DMD-based adaptive spectral imagers for hyperspectral imagery and direct detection of spectral signatures

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ABSTRACT

Dispersive transform spectral imagers with both one- and two-dimensional spatial coverage have been demonstrated and characterized for applications in remote sensing, target classification and process monitoring. Programmable spatial light modulators make it possible to adjust spectral, temporal and spatial resolution in real time, as well as implement detection algorithms directly in the digitally controlled sensor hardware. Operating parameters can be optimized in real time, in order to capture changing background and target evolution. Preliminary results are presented for short wave, mid-wave, and long-wave infrared sensors that demonstrate the spatial and spectral versatility and rapid adaptability of this new sensor technology.

Keywords: DMD, Hadamard, imager, spectrometer, programmable

1. INTRODUCTION

Spectral Sciences Inc. (SSI), has developed a new class of spectral-spatial sensors, called Adaptive Spectral Imagers that exploit digital micromirror arrays to provide imagery with programmable spectral band passes. Hyperspectral imagery or complex spectral discrimination algorithms can be produced using a time sequence of spectrally encoded images and appropriate decoding algorithms. In this work, we describe a variety of spectral imagers which use commercially available digital micromirror arrays (Texas Instruments DMD family).[1] The basic optical configuration is shown in Figure 1 and described previously.[2-6] Light from a distant object is imaged onto a focal plane, dispersed, and reimaged onto a DMD that selects specific spectral and spatial regions of the dispersed image. The reflected light is then recombined to form a polychromatic image on a detector with a spectral passband determined by the programmed setting of the DMD micromirrors. The detector can be a single detector or an array.

In this paper, we briefly describe three hardware implementations spanning the visible through long-wave infrared, and using single detectors, 1-dimensional arrays, and 2-dimensional arrays. We also demonstrate algorithms for 1) the generation of hyperspectral imagery, 2) the application of analog spectral filters in hardware, 3) the production contrast imagery for target detection, and 4) the measurement of temperatures and concentrations through the application of spectral filters. These algorithms are implemented in hardware, thereby achieving substantial advantages in speed, signal-to-noise-ratio, and spectral resolution relative to post-processing of spectral data.

The algorithms are implemented using one of two basic modes of operation. In time-multiplexing mode, a sequence of masks is applied to the DMD and the signals decoded to provide additional spatial and/or spectral dimensions to the retrieved image. For a system with a single detector, time multiplexing can provide both spatial and spectral resolution. This can be particularly helpful in spectral ranges such as the long-wavelength infrared (LWIR), where array detectors can be expensive and unreliable. At the other extreme, systems with two-dimensional arrays can use time multiplexing to add a spectral dimension to a 2-D image. In spectral filtering mode, useful for high-speed continuous monitoring, signals are acquired with a programmable spectral response function of arbitrary shape. The shape of the function is designed to enhance specific spectral features of the scene. A matched filter contrast image can be produced by alternating two such functions.

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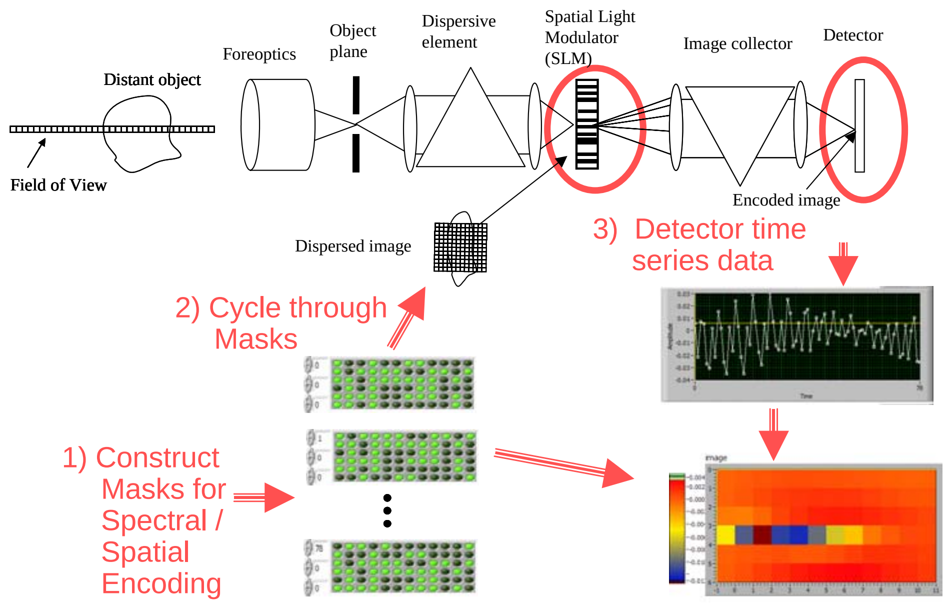

Fig. 1. Schematic representation of an adaptive spectral imager.

The mode of operation, resolution, and details of the detection filters can be changed on-the-fly in real time to meet evolving applications requirements. The same instrument can be used to collect spectra or perform spatial and spectral processing under computer control. Supervisory logic can change detection algorithms and resolution parameters in real time to implement a sequence of measurement functions in a single hardware package.

2. GENERAL FEATURES

Figure 1 illustrates the general features of the hardware and software. The hardware uses a foreoptic to produce an image at the input of the Adaptive Spectral Imager. The foreoptic can be a telescope, camera lens, microscope, or any other standard imaging system. The Adaptive Spectral Imager is inserted between the foreoptic and detector to produce a spectrally encoded version of the input image. The input image is dispersed and re-imaged onto the spatial light modulator, or DMD, which encodes a specific pattern through a spatial mask. We have used standard Texas Instruments DMD, 0.7XGA 12^{o} DDR, chips with associated control electronics. The radiation reflected by the "on" position micromirrors is then collected and refocused onto the detector. The collection optics normally contain a dispersive element that recombines the dispersed image back into a polychromatic image on the detector (Figure 1).

Figure 1 also illustrates the use of time multiplexing to perform spatial and spectral processing of the detected imagery. A series of masks is constructed to interrogate different elements of the dispersed image. Each mask passes selected spatial and spectral elements of the dispersed image. The system cycles through these masks at speeds of up to 13 kHz. The detector collects time series data, which is correlated with the masks and processed to reconstruct the dispersed image on the DMD or some convolution of the dispersed image with the mask filter function.

The system acts as a spectrometer in which the transmitted wavelength is defined by the spatial mask on the DMD and a second physical slit located at either the input image plane or the encoded image plane. In the simplest implementation, a mechanical slit is inserted in the entrance plane. The spectral calibration is determined from the slit and micromirror locations along with the known dispersion of the system. Figure 1 depicts data for this case. A single distant object is focused onto an input slit, producing a dispersed image containing the spectrum of that object, which appears as a row in the reconstructed image. After reconstruction, the spectral dimension of the image is converted into a calibrated wavelength axis.

Other implementations use no entrance slit, but rather use an array detector in the encoded image plane to define the wavelength. In this case, each column of the detector acts as a slit, which, in conjunction with the DMD location, defines a unique wavelength. Note that for a single DMD location, each column records a different wavelength. Therefore, it is necessary to cycle through multiple masks and reconstruct the calibrated spectrum for each column prior to making any direct spectral comparison of different columns.

The adaptive nature of the system arises from the ability to program arbitrary patterns on the DMD masks. Different applications require different mask sequences and different image processing algorithms. Previous workers have described the use of Hadamard encoding to produce spectral imagery.[2,3,7] We will describe this and other coding/decoding algorithms in later sections.

3. HARDWARE IMPLEMENTATIONS

Figures 2-6 illustrate three different adaptive spectral imagers that have been demonstrated at SSI. These implementations use single detectors, one-dimensional arrays, and two-dimensional arrays, and span a spectral range from the near-visible to the LWIR.

The Adaptive Spectral Imager approach provides great advantages in the infrared spectral region. First, the multiplex advantage produces the signal-to-nose gain, which is particularly important in the LWIR where the radiance signals are weak and detectors are noisy. In many applications, the signals are too weak to collect high-resolution spectral data, but high-resolution masks can be used to create contrast signals in hardware. Second, two-dimensional array detectors can be prohibitively expensive, particularly in the 7-13 μm LWIR range. An adaptive system based on a single detector can provide spectral and spatial data at an order-of-magnitude lower cost.

However, there are a number of special challenges associated with the infrared that have discouraged the production of IR Adaptive Spectral Imagers. These include 1) difficulties associated with producing high-throughput gratings, 2) lack of DMDs for the MWIR and LWIR spectral range. and 3) diffraction effects associated with the 14-μm-diameter DMD micromirrors, which can be comparable in size to the wavelength of light. In the designs described below, solutions include the use of curved gratings with low F numbers and high efficiencies (~80%), manufactured to our specifications by Headwall Photonics, Inc., and IR transmitting windows for the DMDs assembled by L-1 Standards and Technology, Inc. Diffraction is accounted for in the spectrograph design, and DMA mask patterns for spatial or spectral discrimination are chosen to be larger than the wavelength scale. We have demonstrated collection of diffracted light from the DMD with efficiencies as high as 80% in the MWIR (3-5 μm) and 10-25% in the LWIR (7-13 μm). Better efficiency could be obtained using DMDs with larger micromirrors.

FAROS - IR imager with 2D detector

The FAst Reconfigurable Optical Sensor (FAROS), shown in Figure 2, is a prototype high-resolution infrared imager designed for tracking and identification applications.[4-6] The system has diffraction-limited image quality and F/2.8 collection optics. It incorporates a dual pass spectrograph of the Offner configuration[2,3] to both disperse the image onto the DMD and recombine the light into a white light image at the detector.[6] The optical path is illustrated in Figure 2. A single spherical mirror and confocal spherical grating define an Offner spectrograph. Input radiation is directed through the spectrograph to form an image on the DMD, and then redirected back through the Offner to form an image on the focal plane array.

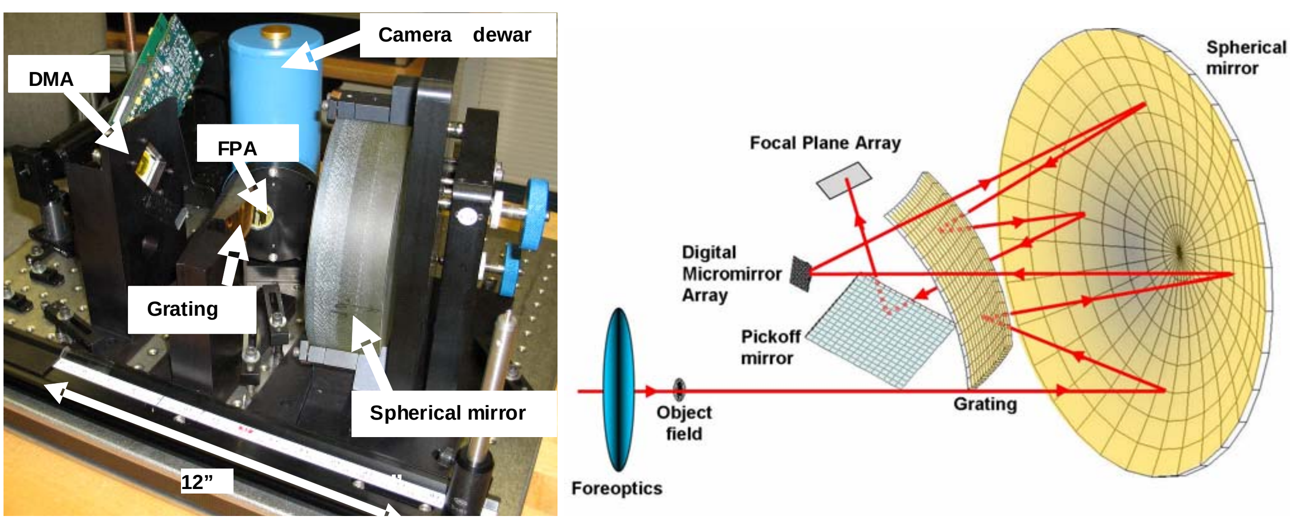

Fig. 2. Photograph and ray path schematic for the FAROS Imager.

Spectrally resolved imagery both in the mid-wave infrared (MWIR) and in long-wave infrared (LWIR) using Hadamard transform spectrometry has been generated with the instrument on Figure 2., to demonstrate the feasibility of the approach.

AMS – IR imager with a single-element detector

The adaptive Multiplexed Spectrometer, shown in Figure 3 uses a single IR detector to produce hyperspectral imagery and contrast images with one dimension of spatial resolution.[4,6] It provides a moderately low-cost platform for IR spectroscopy and target detection in the Long Wave Infrared Range, LWIR (7-13 μm). The system uses two highly efficient, F/1.9 concave gratings to produce a moderate-resolution dispersed image on the DMD and recombine the light on a single detector. The DMD provides addressable spatial and spectral resolution with up to 50 fully resolved spatial channels and 100 fully resolved spectral channels, each channel corresponding to a superpixel comprised of ~100 micromirrors.

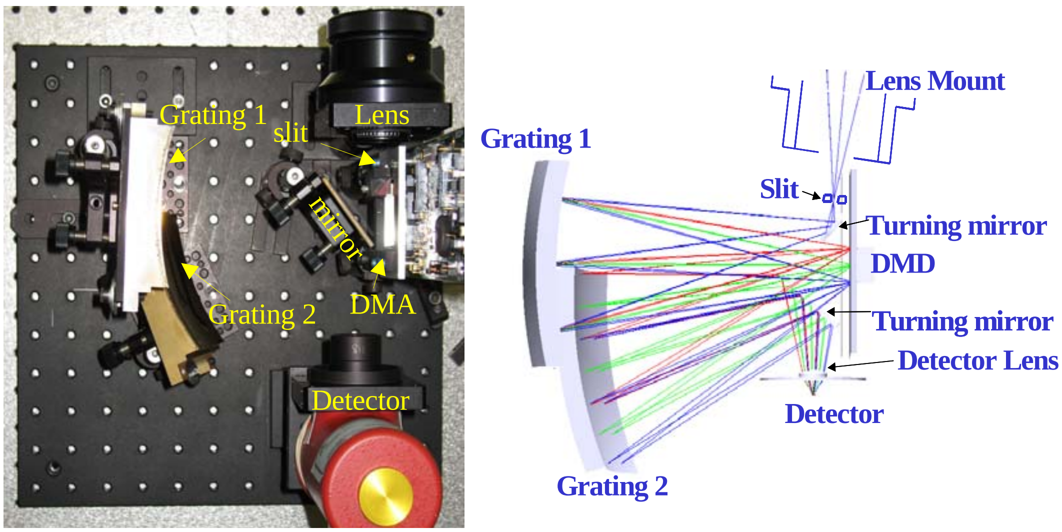

Fig. 3. AMS LWIR single-detector system.

Figure 4 shows example data in two operating modes that are explained more fully in later sections. The left-hand side shows hyperspectral data obtained using Hadamard transform spectrometry over 6 spatial and 64 spectral channels. The right hand side shows a one-dimensional contrast profile obtained by implementing a generalized matched filter, discussed later in this paper, in two hardware gray-scale masks.

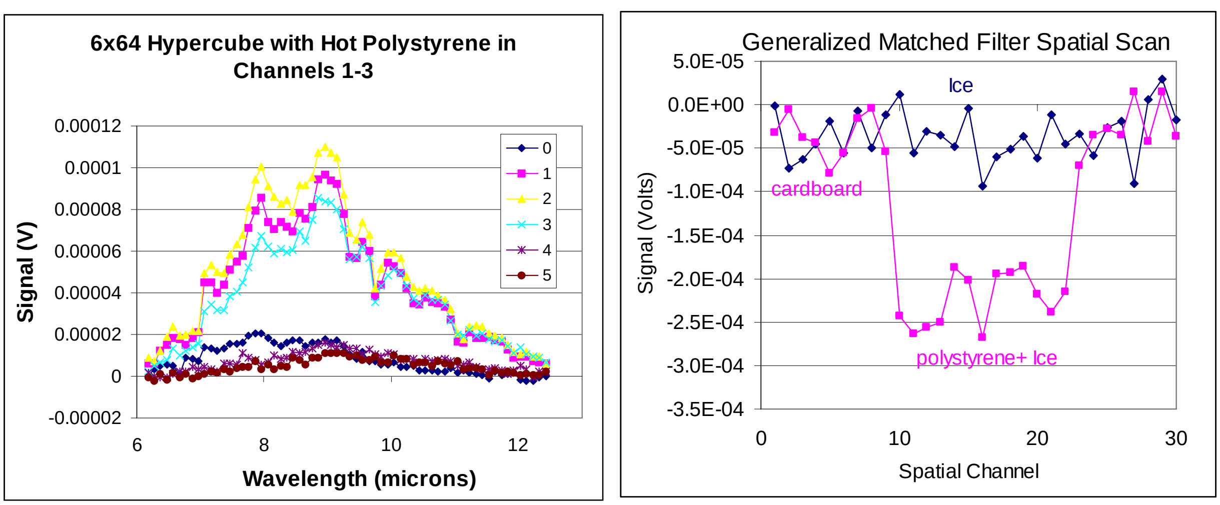

Fig. 4. Example AMS data. At left, spatially resolved spectra; at right, spatial profile of the signal from an analog spectral filter that detects polystyrene.

FASPEC – High-speed SWIR imager with a 1-D detector array

The FASPEC system, shown in Figure 5, applies the Adaptive Spectral Imaging concept to provide uninterrupted, high-speed, spectrally selected intensity measurements in multiple spatial channels.[4,6] It is designed to measure concentrations and combustion products in dynamically fluctuating combustion environments. It uses an Adaptive Spectral Imager to select specific molecular emission bands in the range of 1.0-1.7 μm, which are detected with an array of high-speed photodetectors. Flame dynamics are monitored at 100 kHz, while the pass band can be changed at a 6 kHz rate to monitor different species or measure the temperature of the emitters through a band ratio.

Light is collected using 200μm-diameter optical fibers that are butt-coupled to the input slit and re-imaged onto a linear array. The FASPEC spectrograph is based on the Dyson design, which yields extremely high resolution on the DMD plane.

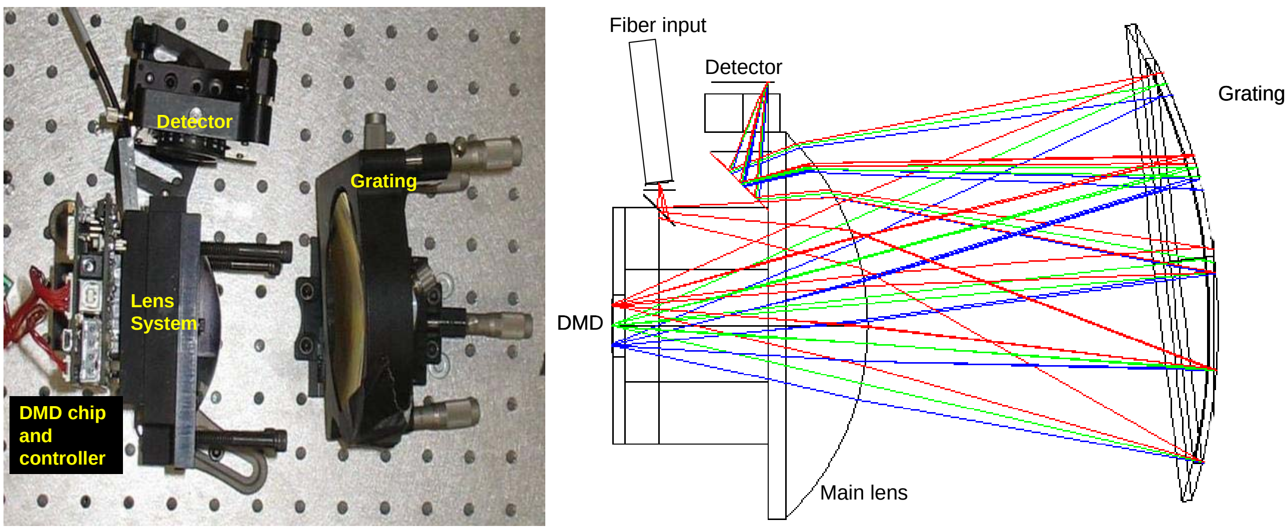

Fig. 5. FASPEC SWIR high-speed imager.

4. IMAGE GENERATION AND PROCESSING ALGORITHMS

As shown in Figure 1, spectral and spatial imagery can be generated by cycling through a set of spectral and spatial masks and then decoding the time-dependent signal to reconstruct the image on the DMD. Generally, we reconstruct a two-dimensional image at a resolution less than that of the micromirror array. Micromirrors are grouped into "superpixels," each representing a resolution unit in the dispersed image plane. The superpixels can be defined as columns to produce a spectral scan, or rows to produce a spatial scan, or as sub-areas that can be scanned to produce a 2-dimensional spatial-spectral image. A complete spectral or spatial scan can be recorded by scanning through the superpixels while recording the intensity on the detector. A simple-minded approach would be to scan through the superpixels one at a time, and then assign the intensity associated with each mask to the active superpixel. More efficient data processing approaches are described below.

Hadamard multiplexing

Hadamard multiplexing can be used to collect the complete image of the superpixel array while maximizing light throughput and signal/noise ratio. Rather than scan one superpixel at a time, a set of orthogonal masks are used, each of which has approximately half of the pixels turned on (see Figure 1). This results in a multiplex advantage where the signal-to-noise ratio is increased by a factor of approximately $m^{1/2}/2$ relative to scanning through m pixels.[7] In this work, we perform Hadamard multiplexing using the set of right cyclic simplexes of order 4m-1[7] to produce a set of Hadamard masks, $H_{m,}$. The detector measures a signal equal to the product of the incident intensity and the mask transmission. The response of the detector to a set of *m* masks is represented by

$$[D] = [H_m][I], \tag{1}$$

where *[D]* is a column vector of *M* detector responses for *m* spectral resolution elements, H_m is the encoding Hadamard matrix, and *[I]* is a column vector of intensities of *m* resolution elements on the DMD. The encodegram *[D]* is transformed into the intensity of the superpixels by applying the inverse Hadamard matrix H_m^{-1}.

$$[I] = [H_m^{-1}][D], \tag{2}$$

Figure 1 shows an example of several spatial masks that are part of an $[H_m]$ sequence for collecting a 2-dimensional image. Here the superpixels are arranged in an ordered vector corresponding to a raster scan through a 6x12 grid of DMD superpixels. The 72 superpixels, along with several blank superpixels, are placed in a defined order to form a vector representation of all the superpixels with m=79. Then the Hadamard transform is applied to produce a set of *m* ordered orthogonal masks, $[H_m]$. As the system cycles through the masks, the detector data, *[D]*, are recorded, transformed into the original intensity vector, and recast as a two-dimensional grid to produce the reconstructed image.

The Hadamard transform can be applied to any ordered set of superpixels. The superpixels can be selected to represent either one- or two-dimensional scans. For example, a simple spectral scan would employ a set of superpixels corresponding to a set of columns on the DMD. A simple spatial scan would correspond to a set of rows on the DMD. Alternatively, a selected set of image subarrays can be scanned in any order. In many applications, the ordering of the superpixels can be important. Figure 1 demonstrates a YX raster scan. More complicated ordering schemes can be used to exploit or depress time-varying fluctuations of the system. For example, a superset of randomly ordered superpixels can be used to suppress aliasing of time dependent signals.

Gray-scale filters

Any arbitrary analog spectral transmission function can be implemented in the DMD using gray scales (i.e., fractional scalings of the DMD reflectance). They can be implemented either by pulse-width modulation of the micromirrors or by using a pattern of “on” micromirrors within the superpixel. An example of the latter in shown in Figure 6, where 17 of the micromirrors in the 16x16 superpixel are turned on to yield a nominal 15% reflectance factor. With proper calibration of the transfer function, gray scales can be implemented with better than 1% accuracy, even in the LWIR where diffraction effects are important.

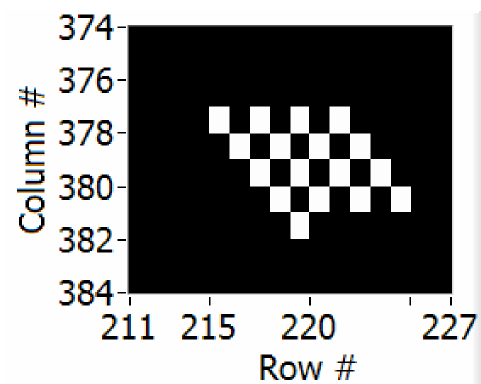

Fig. 6. Gray-scaled superpixel

Linear matched filters

Detection algorithms can be implemented in hardware by applying a single analog response function, or linear filter, or a small number of such filters. Rather than record complete hyperspectral data and apply the filters in post-processing, the filters can be applied in hardware, followed by simple algebraic manipulation of the filter outputs. This mode of operation reduces data collection time and bandwidth requirements and can increase signal/noise performance.

Figures 7 and 8 illustrate the generation of a one-dimensional contrast profile using an analog spectral filter in conjunction with a spatial Hadamard scan. The filter was designed to detect PTFE plastic in the presence of a background of hot blackbodies. The spectral filter was constructed using the equation

$$h_{matched\ filter} = R^{-1} s \tag{3}$$

where h is the spectral filter function, s is the spectrum to be detected, and R is the spectral correlation matrix of the background. In the standard matched filter formalism, the data are mean-subtracted, so that R is the background covariance matrix. When used with non-mean-subtracted data, as in the case of our adaptive sensors, this filter is properly known as the Constrained Energy Minimization (CEM) filter.[8] CEM and matched filters are popular for detecting specific signatures in the presence of structured backgrounds, and are often used for hyperspectral target detection. As with any linear filter, it can be implemented in two gray-scale masks, one positive and one negative; the masks are alternated and subtracted to obtain the filtered output signal.

In Figures 7 and 8, the CEM filter is implemented in conjunction with Hadamard spatial scanning by multiplying each of the Hadamard masks by the positive and negative gray-scale masks that define the filter. The resulting masks are then scanned, the filter outputs calculated for each spatial mask, and the inverse Hadamard transform applied to form a one-dimensional contrast profile. Figure 8 shows the results of such a scan over 30 spatial channels.

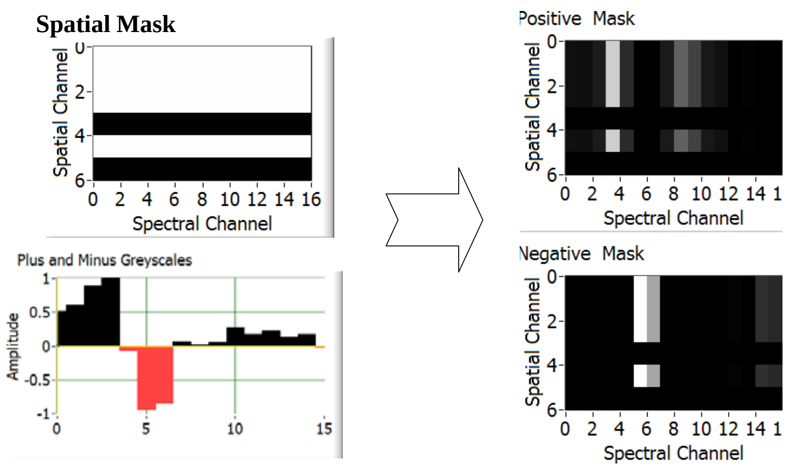

Fig. 7. Implementation of a CEM spectral matched filter (lower left) with Hadamard spatial scanning.

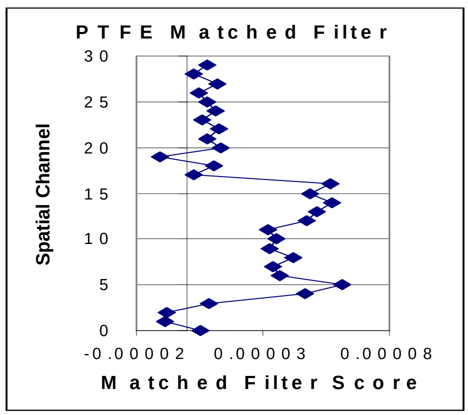

Fig. 8. Matched filter scan results using 30 spatial channels.

In the presence of significant detection noise, Eq. (3) turns out to be sub-optimal for a hardware-implemented filter. In ordinary spectral measurements, the filter is applied in post-processing, and the detection noise from each spectra channel is contained in the correlation matrix and passes through the filter. In contrast, in an Adaptive Spectral Imager system with a hardware-implemented filter detection the correlation matrix is free of detector noise, and the detector noise adds to the filtered signal as a separate additive term, *C*, that is independent of spectral resolution. The concept of the CEM filter can be generalized to include such a noise term. The optimum filter is the filter, *h*, that minimizes the signal to noise ratio (SNR):

$$\mathrm{SNR}^2 = h^T s\, s^T h \,/\, (h^T R\, h + C^2) \qquad (4)$$

Where the superscript T denotes the transpose. In the limit C = 0 the optimum filter is the CEM filter of Eq. (3). In the presence of detector noise, C>0, the optimal filter, *h*, may be derived using numerical nonlinear optimization. This generalized linear filter was used to obtain the polystyrene signal in Figure 4 at a signal-to-noise level around twice that of the CEM filter.

If the read noise is large compared to the background signal variation, the generalized filter maximizes the signal, independent of the background. For cases in between, the filter produces the largest signal without raising the contribution of the background above that of the read noise. Figure 9 compares the shape of the generalized filter from Eq. (4) to that of the CEM filter for detection of the polystyrene spectrum in the presence of blackbody backgrounds. When the detector noise is greater than the background contribution, the generalized filter produces a larger signal, with only a marginal impact on the total noise. Figure 10 shows the systematic variation in the signal and noise as a function of the relative size of the readout noise. For practical applications in the LWIR, the read noise is one to two orders of magnitude larger than the background signals, and the signal-to-noise ratio is 2-3 times better with the generalized filter than with the CEM filter.

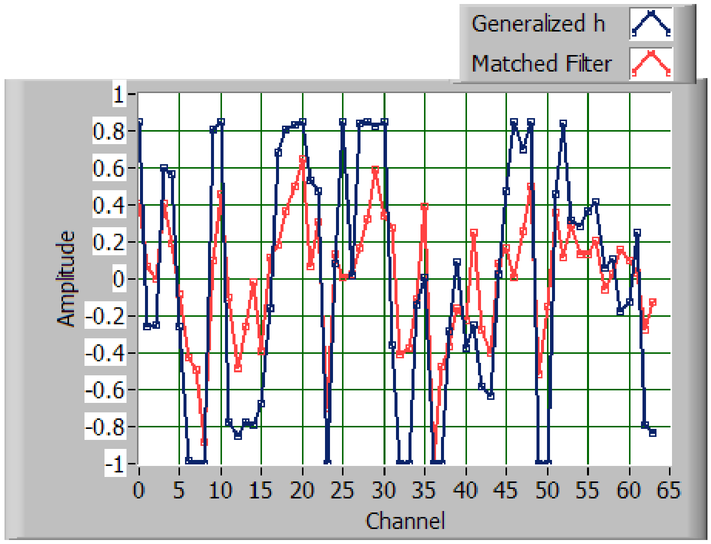

Fig. 9. Comparison of the generalized filter and matched filter for the case: C=50x $(h^T R h)^{1/2}$.

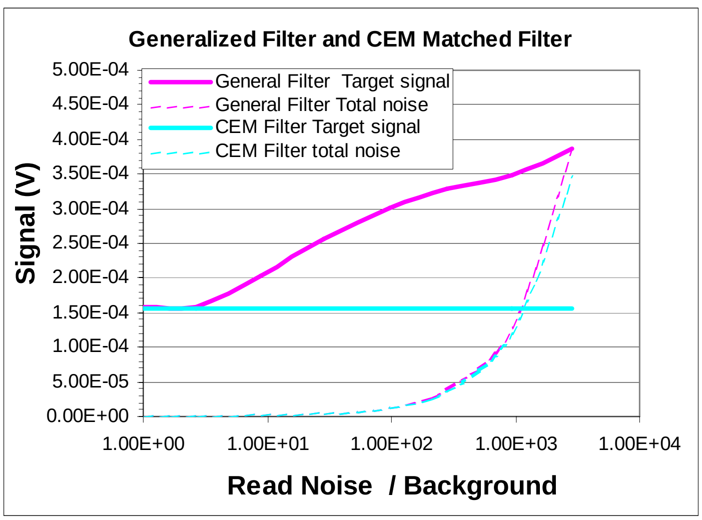

Fig. 10. Dependence of signal *and* noise on the relative size of the read noise vs. background, $(h^T R h)$

Temperatures and concentrations from band ratios

In many applications, the spectral characteristics of the scene have a well-understood relationship to a physical property of interest. For example, in combustion systems, the temperature and concentration of the exhaust gas can be determined form the spectral shape and intensity of the emission.[9,10] In that case, an Adaptive Spectral Imager can be used to extract the temperature through a ratiometric comparison of intensity in two spectral bands. The FASPEC system shown in Figure 5 has been used to monitor rapid fluctuations in combustion systems based on the shape of the H_2O spectrum. Figure 11 shows the spectrum of the H_2O emission observed at various temperatures. The entire spectrum can be represented by just two parameters, the intensity of the spectrum and the width of the water band. These parameters can be extracted by observing the intensity in just three spectral bands, labeled center, wing and null. The FASPEC system rapidly alternates between the three bands to produce temperature and intensity information at a kHz data rate. Figure 12 shows the extracted temperature and concentration (as represented by a column density) as a function of flame operating conditions. These values match the known physical properties of the flame.

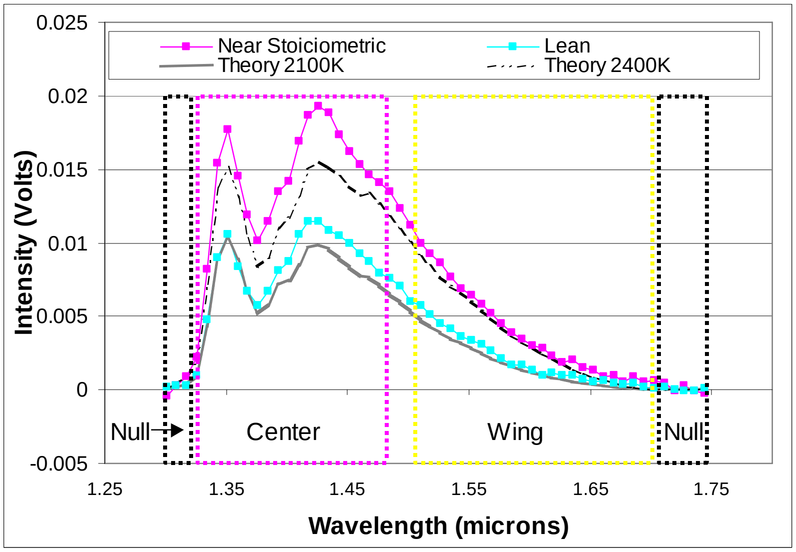

Fig. 11. Flame spectra and spectral bands.

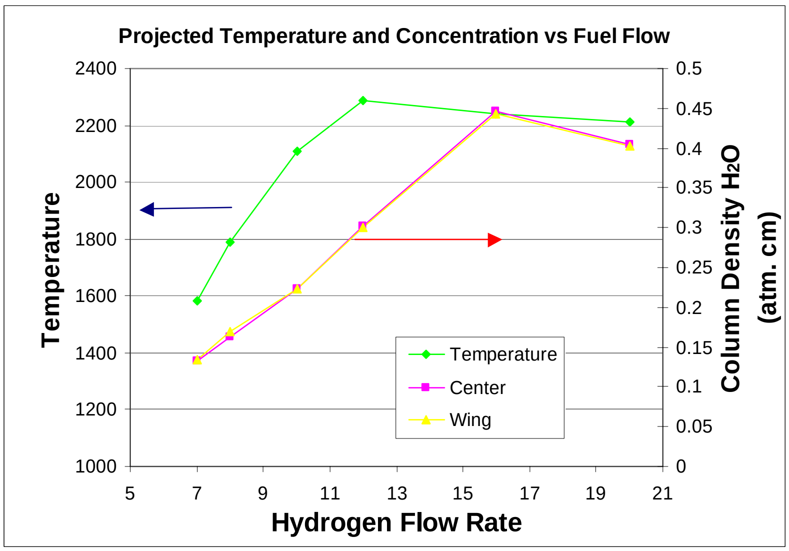

Fig. 12. Temperatures and concentrations extracted from band ratios.

5. SUMMARY AND CONCLUSIONS

We have built and demonstrated prototype Adaptive Spectral Imagers in three configurations, distinguished primarily by operating spectral band and detector format. By fully exploiting the flexibility of the programmable SLM at the heart of this technology, these sensors can be operated in a variety of modes that trade spatial and spectral resolution, and/or change hardware processing algorithms. Furthermore mode selection can be adapted on-the-fly to meet evolving functional requirements. The sensors demonstrate simultaneously high spectral selectivity and high throughput, and are well suited to low-signal and high speed applications.

The adaptability of the SLM-based sensor results in a wide range of possible output information formats. The systems can be used to produce hyperspectral imagery or perform detection in hardware. Contrast imagery indicating material abundances can be produced using any analog filter function, including high-resolution spectral or spatial masks and linear spectral filters of arbitrary spectral resolution. The spectral and spatial resolution can be selected in software, and detection algorithms can be selected to emphasize or de-emphasize specific spectral features in the scene.

Designs have been developed for both single detectors and arrays of detectors. Sensors with single detectors can produce 2-dimensional spectral-spatial imagery through time multiplexing, exploiting high detector data rates to produce a low-cost, compact and rugged sensor. Array-based sensors have the advantage of parallel signal processing. Linear detector arrays can be used to provide continuous high-speed monitoring of multiple spatial channels with a programmable spectral filter. A two dimensional imaging detector with time multiplexing can produce a sequence of multispectral images at video frame rates. Since half the spectral channels are passed in each image frame, a high frame-rate wideband image useful for acquisition and tracking purpose is also produced.

In addition to providing the flexibility of programmable resolution, the Adaptive Spectral Imagers are advantageous in terms of data collection speed and the multiplexing of spectral or spatial channels to overcome readout noise. Multiplexing advantages are particularly important in the infrared spectral region where detector readout noise limits detection sensitivity. Performance in comparison to other dispersive spectral imagers is significantly improved, and compares favorably to FTIR instruments in this regard, but with no vibration-sensitive, macro-scale, moving parts. In applications in which high-resolution spatial information is to be reduced to a detection probability, time response is enhanced by minimizing the image acquisition time, which typically limits system performance. This provides a considerable speed advantage relative to standard hyperspectral instruments combined with post-processing detection algorithms.

6. ACKNOWLEDGMENT

The authors wish to acknowledge government support for this research under the following contracts: Fast Adaptive Spectrometer Programmable for the Evaluation of Combustion (FASPEC), Contract No. W31P4Q-06-C-0186 (Army), Adaptive Spectral Imager (ASI) for the next generation EKV, Contract No. FA8718-04-C-0058 (MDA), Chemical/Biological Agent Standoff Detection, Contract No. HDTRA1-05-P-0126 (DTRA).

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