High Speed Acousto-Optical Tunable Filter (AOTF) Based Spectral Imaging and Polarimetry for Field Chem-Bio Hazard and Explosives Detection

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Abstract

Acousto-Optical Tunable Filter (AOTF) Based Spectral Imaging technology, also known as hyperspectral imaging, has demonstrated particular promise for rapidly scanning surfaces, capturing and identifying different spectral signatures present in an optical field to measure levels of biological contamination. Since each surface has unique spectral profiles, changes in the spectral profile can be identified and analysis of the changes in the spectral profile can enable determination of residual contamination on a range of such surfaces. Moreover, the intrinsic polarimetric capabilities of AOTFs can be useful in applications such as IED detection since it can be used to identify regions of disturbed surface material, e.g., road surface, dirt, etc., thereby bringing to attention areas of potential buried IEDs. It also offers the unique potential to detect unburied IEDs by their spectral or polarimetric signature. We will present research into solutions and initial results based on recently patented hyperspectral polarimetric imaging technology in these domains. The development and evaluation of this technology is expected to result in the demonstration of a "first-of-type" new sensor capability with remarkable operational characteristics. This sensor, which can be flown on an unmanned aerial vehicle (UAV/UAS) platforms.

1.0 Introduction

Hyperspectral imaging (HSI) slices up the visible spectrum into hundreds of wavelengths and extends the observed spectral range into the ultra-violet and infra-red. This enables changes in coloration to be detected that would not be seen by RGB cameras or the human eye. For example, imaging at a wavelength corresponding to the chlorophyll absorption band allows camouflaged materials to be distinguished from natural foliage. Additionally, some hyperspectral cameras can be configured to analyze the state of polarization of images and therefore distinguish between smooth surfaces such as road surfaces and rough surfaces such as disturbed road surfaces where something may have been buried. Glass windows may not only be detected with polarimetric HSI but can be rendered transparent where otherwise sunlight glare would obscure vision.

Many HSI systems use a diffraction grating to split up a line of an image into strips with different wavelengths, and so build up a three dimensional image cube. This *push-broom* process works well for capturing hyper-spectral images where there is a built-in one-dimensional relative movement between the camera and the object, such as in straight fly-over surveillance applications. In many situations, this is not the case and *band sequential* imagers can be more effective. We have developed a band-sequential HSI camera that uses an Acousto-Optic Tunable Filter (AOTF) to capture an entire two dimensional image with each exposure, thus not requiring the optics to scan the scene in order to build up the image. Simultaneously, the system can rapidly sequence through a series of wavelengths and polarization states in order to build up a multi-dimensional image cube. The extra dimensions provide additional information that can aid security systems to detect intrusion.

2.0 Proprietary Imaging AOTF Technology

AO devices are found in diverse areas including bio-medical systems, industrial systems and aerospace/defense systems. AOTFs can be qualified to temperature ranges associated with aerospace and defense specifications. But in addition, uniquely among AO devices they are routinely designed with a relatively large aperture and field of view so that they are appropriate for imaging applications.

We have designed an AOTF that is optimized for spectral imaging applications. One of the key features of this device is the apodization of the transducer electrode. This modifies the distribution of the intensity profile of the acoustic wave in the AO cell which in turn significantly reduces the side-lobes associated with the pass-band. This, together with the relatively long ‘interaction length’ which reduces any blur associated with the AO interaction, allows imaging without degrading the resolution of the optical system.

The centre of the wavelength pass-band is determined by the frequency of the sine-wave input to the AOTF and the height by the input power. Multiple pass-bands may be induced simultaneously by applying the equivalent drive frequencies. This functionality is controlled through the RF driver. To exploit the functionality of the AOTF, a corresponding driver has been developed. The driver has 16 independently addressable digitally synthesized frequency (DFS) channels, which are combined into a singe output that is then connected to the AOTF input to permit channel stacking. Each individual frequency and amplitude as well as phase may be controlled via a common software interface.

The interaction length primarily controls the width of the pass-band together with the field of view. Both become narrower as the interaction length is increased. We have chosen a pass-band of 1.5nm – 3nm, but this may be artificially broadened by powering the AOTF with multiple drive frequencies. As additional drive frequencies are added, the corresponding pass-bands are introduced in the wavelength domain. By bringing the frequencies close together so that the pass-bands are adjacent, the overall pass-band may be broadened (Figure 1). The advantage of this “dynamically variable pass-band” is that the filter can be programmed to increase the light throughput in regions of the spectrum where the need for high spectral resolution is not paramount. In addition, since the amplitude of the RF drive frequency controls the height of the pass-band (i.e. modulation depth), within a limited range. Pass-bands with a customized width and profile may be synthesized.

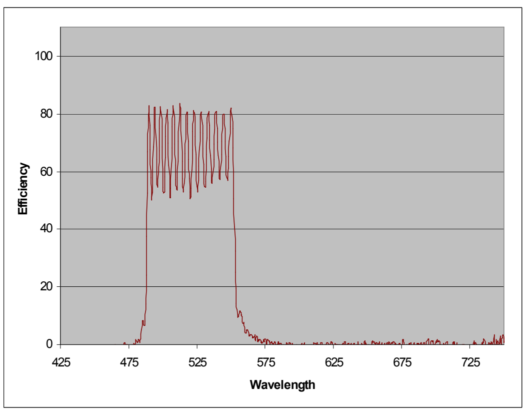


Figure 1 - AOTF Driven With Multiple (13) Frequencies

The material of choice for AOTFs is tellurium dioxide (also known as paratellurite or TeO_2). This is transparent across the range 400 nm to 4.5µm. Other materials have been proposed, especially for operation in the IR beyond 4µm, but these materials so far are not commercially available in adequate size and quantity. For this reason, and because of the easy availability of appropriate cameras, we have so far limited ourselves to HSI systems in the VNIR and SWIR regions.

2.1 AOTF for Dual-Polarization Operation

The AO interaction in an AOTF is polarization-sensitive. An incident ordinary ray will be diffracted as an extraordinary ray and vice versa. Hence, an unpolarized white light input will result in two simultaneous orthogonally polarized and angularly separated outputs. The two orthogonal polarizations are diffracted on opposite sides of the (undiffracted) 0 order. Thus the AOTF will act as an efficient polarizer. In general, the two diffracted beams will not be at exactly the same wavelength. However, with careful design, the AOTF may be optimized so that so that diffraction occurs at the same wavelength for both of the two orders. See Figure 2.

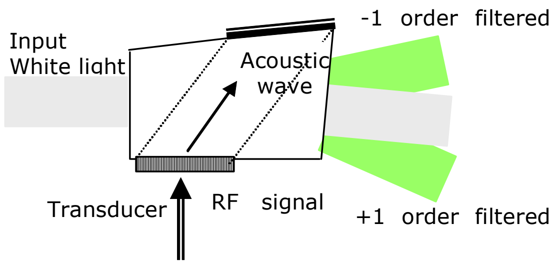


Figure 2 - AOTF with Dual Output

3.0 Hyperspectral Imaging Cameras

Gooch and Housego has designed and built commercial AOTF-based Hyperspectral Imaging Systems optimized for use with microscopes, the HSi-300 (Figure 3) and HSi-400 series. These systems exploit the G&H AOTF technology and typically cover the range 450-800nm, with an inherent pass-band width of 1.5nm 3nm, although they are also available for the range 500 to 900 nm. Key to the system performance is not only the inherent fast tuning of the AOTF, but its adaptability. Not only does it operate in band-sequential mode (as opposed to push broom), but the random access of the tuning means that only wavelengths of interest need be addressed so further increasing the speed. In addition, multichannel operation means that wider pass-bands may be selected to further enhance the light throughput and thus increase the speed. On the standard microscope systems this function is controlled within the software. The system is designed to operate at "F/11".

Versions of the HSi-300 have been modified for use in stand-off applications (Figure 4). Systems have also been built covering the VNIR and SWIR, and at F-numbers down to "F/9". Lower F number designs are also possible. Typically, the VNIR system covers the range 450-800nm or 500 900nm. The SWIR system typically covers the range 1-1.6µm or 0.9 to 1.7µm, the exact range being determined by the InGaAs CCD camera.

A key feature of the AOTF HSI system is the exploitation of the flexibility of the AOTF. This not only includes the speed (typical AOTF access time 20µs) but also the adaptive passband bandwidth and intensity control. This can be useful, if for example the lighting condition has a particular spectral feature. The spectral profile of the illumination can in principal be compensated by the HSI unit.

Figure 3 -For Microscope Mounting

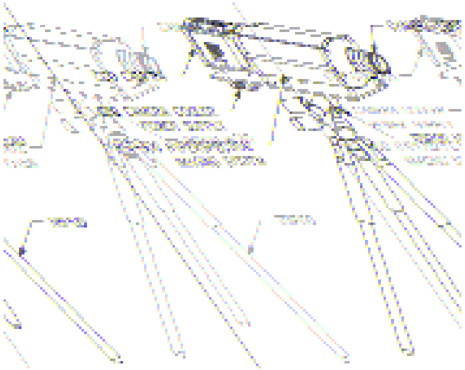
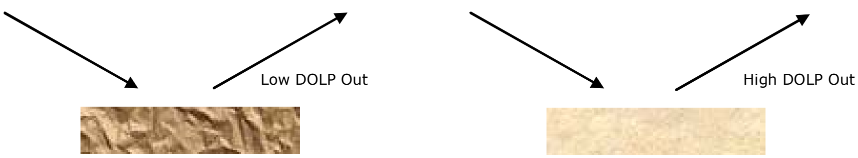


Figure 4- Tripod Mounted for Stand-Off Applications

3.1 Polarimetric Spectral Imaging Systems

The stand-off systems have proved to operate effectively over a range of 1m to 1km or more. In order to enhance the systems and to access additional information regarding the scene, a capability to examine the polarization state was added. While hyperspectral imaging gives information about the nature of the material being imaged, polarimetric imaging (in particular the Degree of Linear Polarization (DOLP) image) gives information about the roughness of the surface of the object being imaged. While there are many factors to consider, heuristically one may say that DOLP increases with decreasing surface roughness (Figure 5).



$$DOLP = \frac{\sqrt{\left(I_{0\,\deg} - I_{90\,\deg}\right)^2 + \left(I_{45\,\deg} - I_{135\,\deg}\right)^2}}{\left(I_{0\,\deg} + I_{90\,\deg}\right)}$$

Figure 5 -Degree of Linear Polarization by Reflection (Scatter)

A basic approach to measure the DOLP is to simply rotate the whole camera about the axis through the centre of the objective lens. Using the AOTF as a polarizing element, the camera may be rotated to the 0 and 90º orientations to allow simple polarimetric analysis (Figure 6). By additional rotation of the camera to the ±45º orientations, further information may be obtained allowing the degree of linear polarization (DOLP) to be determined.

Figure 6 -AOTF HSI camera. Mechanical rotation about an axis along the optical centre of the objective lens allows capture of images polarized at 0º, 45º, 90º & 135º

While the configuration described above provides a wealth of useable information, it is unable to supply the full set of "Stokes Parameters" to unambiguously define the polarization state of each point within the scene, and clearly the system as outlined is not ideal for deployment in any but the most benign of applications. Another technique that will add polarimetric data (but not all of the Stokes parameters) is to introduce a single multi-order retardation plate into the optical train and exploit the polarization properties of the AOTF (Figure 7). With the optic axis of the retardation plate aligned at 45º to either of the polarization planes of the AOTF, a cyclical modulation to the polarization state will be introduced in the wavelength domain. The number of cycles will depend upon the thickness and birefringence of the retarder – the larger the thickness the more cycles. This cyclical variation can of course be recovered using an analyzer, in this case the AOTF.

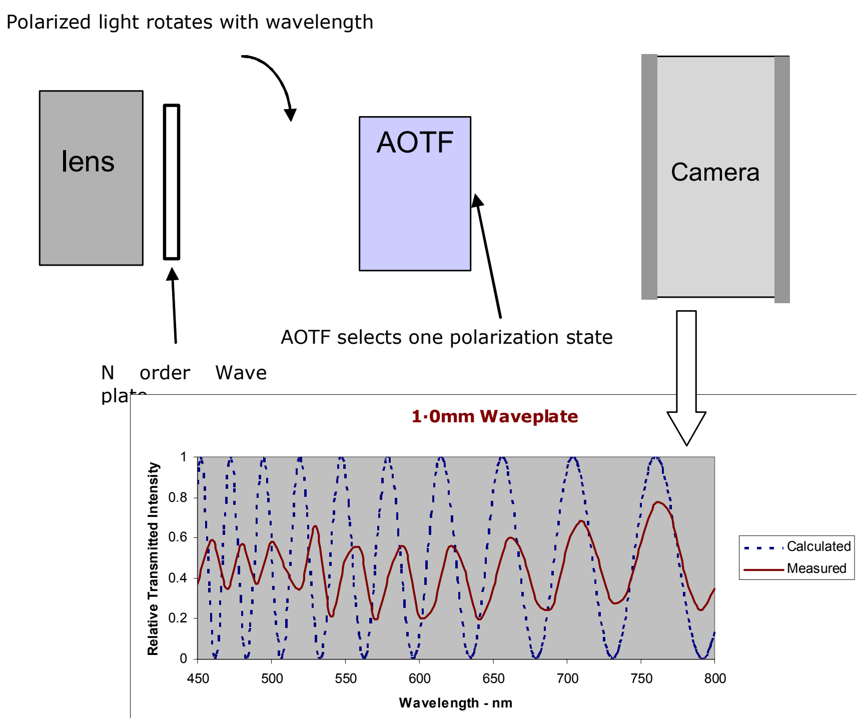
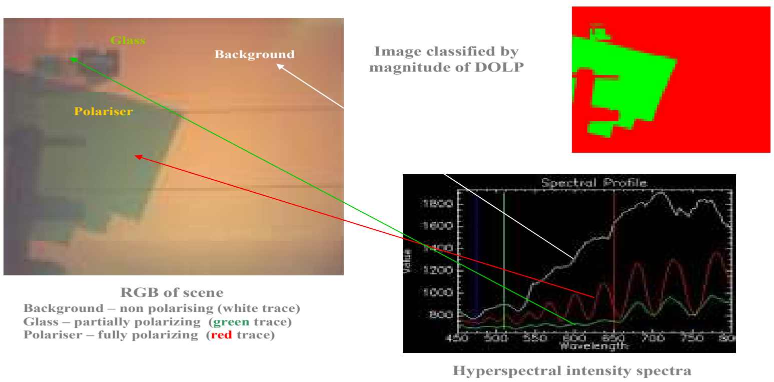


Figure 7 -Schematic of Spectral-Polarimetric Imager Using A Single Multi-Order Wave plate.

Gooch and Housego has built a system to demonstrate this effect. The choice of wave plate thickness will depend upon two main factors - the rate at which polarization characteristics of the target to be imaged change with wavelength and the pass-band resolution of the optical filter. The first factor is generally unknown a priori. A single quartz retardation plate, of nominal thickness 1.0mm was placed in front of the AOTF in our HSi-300 system. A scene, incorporating a polarizer and a glass plate (partial polarizer) was then captured across the 450-800nm range. Figure 8 shows good agreement with the calculated intensity variation for a wave plate thickness of 1mm. Wave plate thicknesses of 0.5mm and 1.3mm were also evaluated (with similar results). At a wave plate thickness of 1.3mm, 10nm steps were too wide for good resolution, while the 0.5mm wave plate gave too few cycles; however, these factors could be optimized by design. The cyclic spectral modulation, which is produced by polarized light passing through the wave-plate AOTF optical train, can be detected in an image by Fourier analysis or spectral angle mapping classification.



RGB of scene
Background – non polarizing
Glass – partially polarizing
Polarizer – fully polarizing

Hyperspectral intensity spectra

Image classified by magnitude of DOLP

Figure 8 -Transmitted Intensity Through Retardation Plate

Figure 9 shows how the scene may be analyzed. The method was tested by observing a scene that included natural materials, rough man made materials and glass windows as shown. Spectral analysis was then applied to the image of the window. Light scattered from window glass is generally partially polarized. A spectral signature that was derived from the wave-plate thickness and birefringence was used to perform angle map classification of the image. As can be seen, the classified image can be processed to reveal hidden detail behind the window.

This simple approach is suitable for scenes with light polarized in the plane or perpendicular to the plane of the AOTF. However light polarized in the plane of the retarder axis will not have its state of polarization modified, but if the observer has prior information about the probable plane of polarization of light scattered by a target then the camera could be oriented accordingly.

Recovery of the full Stokes parameters is possible. Snik et al have proposed a means of achieving this by using two retarders and a polarizing beam-splitter. Another approach is to use Liquid Crystal Variable Retarders (LCVR).

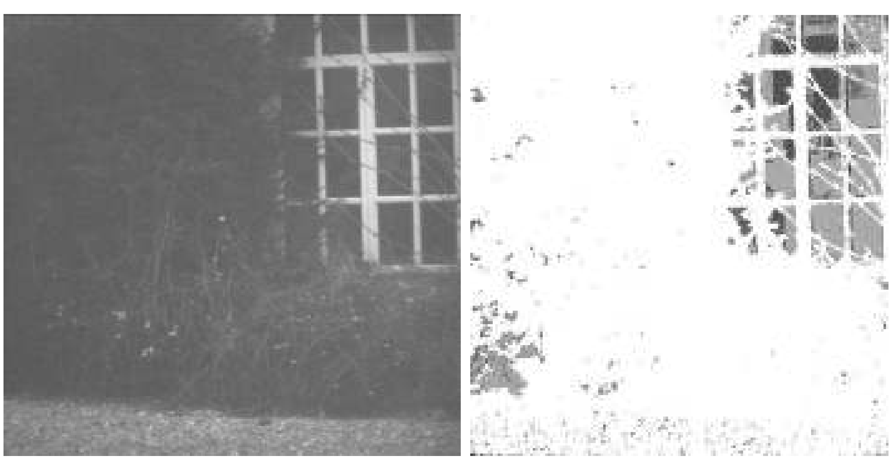


Figure 9 - Grey scale and classified image

4.0 Spectral Imaging and Bio-Hazard Detection

HSI technology has the potential to detect specific microorganisms and distinguish them from organic debris. A pilot study was carried by the Biosafety Unit of the UK Health Protection Agency, Centre for Emergency Preparedness and Response in collaboration with Gooch and Housego and to determine the effectiveness of HSI techniques for rapidly measuring levels of biological contamination in health care environments. HSI could be utilized to assess risk and countermeasures as it may be possible to view large surface areas, and the method does not require sample processing, expensive reagents or skilled scientists to determine the desired information.

As every surface has a unique spectral profile, any changes in the spectral profile are identified. By analyzing the changes in the spectral profile, it may be possible to identify residual contamination on a range of surfaces. This pilot study has contaminated commonly used hospital surfaces with a range of microorganisms and organic material, and this novel application of HSI is being investigated to determine if contamination can be rapidly distinguished from organic material.

Figure 10 - White tiles with artificial soil (LHS) and bacteria (RHS).

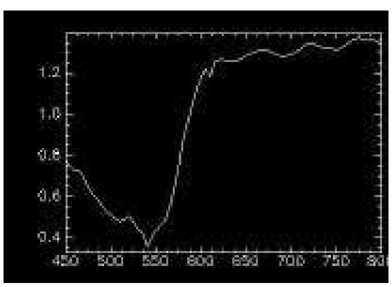


Figure 11 - Reflectance spectrum of artificial soiling.

Figure 12 -HSi image of artificial soiling.

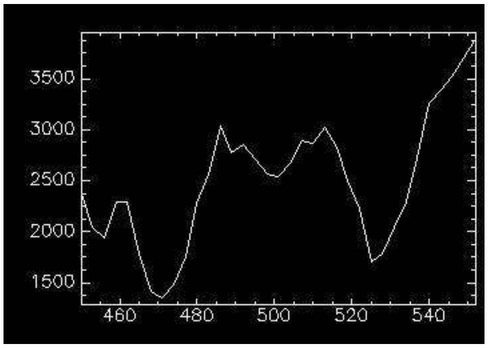


Figure 13 - Fluorescence spectra of C. difficile with background subtracted.

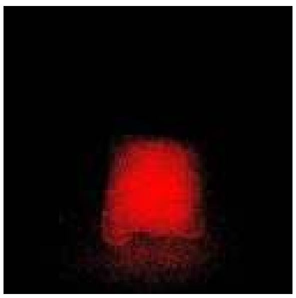


Figure 14 - HSi image of C. difficile

The organisms tested were methicillin resistant Staphyloccus aureus NCTC 13412 (MRSA), Clostridium difficile 11209, E. coli 9481, Bacillus atrophaeus, Brendomonas diminuta 11091, Aspergillus niger ATCC 16404. Squares ($2cm^2$) were etched on white ceramic tiles and contaminated with suspensions (100ul) of microorganisms (Figure 10). One tile was dried by incubating at 37°C for 1 hour. Images were taken of the microorganisms, Browne's soil and UV hand cream by the HSi-300 camera under different lighting conditions and by changing the parameters on the HSi software. A UV lamp was used as an alternative light source to see the possibility of using fluorescence.

While artificial soiling could be detected using the reflectance methodology (Figures 11-12), the microorganisms were not easily distinguishable by the reflectance imaging method. However, bacteria e.g. C. difficile (107cells/ml) could be detected by fluorescence imaging by virtue of their fluorescence in the visible spectrum (Figures 13-14). The HIS fluorescence imaging system does have the potential to identify pathogens such as C. difficile; however, currently relatively high concentrations of pathogens are required for positive identification. Further work is required to optimize the HSI system for this application.

4.1 Polarimetric Spectral Imaging Systems and "Disturbed Earth" Applications

A system has been built, and limited trials conducted to demonstrate the potential use of AOTF based polarimetric spectral imaging systems for "disturbed earth" applications. Three different types of soil were imaged at different angles of incidence and different times of day, using both a VNIR and a SWIR AOTF hyperspectral polarimetric imager. The results suggested that soil compaction can be detected with polarimetric hyperspectral imaging, especially in the SWIR region. Representative results taken in the SWIR are shown in Figures 15 though 17.

Figure 15 -Three different types of soil, each with three different surface textures (raked, loose and compacted) were imaged.

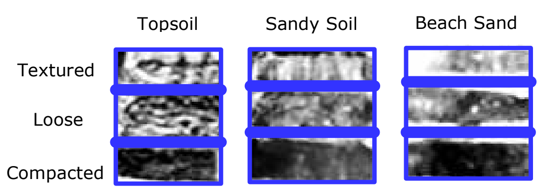


Figure 16 -Spectral DOLP Images of Soil Samples - SWIR Range

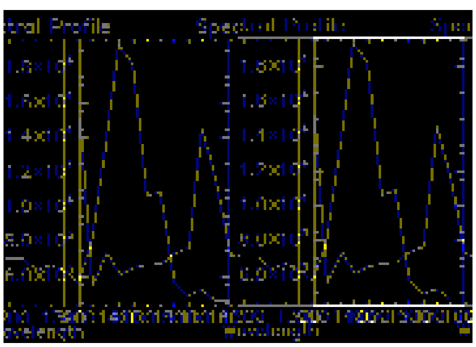


Figure 17-Sample DOLP indicating spectral features.

5.0 Next Steps: Dual-Camera Polarimetric Spectral Imaging System

One of the features of an AOTF is that it can act simultaneously as a pass-band filter and polarizing beam splitter. G&H is now evaluating development of such an HSI system for stand-off applications. The unit will feature an AOTF designed to operate in “dual polarization mode” as discussed in section 2.3 above. By using a pair of similar cameras operating in the +/- orders of the AOTF output two identical images of a scene (as viewed through a common objective) but with orthogonal polarizations will be viewed. The AOTF as proposed will have a large aperture enabling the system to operate at “F/4” making the system fast, capable of real-time imaging operation in reasonable levels of lighting conditions. This mode of operation will give a significant amount of information regarding the polarizations signature of the scene. A third camera may be placed in the undiffracted 0-order beam to give an unfiltered RGB (real-time) color image (Figure 18).

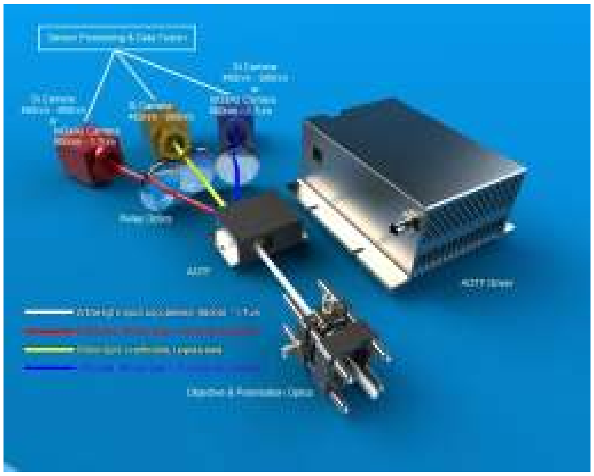


Figure 5 - Three Camera HSI Unit Exploiting AOTF operating in Dual- Polarization Mode

Simple addition (of the camera outputs) will give the unpolarized view of the scene while subtraction of the two camera outputs (pixel by pixel) will yield useful polarimetric information. This configuration alone is likely to yield significant additional information. Retarders (either fixed or LCVR) may be included to give the full Stokes parameters.

When deployed, the operator will view the RGB image, and any features in the scene detected by the HSI/Polarimetry may then be overlaid onto the operator's display in false color. The system will provide (depending upon the implementation).

- White-light imaging (VIS/SWIR camera dependent): via the 0-order output.
- Multispectral imaging (VNIR or SWIR): Function defined in software. Single-channel operation
- Hyperspectral Imaging (VNIR or SWIR): Function defined in software. Single-channel operation
- Differential polarimetric hyperspectral imaging: Utilization of both diffracted orders and comparing (in real time) the two simultaneous images produced
- Full Stokes Parameters analysis of the scene – pixel by pixel (with inclusion of additional polarizing components)

6.0 Summary

The effectiveness of using an AOTF as both an active filter and polarizing element has been demonstrated. The agility, speed and flexibility of the AOTF combined with its ruggedness make it particularly attractive for biohazard, defense and security applications. The configuration of an AOTF Hyperspectral Imaging system in the band-sequential mode further enhances the suitability since in combination with the potentially high frame-rates it simplifies correction for motion blur.

A three camera system for operation at F4, as outlined above should be built to fully test the concept of Polarimetric Spectral Imaging. The practicality of using either single or multiple retardation plates to deconvolve the state of polarization of the imaged scene should be further explored. With appropriate modular design, the effectiveness of simple spectral imaging, simple linear polarization comparison, full degree of linear polarization and full Stokes analysis can be compared.

7.0 References

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8.0 Acknowledgements

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