Hyperspectral Image Projectors for Radiometric Applications

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Abstract. We describe a new type of 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 projector* (DLP) displays, is capable of projecting any combination of as many as approximately one hundred different arbitrarily programmable basis spectra 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 instrument effects, and enable system-level performance testing and validation of space-flight instruments prior to launch. Example applications are testing the performance of simple fighter-fighter infrared cameras under simulated adverse conditions, and system level testing of complex hyperspectral imaging instruments and algorithms with realistic scenes. We have built and tested a successful prototype of the spectral light engine, a primary component of the CHIP, that generates arbitrary, programmable spectra in the 1000 nm to 2500 nm spectral range. We present an overview of this technology and its applications, and discuss experimental performance results of our prototype spectral light engine.

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 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 than that of the Earth scenes that the instrument measures on orbit, but effects arising from this difference are not often discovered until after launch. While proper incorporation of the relative spectral responsivity of the IUT into the calibration can, in principle, be used to correct for 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 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 required spectral radiance images, and testing operation under conditions of smoke, snow, and fog in the path is even more challenging.

Below we describe 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 those used in DLP projectors to project a simulated image. However, in place of the red-green-blue (RGB) color wheel, we use a spectral light engine described below that is also based on another, separate mirror array. 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. Also, the spectral radiance of the CHIP can be measured with an absolute spectroradiometer, providing calibration.

Spectral Light Engine

For the prototype spectral light engine we used a commercially-available computer-interfaced mirror array having 1024 columns × 768 rows illuminated with broadband spatially uniform light as shown in Fig. 1. The tiny mirrors that make up the mirror array are on a 13.6 micrometer pitch. When powered, each aluminum mirror can be set to be either “on,” reflecting light to the projection optics, or “off,” reflecting light to a beam dump (Hornbeck). Switching times are such that binary images can be updated at a frequency on the order of 5000 Hz.

A spectrally dispersive prism (or diffraction grating) maps each column of the mirror array to the exit slit, in a reverse spectrograph configuration, such that each column corresponds to a particular wavelength (Nelson et al.). That is, the entrance slit of the traditional spectrograph is replaced by an image of the mirror array, and each column of the mirror array corresponds to a virtual entrance slit that has a one-to-one correspondence with wavelength. At any instant in time, the number of rows 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 mirror array. Higher fidelity (than 1/768) is conceivable by using pulse-width modulation on the mirror array to form a grey scale. However, depending on how it is implemented, that 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 alternately projected into the instrument under test and a reference radiometer, enabling the calibration of the instrument under test to be tested with controlled arbitrary spectra. In our prototype, we used a mirror array with a protective window antireflection coated in the 1000 nm to 2500 nm range, a grating, all-reflective aluminum and gold imaging optics, and a Fourier-Transform Infrared (FTIR) spectroradiometer with an InGaAs detector to measure the spectra. By writing different binary images to the mirror array, we were able to produce different spectra, as expected.

Calibrated Hyperspectral Image Projector

The concept for the complete CHIP is shown in Fig. 2.

It uses two mirror arrays, optically in series. Mirror Array #1 is used in the spectral light engine to generate arbitrary programmable basis spectra. Mirror Array #2 is illuminated by the spatially uniform light from the spectral light engine, and the spatial image programmed into Mirror Array #2 is projected into the instrument under test. Alternatively, it is projected into the reference radiometer for spectral radiance calibration. For an IUT frame rate of 50 Hz, the 5000 Hz binary update frequency of the spectral light engine means that it can cycle through up to about one hundred basis spectra within the single-frame integration time of the IUT. The duty cycle that a given mirror (image pixel) of Mirror Array #2 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. Thus, arbitrary programmable spectra can be projected into each spatial pixel of the instrument under test.

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 color, the CHIP can have up to about one hundred basis functions limited only by the spectral range and resolution of the broadband source, mirror arrays, and optics. Thus realistic hyperspectral images can be projected into the instrument under test. In addition, after each IUT frame cycle the hyperspectral image can be changed, enabling dynamic testing capability.

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*Any reference made to commercially-available products in this abstract does not imply recommendation or endorsement by NIST; nor does it imply that the products are the best for the purpose stated.

References

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Figure 1. Schematic of the spectral light engine.

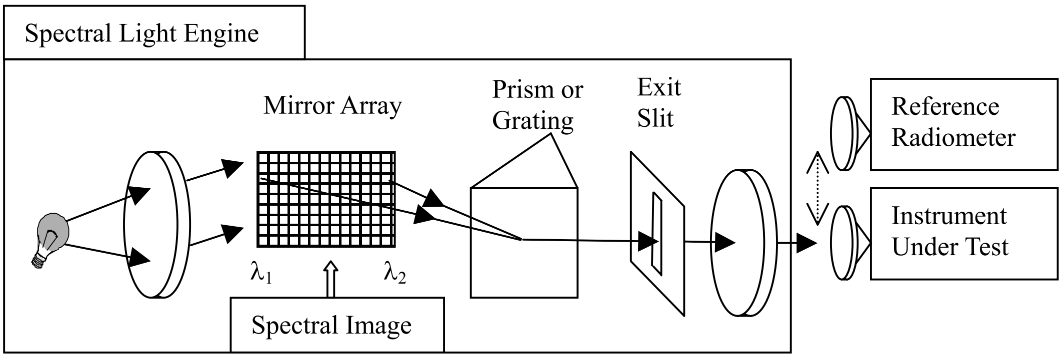

Figure 2. Schematic of the CHIP.