Hyperspectral and Polarization Imaging Applications of Acousto-Optic Tunable Filters

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Abstract

The detection and recognition of objects and backgrounds requires the development of imagers that can detect both spectral and polarization signatures from the scene. An imager designed using an acousto-optic tunable filter (AOTF) is ideally suited to provide both agile spectral and polarization signatures. We are developing small, vibration-insensitive, robust, remotely controlled, and programmable hyperspectral imagers from the ultraviolet to the long wave infrared. Such imagers require minimum amount of data processing because they can collect images at only select wavelengths of interest and the selected wavelengths can be changed based on the scene of interest. We are using AOTFs made of KDP, TeO_2, and TAS with Si based CCD, InGaAs, InSb, and HgCdTe cameras to cover different spectral regions. The operation of each of these imagers and image acquisition is computer controlled. The most developed imager covers visible to near-infrared (VNIR) region from 400 to 900 nm with a 10 nm spectral resolution at 600 nm that uses a TeO_2 AOTF as an agile spectral selection element and an electronically tunable nematic liquid crystal retarder to change polarization. Here we will briefly describe our concept in the development of these imagers and present some results obtained from the VNIR imager.

Introduction

Better object detection and recognition can be done using both spectral and polarization signatures from the scene. Spectral features arise due to the material properties of objects as a result of the emission, reflection, and absorption of light, while the polarization features arise from the physical nature of the object surfaces and edges that influence the polarization properties of the reflected, scattered, or emitted light. Using hyperspectral imaging one can acquire images with narrow spectral bands and take advantage of the characteristic spectral signatures of different materials making up objects and backgrounds. By combining both polarization and hyperspectral detection capabilities in one single imager, we can perform much better object detection and identification than by using either polarization or hyperspectral capability. Traditional hyperspectral imaging systems use gratings and prisms and acquire images in hundreds of bands, requiring a huge amount of data processing. In general, object detection requires spectral images at a few bands that change based on the object and background scenarios. This clearly establishes a need to design adaptive imaging systems.

An imager designed using an acousto-optic tunable filter (AOTF) is ideally suited to provide both agile spectral and polarization signatures. At the U.S. Army Research Laboratory (ARL), we are developing small, vibration-insensitive, robust, remotely controlled, and programmable hyperspectral imagers covering the ultraviolet (UV) to the long wave infrared (LWIR) spectral regions. Such imagers require minimum amount of data processing because they can collect data at only select wavelengths of interest and the selected wavelengths can be changed based on the scenes of interest. The time to change wavelengths is very fast (in tens of μs). This agility in data collection is quite critical for hyperspectral applications because it greatly reduces the data processing requirements associated with the vast quantity of data collection and utilization associated with traditional hyperspectral imaging systems. An AOTF is also a polarization sensitive device because the diffracted beams from it are orthogonally polarized. By combining it with another polarizing device, a polarizer/analyzer system can be developed to obtain polarization information from the scene of interest.

A number of different noncollinear AOTFs fabricated in different birefringent crystals with different cameras are used to cover the wavelengths from UV to LWIR. We use a KDP AOTF with an extended range response Si charge coupled device (CCD) camera to cover the UV to visible region from 220 to 480 nm, a TeO_2 AOTF with an off-the-shelf Si CCD camera to cover the visible to near-infrared (VNIR) region from 400 to 900 nm, a TeO_2 AOTF to cover the short wave IR (SWIR) region from 900 to 1700 nm with a room temperature InGaAs camera, another TeO_2 AOTF with a liquid nitrogen-cooled InSb camera to cover the mid wave IR (MWIR) region from 2 to 4.5 μm, and a TAS (thalium arsenic Selenide) AOTF with a liquid nitrogen-cooled HgCdTe camera to cover the LWIR region from 7.8 to 9.7 μm. Each imager has a suitable optical train. We have used a nematic liquid crystal variable retarder (LCVR) as the first polarization element to cover wavelength regions from 400 nm to 4.5 μm. The operation of each imager and its image acquisition is computer controlled.

The VNIR imager is the most developed imager with a 10 nm spectral resolution at 600 nm that uses a TeO_2 AOTF as an agile spectral selection element and an electronically tunable LCVR to change the incident polarization. Each spectral image is acquired with two retardation values corresponding to the horizontal and vertical incident polarizations. Here we will describe the concept behind the development of these imagers, describe the VNIR imager and present results obtained from it.

Spectropolarimetric Imager Concept

To understand the wavelength tuning operation of such imagers, it is important to know how a noncollinear AOTF works. In an AOTF, a radio frequency (rf) signal is applied to a piezoelectric transducer that is attached to a birefringent crystal to produce an ultrasonic wave that travels through the crystal. This sets up a moving diffraction grating in the crystal. An acoustic absorber absorbs the sound wave after it traverses the crystal. When unpolarized white light is incident on such a crystal, it is diffracted by the traveling acoustic wave, and it produces two diffracted beams with orthogonal polarizations—one with a Doppler upshifted and the other with a Doppler downshifted optical frequency for a given applied rf—based on the phase-matching condition. (The Doppler shift is negligible for the optical frequencies.) The diffracted optical wavelength can be tuned by changing the applied rf [1.2].

The spectropolarimetric imager design concept uses the fact that for an unpolarized incident light, a noncollinear AOTF has two diffracted beams along with an undiffracted beam that contains all the incident wavelengths minus the one that is diffracted. In our imager design we use one of the diffracted beams and block the other diffracted as well as the undiffracted beam as shown in figure 1.

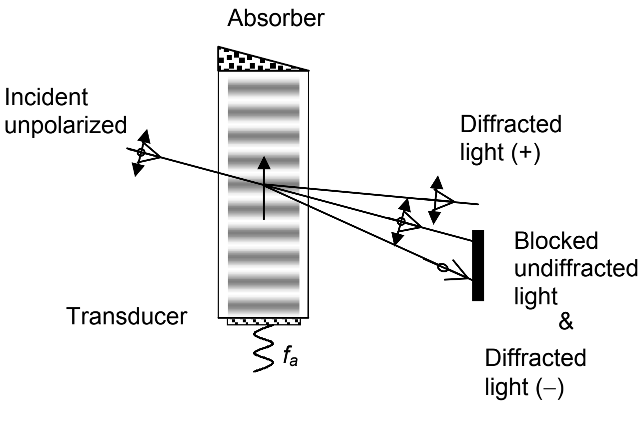

Figure 1. Filtering operation of a noncollinear AOTF.

We place a spectrally tunable nematic LCVR in front of the AOTF and use two retardance values corresponding to the horizontal and vertical polarizations for each diffracted wavelength. The tuning of such a retarder is done by changing the applied voltage. The diffracted beam from the AOTF is imaged on the camera. Since the wavelength filtered by the AOTF can be tuned to any value within the tuning range, we can acquire a spectropolarimetric image cube by tuning over the wavelength range. Since both the retarder and the AOTF are tuned electronically, no moving parts are involved. This makes our imager adaptive and robust as compared to other traditional hyperspectral imagers. Previous work has shown the utility of AOTF based spectropolarimetric imaging [3–5].

Imager Development

At ARL, we have developed AOTF based spectropolarimetric/hyperspectral imagers covering wavelength regions from UV to LWIR using different birefringent acousto-optic (AO) materials as shown in table 1 [6–9]. Spectral range, spectral resolution, AOTF crystal material, retarder, and camera focal plane array (FPA) with its temperature of operation for each of these imagers are listed in this table.

Table 1: ARL spectropolarimetric imagers

Imager	Spect. Range (μm)	Spect. Resolu -tion (nm)	AOTF Xtal	Retard -er	FPA
UV	0.22-0.48	1.4 at 0.3 μm	KDP		Si CCD Rm. Temp
VNIR	0.4-0.9	10 at 0.6 μm	TeO_2	Nemat -ic LC	Si CCD Rm. Temp.
SWIR	0.9-1.7	10.4 at 1.3 μm	TeO_2	Nemat -ic LC	InGaAs Rm. Temp.
MWIR	2.0-4.5	77 at 3 μm	TeO_2	Nemat -ic LC	InSb 77 K
LWIR	8.0-10.0	80 at 10 μm	TAS		MCT 77 K

In our program we are developing new AOTF cells and materials for fabricating such cells and we have developed both KDP and MgF_2 cells operating from vacuum UV to visible wavelengths. For LWIR, we have developed AOTF cell in TAS and are now growing Hg_2Br_2 crystals for fabricating AOTFs operating in the range from 0.4 to 30 μm. We are also developing cells operating over greater than one octave range in wavelength.

VNIR Spectropolarimetric Imager

As mentioned earlier the VNIR imager is the most developed among all the imagers listed in table 1. Now, we would focus on this imager. The AOTF used in this imager was fabricated in TeO_2 for a wide-angle AO diffraction geometry with a Bragg incidence angle of 8° (or the polar incidence angle of 14°) and a tilt angle of 6° for the $LiNbO_3$ transducer with respect to the optical axis in the (1 $\bar{1}$0) interaction plane of the crystal. The transducer size is 1.5×0.5 cm^2 and it is made of four sections connected in series. The transducer was bonded by using cold indium vacuum welding. The input aperture of the AOTF is 1.5×1.5 cm^2 and the input facet of the crystal makes an 82° angle with the transducer plane. Both the electrical and acoustic impedance matching were done carefully to couple most of the applied rf power into the crystal as acoustic power. The electrical impedance matching was done to match the impedance of the transducer to 50 Ω over the full operational rf range. Thin intermediate layers of indium and tin were used in bonding the transducer to obtain better acoustic coupling. The angular separation between the diffracted and incident beams in the air is 4.2°. The output facet is rotated by 4.3° with respect to the input facet to form a wedge to minimize the spectral scene shift of the output diffracted beam. The filter was designed to operate with the ordinary (vertically) polarized incident beam and the extraordinary (horizontally) polarized diffracted beam. The reason for this choice of the filter design is that for a spectral imaging instrument we wanted a fairly broad bandpass and a large linear aperture such that there is a large light throughput.

The filter operates in the rf range from 44 to 126.5 MHz corresponding to the wavelength range from 420 to 880 nm. Experimentally measured tuning curve for this filter is shown in figure 2. The spectral bandpass of the filter is 10 nm at 600 nm. The diffraction efficiency of the filter is close to 95% with 0.9 W of rf power. The acoustic velocity in this crystal is 650 m/s, and for a 1.5 cm aperture we can change the frequency every 23 μs. In other words, we can obtain 4.33×10^4 spectral image frames per second.

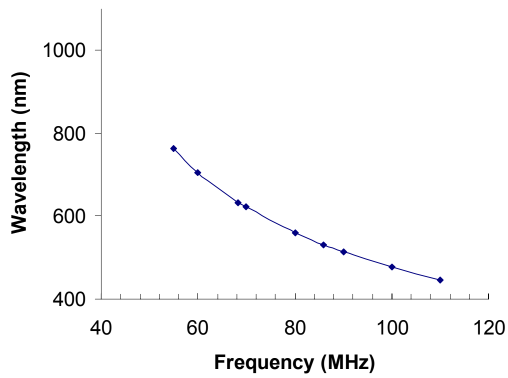

Figure 2. Experimentally measured tuning curve.

The optical layout of the imager is shown in Figure 3 and a photograph of the optical package is shown in figure 4. We use two irises to define the field of view for the incident beam and to block the unwanted beams after the AOTF (as shown in figure 1) in this imager. Also, two single lenses are used in a confocal configuration, such that the light from a distant object is first imaged at the center of the AOTF crystal and then re-imaged on a commercial 640×480-pixel Si-CCD camera with an objective lens. The entire optical system is packaged in a 15×20×10 cm^3 box and weighs around 2 kg. Less than 1 W of rf power is used to drive the AOTF. The imaging system is completely automated. Both the rf synthesizer and the LCVR are controlled using a personal computer. RF is changed between 50 and 120 MHz to correspond to the desired optical wavelength range. The CCD output is captured using a frame grabber and stored on a hard drive. We developed a graphical user interface for a seamless operation of the imager. A photograph of the imager mounted on a camera tripod is shown in figure 5.

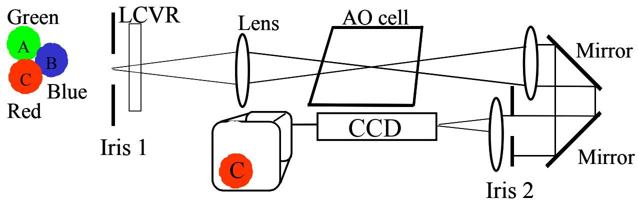

Figure 3. Optical layout of the VNIR imager.

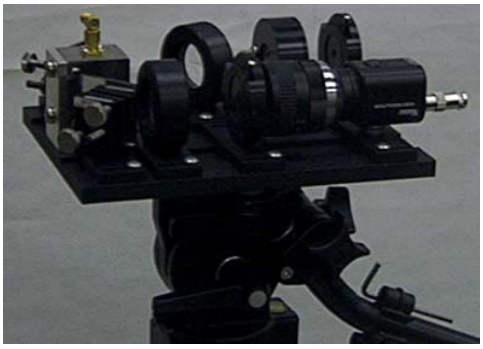

Figure 4. Optical breadboard of the VNIR imager.

Figure 5. The VNIR imager mounted on a tripod.

Data collection and analysis

We have carried out a number of data collection exercises using the VNIR AOTF imager. Analyses of these data have clearly shown that manmade objects have strong polarimetric signatures [7,9] and these signatures are affected by the viewing conditions [9]. Also, it is found that the natural backgrounds like foliage do not have polarization signatures [8]. Here we present one example of the outdoor data collected by the VNIR imager and the results of a detailed analysis of these data.

This example is from a data collection carried out on a clear sunny day on September 13, 2001 around 3 PM. Images were collected from 400 to 800 nm with a 10 nm step. We collected each image with both the horizontal and the vertical polarization. The scene consisted of an open top jeep with a white trailer in the back sitting on a white asphalt top parking lot. The two image cubes shown in figure 6 were formed using the raw images corresponding to the horizontal and the vertical incident polarizations. Each cube contains images at 41 different spectral bands from 400 to 800 nm with a 10 nm interval. The size of each image cube is 12.6 MBytes. There are four colored squares marked on each of the two image cubes corresponding to the four points for which spectral profiles have been plotted in figure 7.

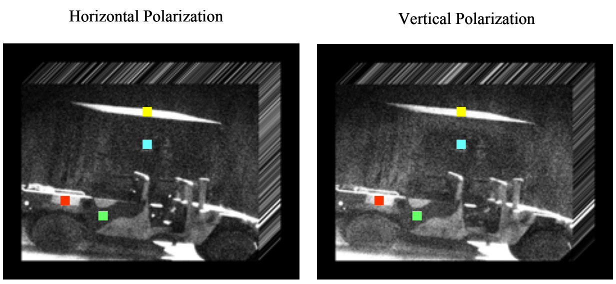

Figure 6. Image cubes for the two polarizations.

We computed the spectral profiles for both these image cubes. These profiles are uncalibrated and included here to show the effect of changes in both the spectral and polarimetric signatures of various pixels in the image. Each profile is an average of 5×5 pixels for the center point of each of the colored squares. These results clearly illustrate that both the jeep and the trailer exhibit spectropolarimatric signatures. The difference in spectropolarimetric signatures is largest for the highly reflecting top of the trailer and relatively small for the side of the trailer and the two painted portions on the side of the jeep.

Conclusions

We developed a compact, portable, agile VNIR spectropolarimetric imager using an AOTF for light dispersion and a liquid crystal variable retarder for polarization selection. Outdoor images were acquired in the spectral range from 400 to 900 nm with polarization settings of 0° and 90° at each wavelength. These images clearly show both the spectral and polarization signatures for various features in a scene. Most natural backgrounds show no polarization signatures because of random distribution of shapes and features [8], whereas man-made objects such as cars with regular shapes and edges, show polarization signatures [7,9]. Our compact spectropolarimetric imager is useful for collecting spectral as well as polarization signatures in the laboratory and outdoors. We have also developed similar imagers operating in the UV as well as in three IR regions. We are carrying out research in growing better birefringent materials and in development of new AOTF cells.

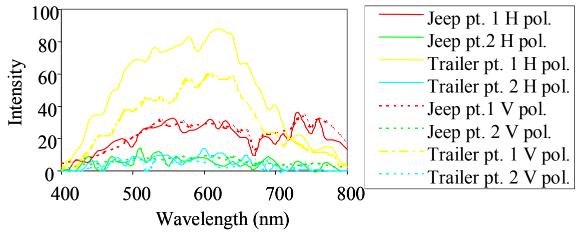

Figure 8. Spectral profiles for both horizontal and vertical polarization for points shown in figure 7.

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