Metrologia **43** (2006) S61–S65 doi:10.1088/0026-1394/43/2/S13

Hyperspectral image projectors for radiometric applications

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Received 20 October 2005
Published 23 March 2006
Online at stacks.iop.org/Met/43/S61

Abstract
We describe a Calibrated Hyperspectral Image Projector (CHIP) intended for radiometric testing of instruments ranging from complex hyperspectral or multispectral imagers to simple filter radiometers. The CHIP, based on the same digital mirror arrays used in commercial Digital Light Processing[1] (DLP) displays, is capable of projecting any combination of as many as approximately one hundred different arbitrarily programmable basis spectra per frame into each pixel of the instrument under test (IUT). The resulting spectral and spatial content of the image entering the IUT can simulate, at typical video frame rates and integration times, realistic scenes to which the IUT will be exposed during use, and its spectral radiance can be calibrated with a spectroradiometer. Use of such generated scenes in a controlled laboratory setting would alleviate expensive field testing, allow better separation of environmental effects from instrumental effects and enable system-level performance testing and validation of space-flight instruments prior to launch. Example applications are system-level testing of complex hyperspectral imaging instruments and algorithms with realistic scenes and testing the performance of first-responder cameras under simulated adverse conditions. We have built and tested a successful prototype of the spectral engine, a primary component of the CHIP, that generates arbitrary, programmable spectra in the 1000 nm to 2500 nm spectral range. We have also built a spectral engine operating at visible wavelengths to be discussed in a separate publication. Here we present an overview of this technology and its applications and discuss experimental performance results of our prototype infrared spectral engine.

1. Introduction

A general problem in radiometric characterization and calibration is that the instrument under test is not easily tested with realistic spatial and spectral scenes that resemble those to which it will be exposed during its use. For example, a typical Earth-observing space-flight instrument is calibrated pre-flight with a spatially uniform source such as a lamp-illuminated integrating sphere or a blackbody. The spectral radiance of such sources is often quite different from that of the Earth scenes which the instrument measures in orbit, but effects arising from these differences are not often discovered until after the launch. While proper incorporation of the relative spectral responsivity of the IUT into the calibration can, in principle, be used to correct spectral radiance differences, in practice, effects such as out-of-band leakage from the calibration source used during calibration (that does not match the Earth scene) still plague many instruments. As multispectral and hyperspectral instruments become more common, so will this problem.

A related problem occurs when testing sensors used in other application areas such as chemical plume detection, in-car video or fire-fighter thermal imaging. In the latter case, for instance, performance testing of the IUT under realistic conditions often requires starting fires in order to generate the

[1] References are made to certain commercially available products in this paper to adequately specify the experimental procedures involved. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology nor does it imply that these products are the best for the purpose specified. DLP and DMD are trademarks of Texas Instruments, Inc.

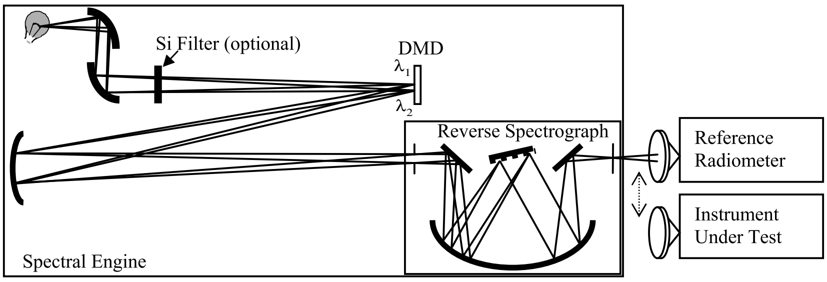

Figure 1. Basic scheme of the SWIR spectral engine in reverse spectrograph mode. Two ray bundles are traced, one for λ_1 and the other for λ_2.

required spectral radiance images, and assessing performance under conditions where smoke, snow and fog are in the path is even more challenging.

We describe below a new image projection technology that has the potential to solve these problems by generating realistic spectral radiance images that can be projected into the IUT in a controlled laboratory setting.

The basic concept is to use a mirror array such as that used in DLP projectors to project a simulated image. However, in place of the red–green–blue (RGB) colour wheel, we use a spectral engine, described below, which is also based on another, separate mirror array. The resulting spectral and spatial content of the image presented to the IUT can simulate, at typical video frame rates and integration times, realistic scenes to which the IUT will be exposed during use. Also, the spectral radiance of the CHIP can be measured with an absolute spectroradiometer, providing calibration.

First we describe the concept of the spectral engine. Next we describe our concept for using a spectral engine at the heart of the CHIP. Then we provide a more detailed description of a short-wave infrared (SWIR) prototype spectral engine, reporting our experimental results to date.

2. Spectral engine

At the heart of the spectral engine is a spatial light modulator. For the results in this paper we use a digital micromirror device (DMD), which is a commercially available computer-interfaced mirror array having 1024 columns × 768 rows. The aluminium mirrors that make up the DMD are on a 13.68 µm pitch. Each mirror tilts on a hinge and can be set to be either 'on', reflecting light to the projection optics, or 'off', reflecting light to a beam dump [1]. Switching times are such that binary images can be updated at a frequency of the order of 5 kHz. Driver electronics are now available to take advantage of the high speed of the DMD [2].

If a broadband light source is spectrally dispersed across the DMD with a grating or prism, such that each column is illuminated by a different wavelength, a programmable output spectrum can be generated by turning on the DMD mirrors corresponding to the desired wavelengths and spatially integrating the output. This would constitute a forward spectrograph configuration of the spectral engine, in which each column of the DMD acts as a virtual exit slit, as was done in some visible-band prototypes [3, 4].

Alternatively, one could reverse the order of the DMD and the spectrally dispersive element, as depicted in figure 1. Here the grating maps each column of the DMD to the real exit slit, in a reverse spectrograph configuration, such that each column corresponds to a particular wavelength. A double-pass version of this has been proposed [5], which has a feature in which the required spatial re-integration occurs on the second pass. In our simplified version, depicted in figure 1, the entrance slit of the traditional spectrograph is replaced by an image of the DMD, and each column of the DMD corresponds to a virtual entrance slit that has a one-to-one correspondence with wavelength.

At any instant in time, the number of mirrors turned on in a given column determines the relative spectral radiance at the wavelength corresponding to that column. Thus, the spectrum can be programmed simply by writing a binary image to the DMD. Higher fidelity (than 1/768) is conceivable by using pulse-width modulation (PWM) on the mirror array to form a grey scale. However, depending on how it is implemented, PWM may begin to use up the degree of freedom afforded by the time domain that is needed for the full CHIP described in the next section. The resulting spectral radiance is projected alternately into the IUT and a reference radiometer, enabling the calibration of the IUT to be tested and validated with controlled arbitrary spectra.

3. Calibrated hyperspectral image projector

The concept for the full CHIP is shown in figure 2. It uses two DMDs optically in series. DMD1 is used in the spectral engine to generate arbitrary programmable basis spectra. DMD2 forms the heart of the spatial engine and is illuminated by the spatially uniform, spectrally structured light from the spectral engine. The spatial image programmed into DMD2 is projected into the IUT. Alternatively, the output is projected onto the reference radiometer for spectral radiance calibration. For an IUT frame rate of 50 Hz, the 5000 Hz binary update frequency of the spectral engine means that it can cycle through about 100 basis spectra within the single-frame integration time of the IUT. The duty cycle that a given mirror (image pixel) of DMD2 spends in the 'on' state during the 'on' time of a particular basis spectrum determines, during that frame, the fractional component of that basis spectrum projected from that image pixel, effectively forming a grey scale. Thus, different programmable spectra can be projected into each spatial pixel of the IUT.

A key difference from the commercial DLP projectors is that, whereas those are limited to the three RGB basis functions defined by human perception of colour, the CHIP can have up to about 100 basis functions limited only by the spectral

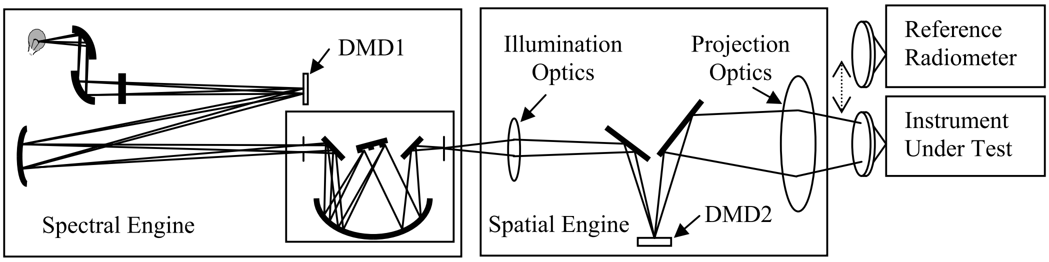

Figure 2. Concept for using a spectral engine in a Calibrated Hyperspectral Image Projector.

range and resolution of the broadband source, DMDs and optics. Thus, realistic hyperspectral images can be projected into the instrument under test. In addition, between each IUT frame cycle, the hyperspectral image can be changed, enabling dynamic testing capability.

4. Prototype SWIR spectral engine

At this point in the CHIP development we have constructed two prototype spectral engines, one operating in the SWIR spectral range in the reverse spectrograph configuration of figure 1 and the other in the visible spectral region in a forward spectrograph configuration [4]. Here we describe the SWIR prototype. A 100 W quartz tungsten halogen lamp was used as the source. A telescope consisting of two off-axis parabolic mirrors imaged the lamp filament onto the DMD, though the filament image was defocused in an attempt to provide a somewhat spatially uniform illumination of the DMD. A silicon filter placed between the source and the DMD was used to block the visible and near-infrared radiation, providing broadband illumination in the SWIR.

The DMD used was the Texas Instruments[1] 0.7 DDR XGA. This consists of an array of 1024 columns × 768 rows of square aluminium-coated mirrors, hermetically sealed behind a glass window. The window had an anti-reflection coating that was specified to provide single-pass transmittance greater than 94% from 1000 nm to 2000 nm, falling to 70% by 2500 nm. The DMD was mounted on a printed circuit board along with commercially available drive electronics that enabled binary images to be loaded onto the DMD from a personal computer (PC) using a universal serial bus (USB) interface.

A single-grating commercial monochromator was used in reverse spectrograph mode: the entrance slit of this monochromator was removed but its exit slit was retained. An off-axis spherical aluminium mirror imaged the DMD onto the spectrograph entrance aperture such that the DMD image width just overfilled the approximately 15 mm wide entrance aperture of the spectrograph. In monochromator operating mode, when the DMD image is a vertical strip, the image at the spectrograph entrance aperture is that of a virtual entrance slit, and through the spectral selectivity of the diffraction grating with the real exit slit, provides a single wavelength. Tuning of the wavelength is achieved by moving the horizontal position of this virtual entrance slit by simply writing a new, horizontally displaced vertical strip image to the DMD, as will be demonstrated below. Thus there is a one-to-one correspondence between each DMD column and the resulting wavelength. The number of row elements turned on in each column determines the height of the virtual entrance slit, and hence the relative spectral radiance at that wavelength. In the more general operating mode, by writing what we call a 'spectral image' to the DMD in which mirror elements from many columns are turned on, many wavelengths are included in the output spectra.

5. Use of an FTIR to measure projected spectra

The output from the exit slit was projected into a commercially available Fourier-Transform Infrared (FTIR) spectroradiometer using a thermoelectrically cooled InGaAs detector to measure the spectra. This instrument can be thought of as the absolute reference radiometer depicted in figures 1 and 2, though in our initial experiments we concentrated only on relative spectral measurements, and we omitted the IUT.

For all spectra discussed in this paper, three different interferograms were collected, each with a different image displayed on the DMD: all mirrors on (1), all mirrors off (0) and the spectral image (ν). For calibration, we then used a modified version of equation (12) from [6], using all-mirrors-on and all-mirrors-off spectra in lieu of the usual hot blackbody and cold blackbody spectra, respectively. Specifically, $\tilde{F}_1$, $\tilde{F}_0$ and $\tilde{F}_\nu$, representing the complex fast Fourier transforms of each of the three interferograms, respectively, were combined according to

$$L_\nu = \mathrm{Re}\left[\frac{\tilde{F}_\nu - \tilde{F}_0}{\tilde{F}_1 - \tilde{F}_0}\right], \qquad (1)$$

to arrive at the reported scene spectrum, L_ν. Because of the use of all-mirrors-on and all-mirrors-off spectra instead of the calibrated source spectra, the resulting spectra reported here are not calibrated in terms of absolute radiance but are only intended at this point to show relative spectral radiance. Unless stated otherwise, all spectra were taken with the FTIR interferometer set to a resolution of 16 cm^{-1}.

6. Spectral calibration and resolution

When the DMD spectral image is a vertical strip consisting of only one or a few adjacent columns on, with all other columns off, narrow line spectra are obtained as shown in figure 3. In this figure, each spectrum was taken with a 10 column wide vertical strip as the DMD image. Eight spectra are shown, each corresponding to turning on a different set of columns. A plot of the peak wavelength for each spectrum versus the corresponding DMD strip central column number is shown in figure 4. A linear fit of the wavelength versus column

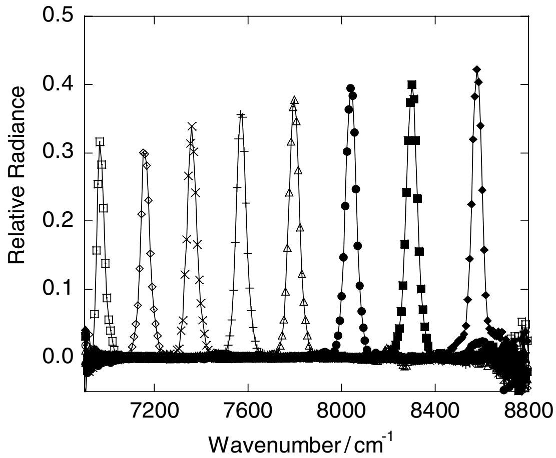

Figure 3. Spectra used for wavelength calibration.

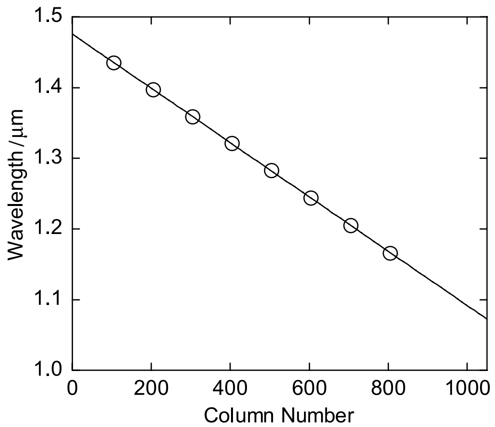

Figure 4. A plot of peak wavelength of the spectra of figure 3 versus the corresponding DMD strip central column number, along with the linear fit used for wavelength calibration.

number relationship from figure 4 constitutes the wavelength calibration.

Spectra were measured using different widths of the vertical strip, ranging from 1 column to 40 columns. This is analogous to varying the entrance slit width in a monochromator. The full width at half maximum of all spectra in this vertical strip width range was about 50 cm^{-1} (8 nm) at a frequency of 7800 cm^{-1} (wavelength of 1282 nm) and was independent of the strip width. Spectra from a vertical line DMD spectral image consisting of only a single column are shown in figure 5. Spectra collected with two different FTIR resolution settings, 16 cm^{-1} and 1 cm^{-1}, gave the same spectral width of 50 cm^{-1}. The measured 8 nm limiting resolution is set by the particular 125 mm focal length spectrograph used, as 8 nm is the spectral resolution computed from the product of the 280 mm exit slit width and the reciprocal linear dispersion of the 300 lines mm^{-1} diffraction grating.

Note that routine spectral radiance measurement from the spectral engine may not necessarily require an expensive, absolutely calibrated spectroradiometer. If the sum of radiance measurements from a set of component monochromatic spectra can be shown to agree with the spectral radiance measurement from a full spectrum, then a simple detector can be used to measure the spectral radiance by cycling

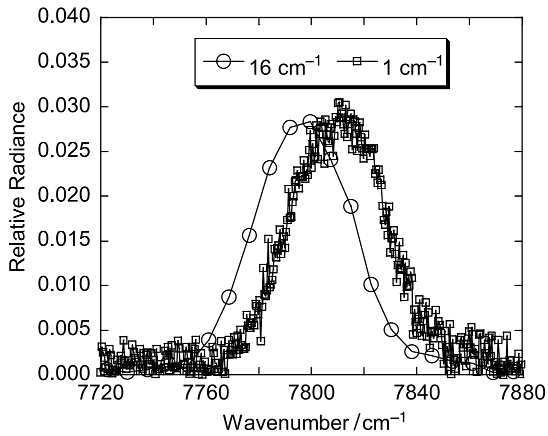

Figure 5. The spectrum from a vertical line DMD image consisting of only a single column, using two different FTIR resolutions.

through the component spectra and then adding these up numerically. This 'sum-of-components' method requires only a broadband detector, as opposed to a relatively expensive spectroradiometer.

7. Example of a generated spectrum

We have developed software that generates the binary spectral image that corresponds to an arbitrary target spectrum. The target spectrum is input from a spreadsheet file, peak normalized, then resampled as necessary to place it on the wavelength grid of the 1024 DMD image columns. Then the linear wavelength calibration as determined above is applied. While it is also possible, in principle, to apply an intensity calibration to correct the spatial non-uniformity of the illumination source at the DMD, it was not done for the data reported here. Rather, it was simply assumed that the relative intensity at a given wavelength, corresponding to a given DMD column, is proportional to the number of mirrors (from 0 to 768) turned on in that column. Figure 6 shows an example target spectrum. Figure 7 shows the corresponding binary spectral image computed by our software. Note that the binary spectral image is symmetric about a horizontal line drawn through its centre. This is to take advantage of the symmetry of the illumination source, which, though not necessarily very uniform in our prototype, is generally aligned such that it is centred on the DMD.

Displaying the image of figure 7 on the DMD resulted in the measured spectrum shown in figure 6, which is plotted along with the original target spectrum. There is a good match to the wavelength and the general features of the relative intensity. However, there are errors of several per cent in the relative radiance, resulting from the lack of relative intensity calibration.

After implementing relative intensity calibration, future work will involve interfacing the spectral image production software with the FTIR spectra measurement software, enabling the addition of feedback to iteratively adjust the displayed DMD image to result in better matches to the target spectra.

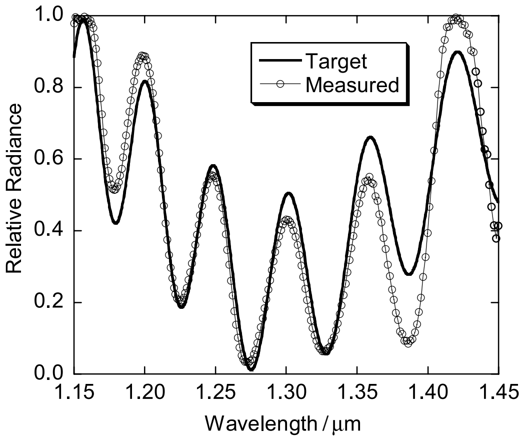

Figure 6. An example target spectrum (——), plotted with the resulting measured spectrum (—○—) from the SWIR spectral engine.

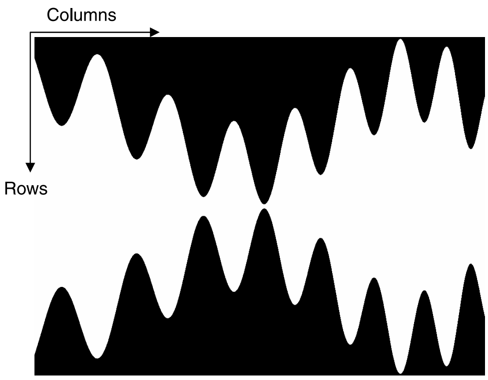

Figure 7. The binary spectral image written to the DMD in the SWIR spectral engine that resulted in the measured spectrum of figure 6. For a display of such images on the DMD, white regions map to 'on' mirrors and black regions map to 'off' mirrors.

8. Conclusion

We have described the concept of a spectral engine to provide a programmable spectral source that can be calibrated and have discussed how a CHIP could be made using such a spectral engine. We then described the design and initial results from a prototype SWIR spectral engine. With continued development, this technology appears capable of enabling validation testing of a variety of spectroradiometric instruments with realistic spectra and, eventually, with simulated hyperspectral images.

Acknowledgments

This prototype was built and tested with support from the NIST Advanced Technology Program. We thank Jerry Fraser, Anthony Hamins and Francine Amon of NIST for useful discussions of applications.

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