. This guarantees that the pixel locations used to generate the average digital count in each geometry span the same area of the sample surface. A sample set of imagery using a Fluorilon square was first collected to be used as a known white reference. This sample has been characterized using the Cary to obtain diffuse hemispherical reflectance (DHR). There is also a nominal BRDF data set for Fluorilon collected by the NIST measurement lab\(^2\). The reference sample characterization data are presented in Figure 8 showing a good match.

![Figure 8. Characterization of Fluorilon used as a reflectance standard in measurements.](image)

A spectral scan was performed at the chosen geometry and the equivalent DHR was calculated using the average digital count obtained from the warped ROI. Eq. 1 was used to calculate the DHR, which assumes Lambertian behavior of the sample and reference. Figure 9 shows the DHR obtained using Eq. 1 for the pristine Khaki fabric sample.

\[
DHR_{\text{samp},\lambda} = \frac{DC_{\text{samp},\lambda}}{DC_{\text{ref},\lambda}} \ast DHR_{\text{ref},\lambda}
\]  

(1)

This comparison show a good match in the spectral shape of the retrieved DHR reflectance. There is a bias between the two DHR curves which is due to the fabric sample violating the Lambertian assumption in Eq. 1. Since the view geometry of the BRDF machine is not in the expected location of the specular lobe it is predicted that the BRDF DHR should be lower in magnitude than the Cary DHR measurement. This is the behavior that is observed in the data which indicates that the fabric is not exactly Lambertian.

The next set of measurements performed explored how the BRDF of the light cream and khaki samples behave before and after being soiled. The details of this soiling process were explained in Section 2 of this paper. While these experiments were performed on both the light cream and khaki samples, there were not significant differences in the results of the BRDF effects. The results for the light cream fabric sample are therefore presented.

To obtain the BRDF values for the fabric samples, the average digital counts at each sample location were found using the above ROI method. This was repeated for the Fluorilon sample which then allowed for conversion from digital count to BRDF reflectance values.
The effect of changing the incident zenith angle is explored in Figure 10. While the BRDF shape changes as expected, it is interesting to note that the addition of dirt particles into the fabric geometry simply changes the magnitude of the BRDF curve. There is also a trend which suggests that a decrease in wavelength will produce an increased magnitude in the downward shift.

The effect of changing the source and view zenith angles on the BRDF shape are shown next in Figure 11. The data suggest very little change in BRDF shape before and after dirt contamination.
Finally, since the LCTF acts as a linear polarizer, the degree of linear polarization (DOLP) was found for the sample using the same geometries as in Figure 11. This is shown for both clean and dirty samples in Figure 12.

In summary, the BRDF shape along the principle plane appears to be primarily constant across the measured wavelengths (450, 550, and 650 nm) with a bias difference between bands attributed to multiply scattered photons. The BRDF shape is likely due to primarily first and second generation bounces, which are quite independent of wavelength. This is because they are surface based, whereas the color of the fabric is due to the dye below the surface of the yarn fiber. The effect on dirt contamination of the fabric on the BRDF shape appears minimal except for a slight backscatter enhancement from the dirty surface.

The presence of dirt does not significantly change the observed degree of linear polarization compared to the pristine surface. This is likely due to the low reflectance soil particles primarily blocking some of the first surface fiber glints which reduce both the reflected S0 and S1 radiance resulting in no significant change in degree of linear polarization. Although the lower reflected S1 radiance from the dirty surface results in a similar DOLP, the magnitude of the reflected S1 radiance is higher for the pristine surface making the pristine fabric potentially easier to detect in noise limited polarimetric imaging systems.
4. MODELING OF REFLECTANCE PROPERTIES OF FABRIC SAMPLES

4.1 Micro-scale modeling of fabric samples

The objective of modeling fabric reflectance properties in a virtual environment is to enable the characterization of a wider range of surface states and conditions potentially not easily measured either in the laboratory or the field. However, the scope of the modeling effort for this initial study was only a pristine fabric surface to build confidence in the simulation process before proceeding to more complex surface states.

Simulation of the BRDF of the supplied fabric samples requires a solid understanding of both material optical properties (at the fundamental fiber element level) and the fabric geometric construction. Information supplied from the vendor indicated the fabric samples were constructed of 100% polyester fibers. A literature search found that fibrous polyester typically has an index of refraction ranging from 1.58 to 1.64. Therefore, we choose to model the fibers as dielectric materials having an index of refraction of 1.61. Additionally, we also assume no significant texture exists on the fiber surface resulting in a perfectly smooth Fresnel interface (permitting both specular reflection and transmission) with no internal scattering or absorption mechanisms (note: the different color fabrics are likely resulting from chemical reaction of dyes within the bulk of the fibers which are not considered in this initial effort).

The geometric construction of the fabric surface is best understood at 3 levels: (1) individual fiber level, (2) the yarn level, consisting of hundreds of fibers in a bundle, and (3) the fabric level where the yarn is woven together (in a ‘twill’ pattern in this case). Individual fiber elements are modeled as curved cylindrical objects, facetized with 120 facets and shaped with a cosine function to follow the weave. The yarn is modeled as a random collection of over 100 individual yarn fibers, while the fabric geometry is simply multiple instances of the same yarn geometric object “woven” together by carefully choosing the offset and angular orientation of each yarn object instance (see lower right of Figure 13).

4.2 BRDF modeling of samples

In order to simulate a BRDF measurement of the fabric surface with the Digital Imaging and Remote Sensing Image Generation (DIRSIG) software, we ingested the assembled fabric surface geometry, attributed each facet with the optical properties described above and simulated its appearance under illumination from a single point source at a large distance. The challenge with perfectly specular material surfaces is that it creates a difficult sampling problem for a reverse ray-tracer such as DIRSIG (very unlikely the source will be hit from rays cast from the detector elements). Therefore, we choose to enable the photon mapping option in DIRSIG. This option shoots photons from the illumination source in a Monte Carlo fashion, allowing them to propagate throughout the scene until the maximum number of surface interactions (15 reflections and/or transmissions in this case) are reached. The reverse ray tracing then sends sample rays...
from the detector elements of the camera and probes where the source photons landed, and calculate their total radiance. An example of a photon mapped simulated BRDF image is shown in the lower right of the Figure 13 above. Computationally, this still remains a quite intensive sampling problem and gives the user simply one incident geometry and one reflected geometry for one run of the computation (about 4 hours for a 512x512 BRDF camera image).

Another approach is to utilize a modified form of the DIRSIG software, developed under an RIT postdoctoral research program, called microDIRSIG. This software is a forward ray tracing software that shoots photons from the source, permits them to bounce around the scene geometry and collects every photon in either the hemisphere above or below the sample creating a fully hemispherical BRDF collection for a single simulation run. Although this modeling process is still computationally intensive given the complex geometry of the fabric and millions of resulting facets in the fabric geometry, it does provide much more information than a traditional DIRSIG simulation run for the same run time. In other words, the output of microDIRSIG is not a camera image, but a fully spectral-polarimetric hemispherical BRDF map (see Figure 14).

Both the microDIRSIG and traditional DIRSIG (with photon mapping enabled) BRDF simulations show a BRDF shape similar to the measured values (compare Figure 14 with Figure 11a). However both simulations suffer from a combination of statistical sampling noise and a lack of fiber geometry variation. The first is easily remedied by permitting more samples and longer run times, the later is improved by increasing the randomness of each fiber orientation (beyond simple 3D spatial random offsets as this initial effort utilized) with additional random rotations and kinks similar to the real fabric. Future modeling work will improve on the pristine fabric surface BRDF predictions in these ways, and permit modification of surface states to examine effects of wear, moisture and weathering on the spectral-polarimetric reflectance behavior.

5. CONCLUSIONS AND FUTURE WORK

This paper describes the results of a study of reflectance measurements and modeling, with an objective of better characterizing and understanding the role of variability in hyperspectral image target detection. The measurements and modeling focused on the polarized spectral BRDF reflectance properties of several fabric samples. While the results of the measurement and analysis activities are interesting and useful, perhaps the most significant outcome of the effort was the further development and verification of the techniques.

The spectral reflectance (diffuse hemispherical reflectance – DHR) of the four fabric samples were measured under three conditions: pristine (as supplied), weathered, and dirty (soiled). The results of these measurements found the reflectance changed most in the visible spectral region due to the soiling and weathering, with little changes at spectral wavelengths...
beyond 1000 nm. In the visible region, the contamination generally reduced the magnitude of spectral features, leading to a smoothing of the spectra.

The fabric samples were also measured with an in-house spectro-polarimetric imaging goniometer. BRDF measurements were collected over many angles, wavelengths, and polarizations. It was found the weathering and soiling of the samples had relatively little impact on the BRDF and polarization characteristics.

First-principles modeling of the fabric was accomplished for the pristine condition and resulted in similar BRDF shape characteristics as those found in the empirical measurements.

In each of the above areas, much additional work remains to be accomplished within the overall framework of the objective stated above. In particular, additional reflectance variability measurements should be made to further characterize materials through statistical metrics and their dependence upon additional modes of contamination. In the modeling area, while an initial model of the fabric samples was developed, future work will model the contamination of the fabric. Finally, further work remains to incorporate the results of the target variability findings in the study of the predictive relative target detection performance for various images and scene types.

REFERENCES