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Adaptive hyperspectral imaging with a MEMS-based full-frame programmable spectral filter

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ABSTRACT

Rapidly programmable spatial light modulation devices based on MEMS technology have opened an exciting new arena in spectral imaging: rapidly reprogrammable, high spectral resolution, multi-band spectral filters that enable hyperspectral processing directly in the optical hardware of an imaging sensor. Implemented as a multiplexing spectral selector, a digital micro-mirror device (DMD) can independently choose or reject dozens or hundreds of spectral bands and present them simultaneously to an imaging sensor, forming a complete 2D image. The result is a high-speed, high-resolution, programmable spectral filter that gives the user complete control over the spectral content of the image formed at the sensor. This technology enables a wide variety of rapidly reprogrammable operational capabilities within the same sensor including broadband, color, false color, multispectral, hyperspectral and target specific, matched filter imaging. Of particular interest is the ability to implement target-specific hyperspectral matched filters directly into the optical train of the sensor, producing an image highlighting a target within a spectrally cluttered scene in real time without further processing. By performing the hyperspectral image processing at the sensor, such a system can operate with high performance, greatly reduced data volume, and at a fraction of the cost of traditional push broom hyperspectral instruments. Examples of color, false color and target-specific matched-filter images recorded with our visible-spectrum prototype will be displayed, and extensions to other spectral regions will be discussed.

Keywords: hyperspectral imaging, matched filter imaging, tunable spectral filter, micro-mirror array, DLP, DMD

1. INTRODUCTION

The human eye collects both spatial and spectral information (e.g. color in the visible spectrum) and enables the brain to identify and classify materials in its surrounding environment. Spectral imaging sensors replicate this function by collecting spatial information along with spectral information in many regions of the electromagnetic spectrum, including the ultraviolet (UV), visible and infrared (IR). By combining both spatial and spectral information, spectroscopic techniques can be applied on a pixel-by-pixel basis to elicit more information about a scene than is available in the image alone, including medical information such as detecting diseased tissue either *in vivo*[1] or in laboratory samples[2], object properties such as temperature and photosynthetic activity[3], material composition for land-use studies and precision farming[4], and chemical detection for climate change studies and industrial effluent monitoring. Spectral imaging sensors are rapidly becoming highly valuable tools for many applications ranging from planetary science and environmental monitoring to medical imaging, industrial quality assurance and national security.

Not all spectral imaging techniques are appropriate for all tasks. Depending on the particular objective at hand, one might want to collect a small number of low-resolution spectral bands (e.g., three-band color imaging), a modest number of medium-resolution spectral bands (i.e., multispectral imaging), or a complete high-resolution spectrum (i.e., hyperspectral imaging). For applications where the spectral target signature is well defined and conditions are relatively well controlled, requirements may be met with a few, well-chosen spectral bands, reducing the acquisition time, collected data volume and simplifying the processing required to produce an image highlighting the presence of the target in a scene. Other applications don't rely on detailed spectra so much as coarse spectral properties. For instance, machine learning techniques have been successfully applied to multispectral satellite data consisting of fewer than 10 fairly broad spectral bands for a large number of remote sensing applications including land-use studies, forest management, etc. where no "signature" exists[5]. Multispectral instruments are typically designed to image through single band-pass filters in succession to build up its data cube and are often reliant on available filter technology. Because these target-specific spectral bands are typically "hard-wired" into the instrument hardware, multispectral sensors are not easily adapted to new objectives or changing conditions in the field.

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For applications where the target signatures may be multiple, unknown *a priori*, unstable due to changing conditions, or embedded in complex spectrally cluttered backgrounds it can be important to collect all of the available spectral information and at high resolution. The hyperspectral data cube, where every pixel of the two-dimensional image contains a high-resolution spectrum (x, y, λ), represents a complete set of spatial and spectral information from a scene, and powerful spectral processing algorithms have been developed to detect the presence of even faint signatures of interest in a scene. Though HSI has proven to be a highly sensitive and selective tool for chemical detection and materials characterization, traditional HSI systems have several operational drawbacks that limit the applicability of high-resolution spectral imaging in some cases. Most notably, these systems require significant scanning time to acquire a complete data cube, generate large data volumes that tax bandwidth bottlenecks, and require sophisticated post-acquisition data analysis routines. Several recent efforts to develop faster hyperspectral imaging cameras have been reported, achieving in some cases, "snapshot" and video-rate acquisition, extending the HSI modality to transient and short time-scale phenomena.[6-10] But despite faster data cube acquisition, resources must still be allocated to processing and analyzing the hyperspectral data. Time-sensitive applications, such as broad-area search and multi-sensor cueing that depend on real-time answers require the camera-like imaging capabilities and speed of the multispectral approach combined with the sensitivity of the high-resolution hyperspectral approach.

A new MEMS-based Adaptable Hyperspectral Imaging (MAHI) sensor developed at Los Alamos National Laboratory incorporates a Texas Instruments DLP® digital micro-mirror device (DMD) in a full-frame, programmable, multi-band spectral filter that gives the user complete control over the spectral content of the final image formed at the detector.[11] Based on a new optical design capable of modifying the spectral content of the entire two-dimensional field of view simultaneously, our spectral filter is capable of converting broadband, COTS cameras into spectral cameras. These cameras are capable of rapidly reprogrammable operational modes that include broadband and color imaging, multispectral and hyperspectral imaging and multi-band matched-filter imaging.[12] In standard imaging mode, the sensor acquires either broadband, panchromatic images or creates color (false color) images based on three-image sequences through red, green and blue filters (or user-defined false color bands). In multispectral mode, customized filters are programmed on the DMD, adapt to changing conditions, and quickly switch to new targets. In hyperspectral mode, data cubes are collected for analysis to perform signature discovery, evaluate changing conditions or increase confidence in weak detections. In matched-filter mode, the DMD encodes hyperspectral matched-filter coefficients into each spectral band directly in the optical hardware, providing real-time signature detection. We'll discuss the basic functionality of our MEMS-based programmable spectral filter, show examples from the various operating modes and discuss the synergies that may develop in the field due to the ability to rapidly switch between them.

2. DMD-BASED PROGRAMMABLE SPECTRAL FILTER

DMD arrays have long been viewed as good candidates for inline spectral filters. Early designs for using DMD arrays as a spectral filter were single-pixel applications for fiber communications[13, 14] and spectrometry.[15] More recent designs have expanded this capability to 1-D pixel arrays for pushbroom imaging applications.[16, 17] In each case, the concept is straightforward: light emerging from each source is collimated, dispersed by a grating or prism, and re-imaged on a 1-D array of micro-mirrors (2-D for imaging), forming a spectrally dispersed image of the source. Each mirror (column) in the array controls a different narrow wavelength band, and can be independently addressed or tilted to either of two positions. One position corresponds to the "on" position and directs the light along the optical train while the second position corresponds to the "off" position and directs the light to a beam dump. Light from the "on" mirrors is recombined on a fiber or detector pixel with a lens. The result is a spectrally filtered information stream whose signal S, if directed onto a detector, is the sum of signals from each of the N mirrors:

$$S = \sum_{i=1}^{N} w_i s_i \tag{1}$$

where s_i is the signal due to the radiance in the spectral channel controlled by the i^{th} mirror, and w_i is either "0" if the mirror set to the "off" position or "1" if the mirror is "on". Many DMD arrays are capable of intensity modulation and can deliver a precise fraction of the light in that channel ($0 < w_i < 1$) to the detector. As we'll show below, the capability to modulate the intensity of each spectral band independently enables the MAHI sensor to optically encode matched-filter coefficients into each spectral channel and sum them at the detector.

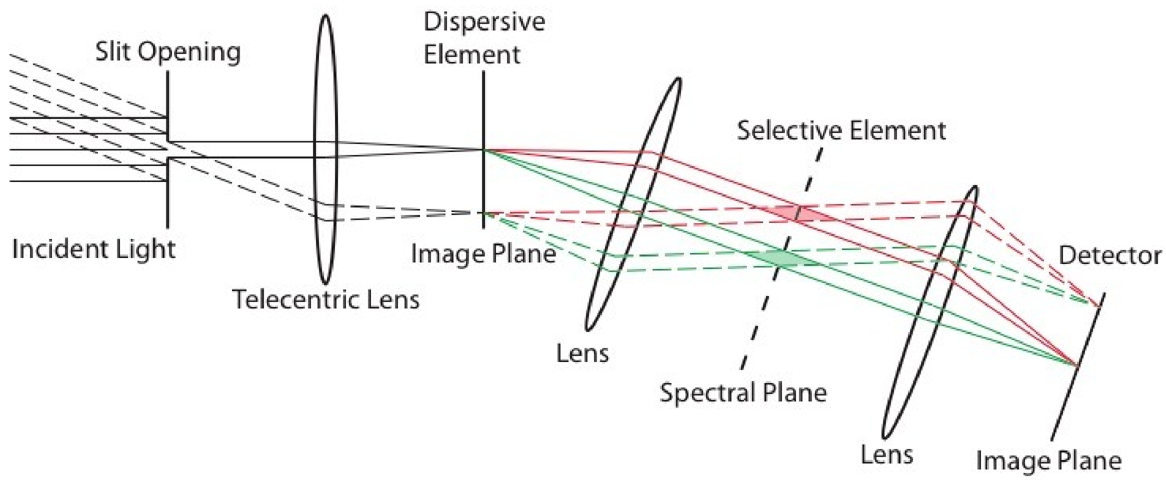

Figure 1. The optical design concept for MAHI's programmable spectral filter. The slit opening and telecentric lens forms a telecentric image on the dispersive element comprised of light bundles travelling parallel to the optical axis. A second lens creates a dispersed image of the slit at a spectral plane and a third lens creates a non-dispersed image of the scene on the detector. Because the spectral information is encoded orthogonal to the spatial information, a spatial light modulator placed at the spectral plane will control the spectral content of the image while preserving the spatial information. MAHI's programmable spectral filter provides complete control over the spectral content of the image. (color in electronic version)

Our current efforts represent the extension of spectral filtering to a 2-D array of pixels for full-frame imaging.[11] MAHI's programmable spectral filter is based on a new optical design concept that enables the simultaneous spectral filtering of the entire 2-D scene without disturbing the underlying image formed at the camera. The central insight, depicted in Fig.1, is that by moving the dispersive element from its traditional position in a collimated pupil plane to an image plane it becomes possible to isolate the spatial scene information in the spatial domain while the spectral information is encoded into the light field angles (orthogonal to the image). If the image is formed such that the angles of incidence at the dispersive element for each source are all nearly parallel to the optical axis, the spectral encoding for each source will be nearly identical and the spectral information can be focused at a spectral plane where modifications to the spectral content of the image will not impact underlying image.

The DMD-based working prototype of the MAHI sensor is pictured in Fig. 2 and incorporates a series of apertures and lenses in a telecentric configuration to maintain parallel light throughout the system. It is capable of collecting 127-channel hyperspectral data cubes in the visible spectral region (390 – 740 nm) with a spectral resolution of approximately 8.3 nm and was used to demonstrate each of the operating modes discussed here. Light enters the system through a slit aperture in the Entrance Pupil and is imaged by Lens Group 1 on the transmission grating. Lens Group 2 focuses the dispersed spectral light emerging from the grating at a spectral plane containing the DMD selector. The spectrum is arrayed in 1-D columns of constant wavelength and spectral filtering is accomplished by programming the DMD selector to turn "on" and "off" vertical columns of mirrors (see inset images in Fig. 2). Following the DMD selector array, reimaging optics recombine the spectral information pixel-by-pixel on a COTS camera, reforming the filtered image. The resulting device is a programmable, multiband spectral filter that provides complete control over the spectral content of the image formed by the COTS camera.

The prototype shown in Fig. 2 incorporates two DLP® arrays, one for spectral filtering and a second to compensate for the dispersion introduced into the image by the first. Compensation is required for the DLP® array because in this configuration, it acts more like a "switched blazed grating" than an array of individual mirrors. Compensation is most easily performed by including a second, identical device with a unit magnification relay between them in the design. This requirement for compensation affects the overall transmission function of the filter, as the efficiency of the compensation can be highly variable across the spectral bandwidth (see Ref. 11 for details).

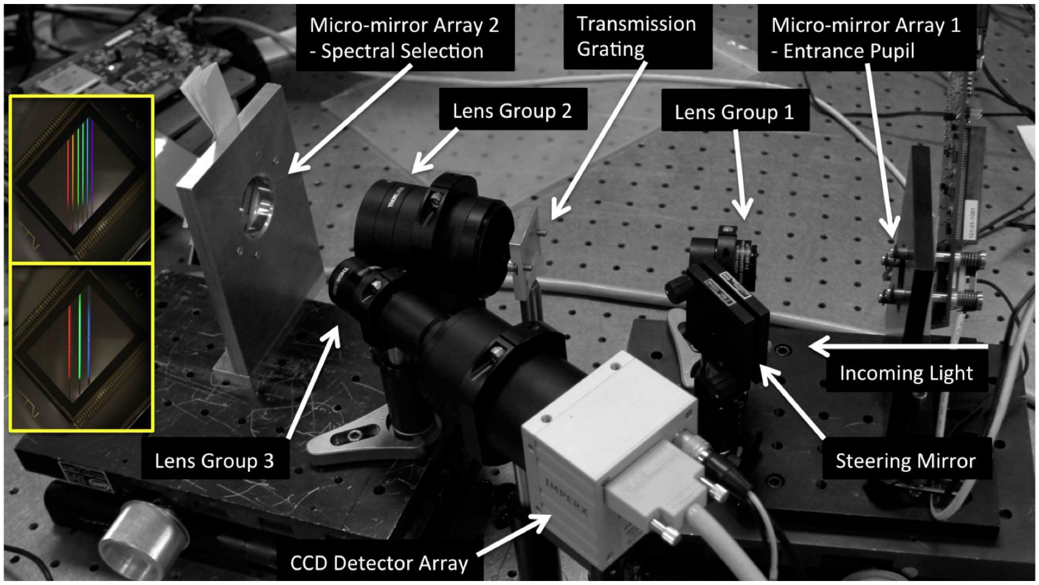

Figure 2. Photograph of the working MAHI prototype incorporating a pair of DLP® micro-mirror arrays. The first array serves two purposes, providing programmable control over the telecentric aperture and compensation for dispersion introduced at the selector. The second array serves as the programmable spectral filter, providing precise amplitude control for each of its 127 spectral channels (see inset photos for example multi-band filters). The MAHI prototype has demonstrated broadband, color, multispectral, hyperspectral and matched-filter imaging. (color in electronic version)

3. ADAPTIVE HYPERSPECTRAL IMAGING

Cell phones take more photos today than point and shoot cameras because people carry them everywhere they go. Similarly, a multifunctional spectral imaging sensor may open up new applications for spectral imaging simply by being there when opportunities present themselves. By providing complete control over the spectral content of the images it acquires, the MAHI sensor is capable of acquiring traditional broadband and color imagery, multispectral and hyperspectral imagery, and matched-filter imagery, adapting in the field to new applications at the touch of a button.

3.1 Broadband and Color Imaging

The heart of the MAHI sensor is a programmable spectral filter that controls the spectral content of the image acquired with a COTS broadband camera. In broadband imaging mode, the filter is programmed to pass every band unaltered and the camera acquires panchromatic images. If desired, intensity modulation can be employed to “white balance” the system for a flat spectral response. Broadband imaging mode can be used to provide important context images for the spectral imaging applications discussed below and might serve as the primary operating mode for a persistent monitoring application that needs a sensor to collect spectral information only sporadically.

Color images are often preferred over panchromatic, black and white images, as the addition of spectral information often makes them easier to interpret. Producing color images with the MAHI spectral filter is straightforward; a series of three images are acquired with broadband red, green and blue filters programmed on the DMD and a composite RGB image is created in software. This process is similar to the Bayer mosaic filter method for creating RGB images in commercial cameras, where a physical filter array converts each detector pixel into a single color detector. Though the Bayer method only requires a single exposure to create color images, it lacks the spectral flexibility of MAHI to create custom false color filter sets. An example of what this flexibility provides is shown in Fig. 3, where false color methods for vegetation detection are demonstrated on a scene created in our laboratory. Here, a live plant and a brightly colored printed image are imaged with both a RGB filter set and a Color InfraRed (CIR) filter set to differentiate the vegetation from the inks of similar color. Switching between the filter sets is fast and both images can be acquired at video rates with no downtime between them. Other false color applications might utilize a set of three multispectral satellite bands or an application-specific set of spectral bands. Like broadband imaging, this operating mode can be interleaved throughout a matched-filter acquisition cycle to obtain color context information about a scene during a target-based search. It can also be the primary operating mode for a persistent monitoring application with sporadic spectral needs.

Figure 3. Example images acquired by the MAHI prototype operating in Color Imaging mode. Each image is assembled in software based on the acquisition of three single-band images, RGB (left) and Color Infrared (CIR) (right). The scene features a live plant with green leaves and white features and a brightly colored cardboard box. The addition of the infrared band in the CIR filter helps to discriminate live vegetation from inks with similar color. The programmable nature of MAHI's spectral filter enables customized band selection to highlight features of interest in any application and rapid switching between filters at video rates. (color in electronic version)

3.2 Multispectral Imaging

Multispectral imaging covers the broad range of parameter space that exists between broadband three color imaging and high-resolution hyperspectral imaging, covering both multispectral satellite data (< 10 bands, low resolution) and target specific remote sensing for chemical detection (10's of bands, high resolution). Imaging a scene through a series of band-pass spectral filters specific to the strong spectral features of a target material will highlight the presence of the target through either a diminished response due to molecular absorption or an enhanced response due to molecular emission or surface reflectivity. Collecting scene information from only the spectral bands needed for adequate discrimination not only greatly reduces the required number of measurements and associated data volume but also simplifies the processing steps required for detection. In each case, *a priori* knowledge about the spectral properties of the phenomena or signature of interest lessens the need for the complete spectral knowledge of the scene provided by hyperspectral methods and enables wide field of view detection. While this promise has led to a significant amount of work to design band-optimized filter sets for target-specific remote sensing applications,[18-20] designing realistic multispectral sensors can be difficult due to a lack of tunable, high-resolution optical filters. Further, the most effective filter sets typically require many tens of spectral band measurements that are closely spaced to take advantage of on-band/off-band combinations. The complexity and data volume of such an instrument, requiring repeated measurements (one per spectral band) and longer integration times to deal with the increased noise of narrow-band imaging, quickly limit the advantages of such a sensor over the traditional HSI approaches.

The MAHI sensor has number of advantages over previous efforts to design multispectral instruments based on filter wheels or filter arrays. First, the programmable nature of the filter provides band center and bandwidth flexibility to the filter designer, eliminating the restrictions of off- the-shelf or custom made filters and enables in-field changes to the filter sets as conditions or targets change. Second, there is no limit to the number of spectral bands that the system can acquire, scaling seamlessly from panchromatic to HSI-level coverage. Third, the ability to image through multiple bands simultaneously mitigates the signal to noise penalty associated with narrow-band imaging through the application of Hadamard multiplexing methods. Hadamard basis functions are linear combinations of spectral bands whose measured values can be inverted to recover the contributions of individual bands. Each Hadamard function contains roughly half of the spectral bands in the set, dramatically increasing the amount of light that falls on the detector, and it can be shown that for an N-band detector-noise-limited system, one can realize a factor of $\sqrt{N}$ improvement in signal to noise compared to single-band collection.[16] Finally, as we'll discuss below, intensity modulation at the DMD enables the direct measurement of common matched-filter detection functions, which skips the data cube collection entirely and performs the multispectral data analysis directly in the optical hardware.

An example of a multi-band, matched filter image acquired with the MAHI sensor is shown in Fig. 4, where two multi-band spectral filters were constructed to discriminate between two light sources, a broad spectrum incandescent light bulb and a Compact Fluorescent Lamp (CFL) light bulb whose spectrum is dominated by the discrete, mercury vapor emission spectrum. Each filter set was custom designed for bandwidth and band center to match either the peaks of the CFL spectrum or the integrated intensity of the incandescent spectrum for background subtraction. Two images were acquired, one each for the positive filter bands and the negative, and differenced to highlight the presence of the target (CFL) and suppress the background (incandescent). The difference image suppresses the incandescent signal sufficiently to detect the weak reflection of the CFL from its glass surface. The simple five-band filter, however, is challenged by the strong side-to-side brightness variation across the incandescent bulb, and can't fully suppress the brighter side.

3.3 Hyperspectral Imaging

Hyperspectral imaging sensors are often referred to as "imaging spectrometers," as they are designed to acquire complete, high-resolution spectra for every pixel in an image. Armed with complete spatial/spectral information, HSI processing algorithms are able to make highly sensitive and selective detections of known spectral signatures embedded in spectrally cluttered backgrounds. There are two main ways to measure a three-dimensional data cube with a two-dimensional detector array: measuring the spectra of one line of the scene at a time while scanning across the second dimension (e.g., pushbroom imaging) and repeatedly imaging the entire scene while varying the spectral content in a known, and invertible, way (e.g., Fourier Transform imaging). As discussed above, the MAHI spectral imager takes the second approach, scaling its data cube acquisition with a Hadamard basis function to HSI resolution and numbers of bands. Collecting HSI data cubes with MAHI still requires scanning, in this case scanning over the N Hadamard functions required to invert the N-band spectrum, and the time investment compared to multispectral methods can be significant. However, the ability to switch into HSI mode and collect a complete spectral data cube may be necessary to adapt multi-spectral or matched-filter functions to changing conditions in the field (e.g. light levels, atmosphere, etc.).

An example of a hyperspectral image acquired with the MAHI sensor using the Hadamard Transform technique is shown in Fig. 5, where a panchromatic image of the multispectral test scene from Fig. 4 is displayed, alongside the measured 127-band spectrum for each source. Each pixel in the image contains the continuous spectrum acquired from that scene element and selected pixels were averaged in a small region of interest to acquire the displayed spectra. The incandescent light bulb spectrum displays the continuous spectrum expected of a thermal source and also shows the effect of the filter response function that arises from the wavelength-dependent efficiency of the dispersion correction. The CFL spectrum displays the strong discrete-line emission spectrum of the mercury vapor-based fluorescent bulb, which will be exploited below in the next section to discriminate between the two sources.

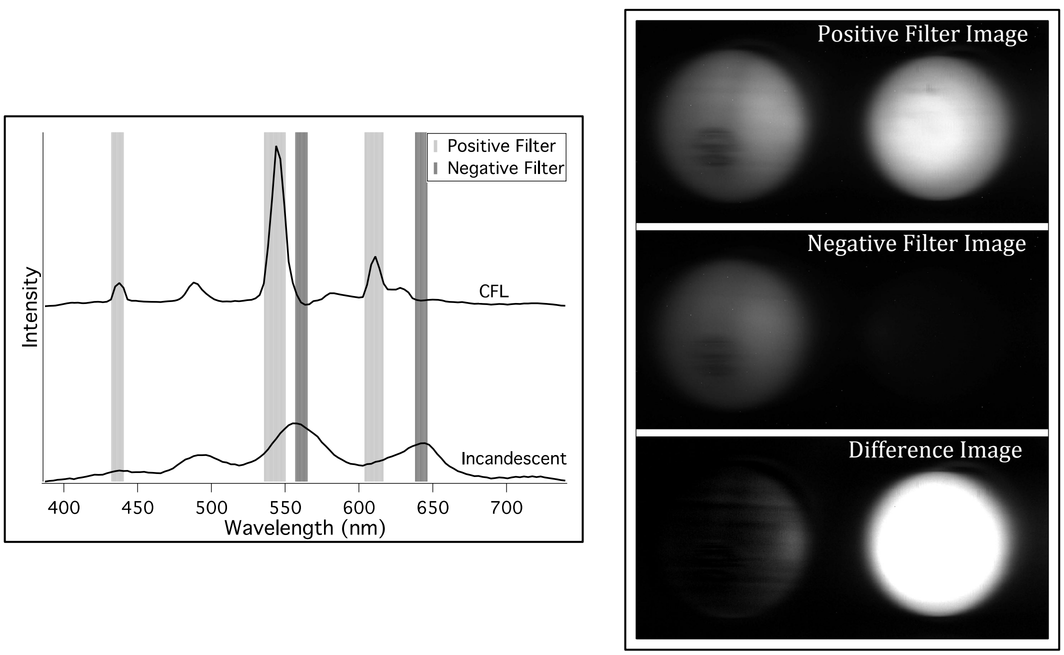

Figure 4. Example of the MAHI prototype operating in Multispectral Imaging mode. The five-band, multispectral filter set designed to discriminate between a continuous spectral source (incandescent light bulb) and a discrete spectral target (compact fluorescent lamp) is superimposed on the measured spectral response functions for each source (left). The three images display the acquired positive image (top) consisting of contributions from the three strongest features in the target spectrum, negative image (middle) consisting of two bands designed to equalize the signal from the incandescent light bulb in each image and computed difference image (bottom), which has been enhanced to highlight the faint reflection of the CFL in the glass of the incandescent light bulb. The programmable spectral filter provides enormous flexibility in both defining the spectral bands required for a given application and adapting them in the field to changing conditions.

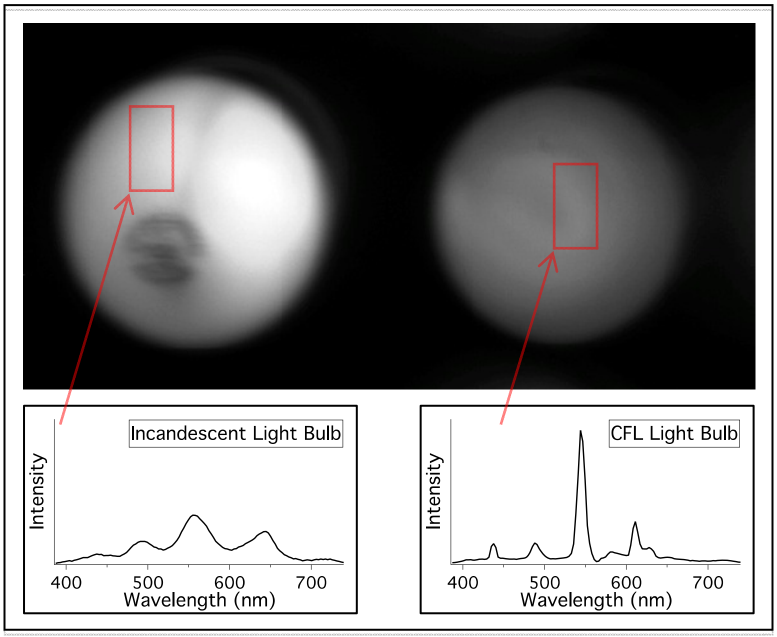

Figure 5. Example of the MAHI prototype operating in Hyperspectral Imaging mode. The panchromatic image displays the test scene consisting of a 100-Watt incandescent light bulb (left) and a 40-Watt equivalent Compact Fluorescent Lamp (CFL) light bulb. Each pixel in the image contains a high-resolution spectrum acquired by the Hadamard Transform method: 127 spectral channels spanning 390 – 750 nm with a spectral encoding resolution of 8.3 nm and a sampling frequency of 3.3 nm. The displayed spectra are pixel averages over a region of interest depicted by the red rectangles. The incandescent signature displays a continuous spectrum expected of a thermal source and the CFL spectrum is dominated by the discrete mercury vapor emission spectrum. Each shows the effects of the spectral response function of the DMD-based spectral filter (see Ref. 11 for details). Operating in this mode provides complete spatial/spectral knowledge of a scene, which can provide confidence to weak detections made in other modes or provide important information on how to adapt those modes to changing conditions.

3.4 Matched-filter Imaging

Spectral imaging sensors typically do not measure spectral properties, perform target detection or fulfill any of the other objectives commonly ascribed to spectral imaging as a method. Instead the spectral imaging sensor is tasked to collect the data required by algorithms and other processing routines to elicit that information. The MAHI sensor, however, is capable of performing some of these tasks directly in the optical hardware.[12] A popular method for spectral target detection in both multispectral and hyperspectral data is to construct matched-filter detector functions, which are weighted sums of the spectral bands that discriminate the target signature from the spectral clutter background. Sophisticated algorithms are typically employed to first analyze the data cube and then calculate the optimal weighing function for each target signature to apply to each pixel spectrum, **s**,

$$MF(\mathbf{s}) = \sum_{i=1}^{N} q_i s_i \tag{2}$$

where the vector coefficient q_i is normalized to range between $-1 < q_i < +1$, and a higher score indicates a stronger match between the pixel spectrum and the target signature. Comparing Eqs. (1) and (2) suggests that given a detection function determined either *a priori*, based on previous experience, or simply guessed, the MAHI sensor can be programmed to directly measure the matched-filter detection functions by encoding the coefficients, q_i into each spectral channel prior to summing the bands at the detector. This capability enables the MAHI sensor to conduct real-time target detection across a 2-D field of view, at both multispectral and hyperspectral scales and at speeds limited only by the performance of the imaging camera. In most cases, matched filter images can be superimposed on real-time color context images or video.

An example of a matched-filter image acquired with the MAHI visible prototype sensor is shown in Fig. 6, where the 127-channel hyperspectral data cube shown above was analyzed to calculate the optimized Adaptive Matched Filter

(AMF) function for discriminating between the two light bulbs in the scene. The AMF coefficients, q_i are shown at left, indicating how much weight each band received in the summation and the resulting matched filter image is shown at right. The positively and negatively weighted bands were recorded separately and differenced to produce the matched-filter image and a detection threshold based on background statistics was applied to every pixel to produce the threshold map. Suppression of the incandescent bulb signal is markedly improved compared to the five-band example in Fig. 4, enabling weaker CFL reflections, including those from the socket surfaces behind the bulbs, to be detected.

This method will necessarily be less sensitive than the traditional HSI processing algorithms that optimize the detection functions for each individual data cube, but will operate in real-time, produce far less data and cover the entire field of view every two exposures (cycling through multiple filters enables multi-target searches). MAHI's multifunctional nature also creates an opportunity to further interrogate a weak detection to provide important clues as to whether an alarm is likely to be real or false. Periodic data cube acquisition provides an opportunity to re-optimize or adapt detection filters to changing conditions. Confidence may also be improved by incorporating context imagery or acquiring more detailed multispectral or hyperspectral data cubes for in-depth analysis.

4. SUMMARY

Rapidly programmable spatial light modulation devices based on MEMS technology have opened an exciting new arena in spectral imaging: rapidly reprogrammable, high spectral resolution, multi-band spectral filters that enable hyperspectral processing directly in the optical hardware of an imaging sensor. We have demonstrated this new concept for spectral imaging with the MEMS-based Adaptable Hyperspectral Imaging (MAHI) sensor developed at Los Alamos National Laboratory. The MAHI sensor gives the user complete control over the spectral content of final image and enables the acquisition of spectral images with broadband COTS cameras. This sensor is capable of operating in a number of imaging modes, including broadband and color imaging, multispectral and hyperspectral imaging and multi-band matched-filter imaging. This new approach toward spectral imaging should have broad appeal to users who want to add spectral capabilities, including real-time spectral target detection to existing imaging applications.

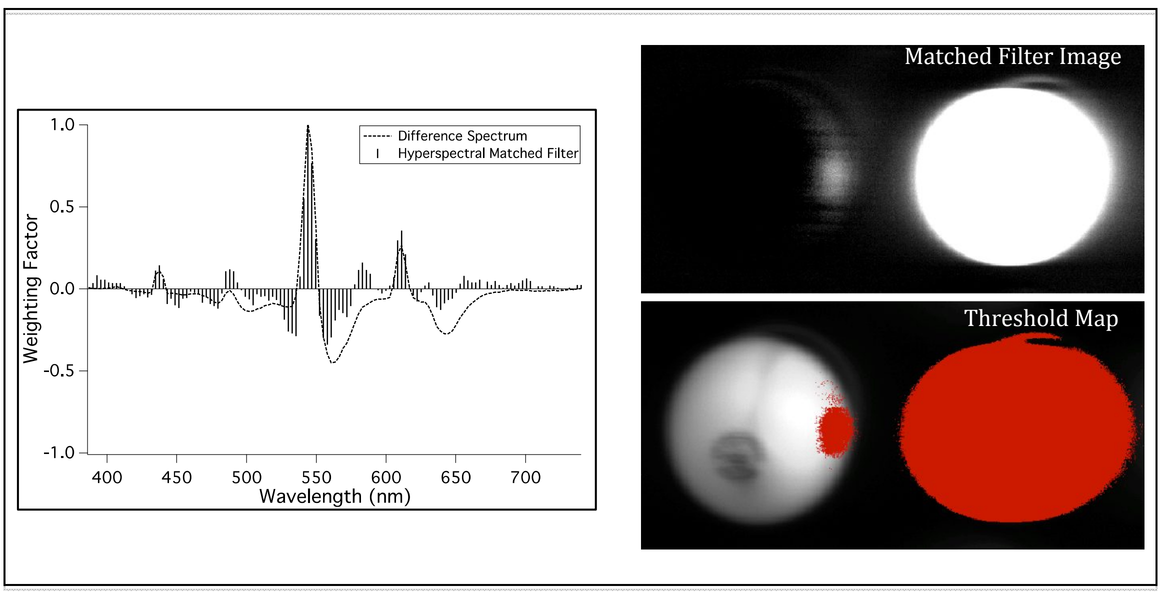

Figure 6. Example of the MAHI prototype operating in Matched-filter Imaging mode. The hyperspectral matched-filter (left) is an example of an Adaptive Matched Filter (AMF) detection function designed to discriminate between light originating from a Compact Fluorescent Lamp (CFL) and light from a broadband source (incandescent light bulb). Each spectral band in the 127-band data cube is given a weighting factor that the DMD encodes into the optical field prior to reimaging. Positive and negative weights are acquired in separate images and differenced to produce the matched filter image. The threshold image is produced by applying a detection threshold based on background statistics to the value of each pixel in the matched-filter image. By applying a full-spectrum matched-filter, the reflection seen in Fig. 4 is more efficiently separated from the brightness variations in the background source. Operating in Matched-filter mode, the MAHI sensor directly measures a matched-filter detection function in the optical hardware, providing real-time detection.

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