A HIGH SPEED SPECTRAL IMAGING CAMERA WITH THE POTENTIAL FOR REAL-TIME SPECTRAL VIDEO IMAGING

Reprinted with permission by M. Farries, J. Ward - Gooch & Housego PLC A. Killey, P. Dale, A.S. Blagg – BAE Systems

June 2011

A High Speed Spectral Imaging Camera with the Potential for Real-Time Spectral Video Imaging

M. Farries, J. Ward
Gooch & Housego Ltd
Exeter, U.K.
mfarries@goochandhousego.com

A. Killey, P. Dale, A. S. Blagg
Advanced Technology Centre
BAE Systems
Bristol, U.K
Ainsley.Killey@baesystems.com

Abstract— **The authors will report on trials using a prototype AOTF based hyper-spectral imaging system that demonstrated the potential for fast image acquisition. The limitations of the prototype system will be discussed, and it will be shown that for the prototype, the speed of the system was ultimately limited by the speed of the camera.**

Keywords- Acousto-optic tunable filter, hyper-spectral imaging

I. Introduction

Hyper-spectral imaging (HSI) has been shown to be a valuable tool for identifying objects by their spectral profiles [1]. For example camouflaged clothing can be detected against a foliage back-ground by utilizing the subtle differences between clothing dyes and chlorophyll based plants. However most HSI systems are used to analyse fixed images and are too slow to capture real time data because they operate on a push broom system, which captures a single line of an image and requires the image to be mechanically scanned across the camera in order to build up a full picture. Push broom systems collect a fixed number of wavelengths and therefore cannot be optimized for speed by selecting a reduced set of wavelengths.

A hyper-spectral imaging system based on an acousto-optical tunable filter (AOTF) operates differently to a push broom system in that the entire image is projected on to the camera [2]. Each image is recorded one wavelength at a time so that the time taken to record a full hyper-spectral image cube depends on the number of wavelengths recorded. Careful selection of the wavelengths enables the HSI to operate at real time video rates and to track moving objects. This has many security applications where a person, vehicle or other object can be identified and followed as it moves amongst other similar objects.

II. Hyper-spectral imaging with acousto-optic tunable filters

Operation of an AOTF is illustrated in (Figure 1 Acousto-optic tunable filterFigure 1). An acoustic transducer generates ultrasound that propagates through the AO cell. The sound wave translates into a periodic refractive-index perturbation that acts as a grating so that light incident at the appropriate wavelength and angle is diffracted into -1 and +1 orders. Un-diffracted light passes straight through into the 0 order.

In order to maximise the performance of a spectral imaging system, an AOTF needs to be optimised in a specific manner. Ideally it should have a large-aperture/field-of-view to maximise light throughput, a long interaction length to minimise acoustic blur and be able to operate over the appropriate wavelength range. In addition, any sidebands (due to the acoustic profile) should be as small as possible in order to maximise the out-of-band rejection, help minimise acoustic blur and to avoid ghost images. Gooch and Housego has developed an AOTF with these attributes, key features being a relatively long interaction-length and a transducer electrode pattern to achieve effective side-lobe suppression.

The current HIS system, that was used for this work has a wavelength switching time of 20µs and an aperture of F 11 which is determined by the acceptance angle of the AOTF cell. The optical pass bandwidth is determined by the rf drive frequencies and can be dynamically controlled in software from 2 to 20 nm. The very high speed of the AOTF offers the potential of an almost snap shot HSI with 2000 images at different wavelengths captured in a 40ms time slot.

However the current system is limited to 35 images a second by the frame transfer rate of the EMCCD camera, which has an image size of 512x512 pixels. This is suitable for real time video at a single wavelength, but not for hyper-spectral imaging at many wavelengths. The consequence of operating at a slow frame rate is that spectral distortion occurs around the edges of moving objects. A number of factors need to be addressed in order to increase the frame capture speed of the HSI system.

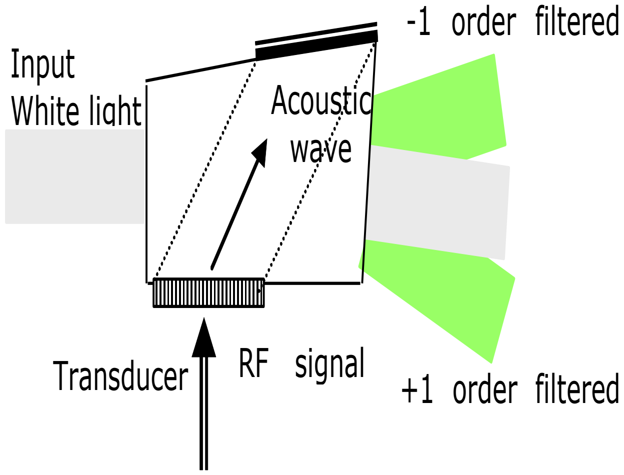

Figure 1 Acousto-optic tunable filter

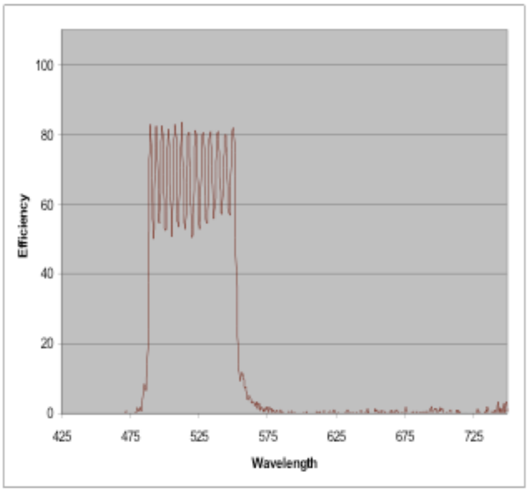

Figure 2 AOTF bandwidth broadened by 16 channel driver

III. Improving HSI performance

A. Camera speed

An EMCCD camera is used with an HSI system to improve signal to noise in low light applications. The frame rate can be increased to 231 frames per second in this camera by a using a process known as binning, which reduces the image size to 64x64 pixels. This would enable snap shot hyper-spectral imaging over 10 wavelengths all be it at low resolution. How ever the small number of pixels would hamper target identification.

Faster cameras are available, for example an EMCCD camera with a 128x128 pixel sensor can operate at 513 frames per second. This would enable 20 wavelengths to be selected for snap shot hyper spectral imaging.

Cameras with CMOS sensors offer even greater speed due to parallel addressing of pixels and on-chip signal processing. For example a 512 x 512 pixel camera is available with a frame rate of 2500 per second or 40,000 per second if the resolution is reduced to 128x 128 pixels.

B. Flexible wavelength selection

An AOTF based HSI system can record an image cube with 200 wavelengths, but by reducing the number of wavelengths to those that are necessary for specific target detection significantly improves the image capture time and the image analysis time. A set of wavelengths can be selected based on the target spectrum and then dynamically programmed into the HSI. Each individual frequency and amplitude, as well as phase, may be controlled via a common software interface. The wavelength switching time is the same for switching between any two wavelengths whether they are adjacent or at opposite ends of the tuning range. We show later that an image cube with only 10 wavelengths will give accurate target identification. This is the significant advantage of using an AOTF as the wavelength selective element in a HSI system.

C. Dynamically selectable bandwidth

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 electronically through the RF driver. The driver has 16 independently addressable digitally synthesized frequency channels, which are combined into a single output that is then connected to the AOTF input to permit channel stacking. The bandwidth of each wavelength band can be dynamically adjusted between 2nm and 20nm.

This flexibility to adjust the bandwidth is a unique feature of the AOTF based HSI that enables it to match pass bandwidths to spectral features and to adjust for low light levels.

D. AOTF aperture

Capturing sufficient light to meet the camera sensor sensitivity requirement is a big challenge for high speed HIS systems. The AOTF is one of the highest through put wavelength filters available and it achieves a 95% diffraction efficiency against an average efficiency of 70% for a ruled diffraction grating. However the diameter of AOTF and the angular separation between the diffracted and non-diffracted orders determines that this system has an aperture of F11 system, which limits light capture. In a further development will use a larger diameter AOTF that will result in a system aperture of F4 and so will increase the light level on the sensor by 8 times.

E. Degree of polarisation

The AOTF has the unique advantage of diffracting the input light into 2 orthogonally polarized orders. This feature enables simultaneous polarization and spectral analysis to be carried out. It has been shown that man made objects can be distinguished from natural objects by measuring the degree of polarisation of an image, which is a function of surface roughness [3]. However splitting the input light into 2 paths reduces the light falling on the camera sensor by a factor of 2.

F. Next generation HSI system

The snap shot speed, defined as the time taken to capture an image cube, is limited by the EMCCD camera speed and the light though-put of HSI system. In order to accurately detect and track small moving objects at a reasonable distance using a spectral matching algorithm the HSI system requires:- a good signal to noise; a significant number (>9) pure pixels on the target and only a small amount of pixel spectral mixing due to optical or motion effects. In the next generation HSI system a high speed CCD camera with a high sensitivity of ISO 1000 will be used. The system aperture will be increased to F4 by using a large diameter AOTF and the AOTF bandwidth will be optimised for light throughput. Therefore the next generation system will be able to detect image cubes with 512x512 pixel spatial pixels and 100 wavelengths pixels in a 40ms snap shot time. This will enable spectral analysis of moving object and target tracking to be carried out.

IV. REMOTE SPECTRAL DETECTION

A trial of the G&H HSI300 AOTF hyperspectral imaging system was carried out in order to determine the potential of the system for finding and tracking people on the basis of the spectral signatures of their clothing. The camera optics was such that the angle subtended by each 16µm pixel was 0.3 mrad, giving a ground pixel size of 16mm at the 50m range.
Each ten band hyperspectral image cube took a total of one second to record. Reference spectra were recorded for three articles of clothing, an orange jacket and two types of camouflage jacket (Figure 3). The orange jacket and camo jacket number 1 were worn; camo jacket number 2 was placed on the grass.

A series of test images were taken at later times when the people had moved to different locations (Figure 4). The images were then processed using spectral matched filter software developed at BAE ATC Filton. The best results were obtained using the Adaptive Cosine Estimator (ACE) [4], which is insensitive to changes in image brightness. Figures 5,6 & 7 show coloured detection maps where red indicates a value of 1 and blue is zero, red being a perfect match and blue being no match. Results obtained with the simpler Spectral Angle Mapper (SAM) were less good.

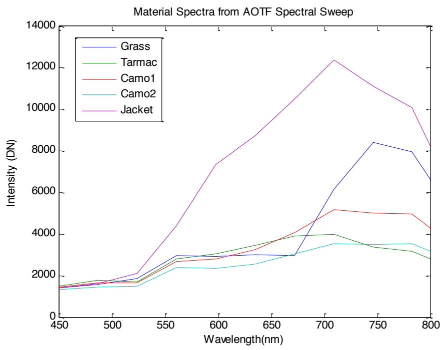

Figure 3 Spectra captured by HSI system

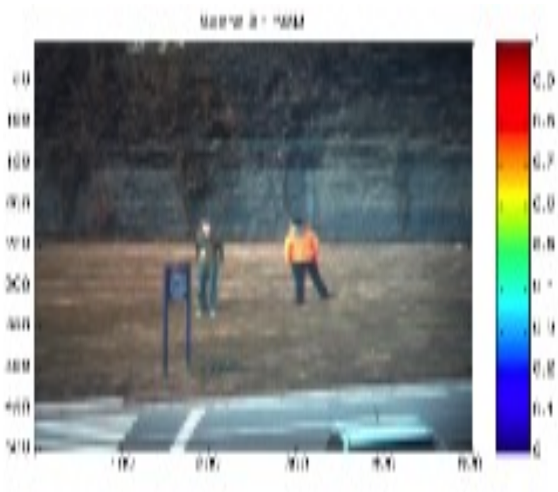

Figure 4 RGB image of scene with people moved.

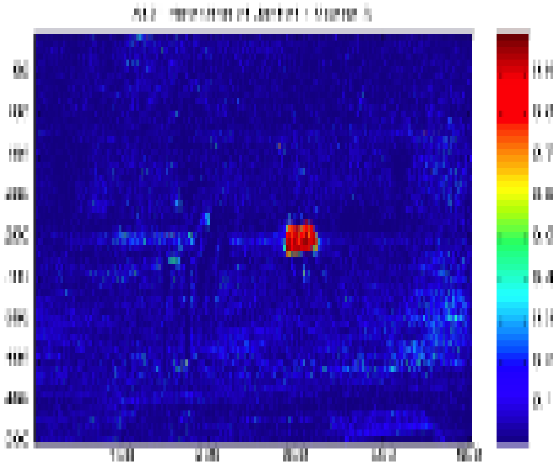

Figure 5 ACE detection of jacket

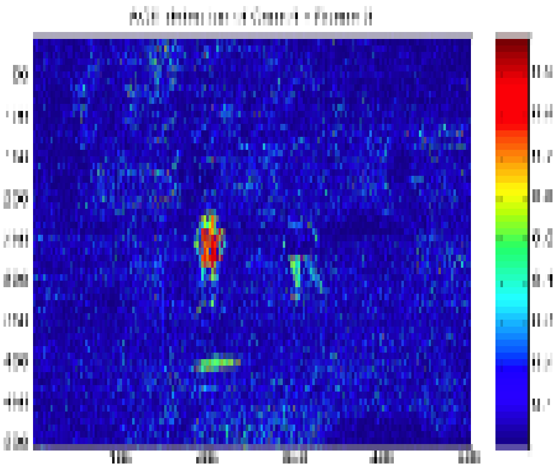

Figure 6 ACE detection of camouflage jacket 1

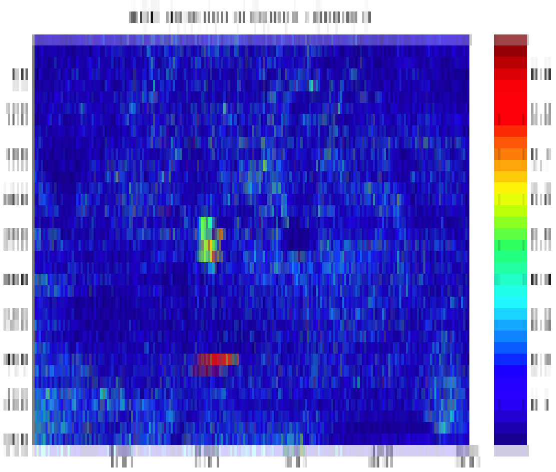

Figure 7 ACE detection of camouflage jacket 2

V. CONCLUSIONS

An acousto-optic tunable filter based HSI system provides an accurate means of finding targets using visible spectral colours, even in circumstances where they are moving slowly during the capture time of the image cube. Overall detection performance is limited by the maximum frame rate of the camera and not the wavelength scanning speed of the AOTF. An AOTF based system provides the ability to select a specific set of wavelengths, within the octave range of the device, in order to maximise the spectral difference between target and background. Further developments are planned to increase light throughput by increasing the aperture of the AOTF crystal, and increase capture speed by employ a faster digital cameras employing CMOS technology.

VI. REFERENCES

[1] J Ward; M Farries; C Pannell; E Wachman "An Acousto-Optic Based Hyperspectral Imaging Camera for Security and Defence Applications", Proc. SPIE 7835, 78350U (2010)

[2] Michael D. Schaeberle, John F. Turner II and Patrick J. Treado, "Multiplexed acousto-optic tunable filter (AOTF) spectral imaging microscopy", Proc. SPIE 2173, 11 (1994)

[3] Acousto-Optic Tunable Filter Imaging Spectrometer with full Stokes Polarimetrc Capability; Gupta N, Suhre; Applied Optics, pp 2632-2637, Vol 46 No 14, May 2007

[4] A. S. Blagg, G. J. Bishop, A. Killey & M. D. Porter, "Temporal performance of spectral matched filtering techniques", SPIE Conference, Florence, Italy, Sep 2007.