Lippmann2000: A Spectral Image Database Under Construction

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Abstract

In support of research projects both within the Munsell Color Science Laboratory and outside which rely on having full knowledge of the spectral makeup of scenes, a number of methods for capturing spectral images are being explored. This project is named Lippmann2000 in honor of Gabriel Lippmann who in 1891 devised a method to perfectly reconstruct the spectral content of real world scenes. In spite of Lippmann's invention, a more primitive three-channel model, first demonstrated by James Clerk Maxwell 30 years prior, has dominated the color imaging field. The Maxwellian model, universal in today's silver halide and electronic color image capture systems, relies on the metameric properties of the human visual system to simulate the appearance of an original color. It has been recognized by those in the forefront of imaging research that the capture of full spectral data holds advantage over traditional three-channel methods. This paper describes our efforts to-date to build our database of spectral images.

Keywords: colorimetry, imaging, multispectral, multi-spectral, hyperspectral, hyper-spectral, spectral, image capture, image output, image database, image processing, metamerism, Lippmann, MatchPrint.

1. INTRODUCTION: SPECTRAL IMAGE DATABASE - BUILDING THE BASIC TOOLS

When a new front opens within the field of image processing, the community benefits when there is wide distribution of images characteristically appropriate for pursuit of the new challenges. Past famous examples include the *Lena* and *Mandrill* images from the early days of computer graphics and the *Utah Teapot*, widely used during the early evolution of 3D computer graphics. More recent examples include the omnipresent *Musicians* often utilized for evaluating color management and image compression techniques. These images have accelerated advancement in the field by, first, allowing scientists and engineers practicing at or near the state-of-the-art to carry out their work without the additional burden of needing to become experts in generating quality images; and, second, creating a small level of *ad hoc* standardization such that processed images are more quickly evaluated due to general familiarity with the original input. Aware of these advantages, Lippmann2000 is an effort to provide the field with easy access to a variety of spectral images created through various means and of various subject matter.

The value of the database comes from the fact that the present state of available hardware and technique is too immature to make trivial the capture or simulation of images with high spectral resolution. Many approaches are currently being investigated worldwide. In the Munsell Color Science Laboratory, some of our experience with capture[1] and simulation[2] of spectral images have been published while other methods are currently under investigation. Progress in creating our database requires first efforts at building many basic tools such as those for capturing arbitrary real world scenes with sufficient spectral integrity.

One major goal we set for ourselves was the spectral capture of a human face. Our efforts to successfully fulfill that goal are documented herein. Additionally, we have found it appropriate to devote a significant portion of our time toward spectral hardcopy reproduction of our images. We have been fortunate to work closely with Di-Yuan Tzeng who's recently completed Ph.D. thesis[3] is devoted to color reproduction minimizing spectral error through the use of multiple inks. While his implementation was only fast enough for transforming color patches, we were able to harness that work and make it practical to transform large complex spectral images such as our spectral portrait. This latter work will also be discussed in this paper.

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2. HISTORICAL MUSING ON METAMERIC IMAGING

Isaac Newton published *Optiks* in 1704, a summary of over 30 years of experiments dealing with light. There he wrote: *From all which it is manifest that if the Sun's light consisted of but one sort of rays, there would be but one colour in the whole world... and by consequence, that the variety of colours depends upon the composition of light.... Colours in the object are nothing but a disposition to reflect this or that sort of rays more copiously than the rest.*[4] The spectral characteristics of real world reflective objects were described in these words succinctly and correctly nearly 300 years ago.

Gabrielle Lippmann in 1891 successfully developed a photographic system[5] which captured exactly the reflective characteristics of real world objects as they had been described by Newton. Lippmann followed the work of his predecessors which had suggested that interference characteristics of light could be harnessed to create spectral reproductions. Lippmann applied the use of so-called grainless albumen emulsions to a camera system which exposed the transparent base of the light sensitive material to a scene while the emulsion side of the film was in contact with a mercury mirror. Light would hit the mirror and reflect back upon itself exactly half a period out of phase. (See Figure 1) This resulted in no exposure at half wavelength increments and maximal exposure half way between the exposureless nodes. When the latent image was processed the super-fine grains yielded minute silver mirrors at the points of maximal exposure. With proper illumination, exact reconstruction of the original wavelengths resulted.

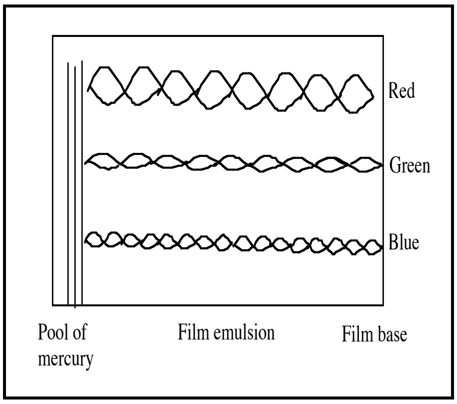

Fig. 1. *Light incident on the film through the base is reflected at the mercury surface. Interference between the incident and reflected light creates standing waves within the film emulsion.* (After Evans, Fig 8.1, page 276)[6]

Three centuries have passed since Newton described the spectral reflectance properties of objects and a hundred years since Lippmann devised a system for their capture and reconstruction. Yet, neither man is celebrated as a forefather of modern color reproduction. They have been forsaken and their contributions to this art nearly fully erased in preference for a system which pays no respect to the object's "disposition to reflect this or that sort of rays more copiously than the rest." Instead, today's system relies on mimicking through use of a bare minimalistic palette the perceived sensation experienced by a human observer when viewing an original object. 1861 saw the birth of modern metameric imaging when James Clerk Maxwell demonstrated the projection of three photographic color separations through three filters.[7] The engineering efficiencies of Maxwell's three channel approach have been far too seductive to be very seriously challenged over the past 150 years. Until recently, the most daring deviations have come from those in the high-end printing industry where Hi-Fi approaches are taking root. Even there, though, Maxwell's metameric principle remains unshakable as there is no attempt to improve reproduction of original spectra, only to better match human's perceived sensation of the original.

At the end of the twentieth century, we, the progeny of James Clerk Maxwell are beginning to recognize the need to return to the genius of Newton, to resurrect the startling beauty of Lippmann and to step outside the constraints of a system which throws away a universe of information as soon as original spectra are converted to three channels of data.

3. SPECTRAL CAPTURE OF A HUMAN FACE

When designing this, our first system for the spectral capture of a human portrait, we developed several criteria. First, we required that the system be robust to any arbitrary spectral shape. This differs from some approaches which benefit from an amount of precharacterization of the constituent spectra being imaged.[1] Our system, thus, needed to be spectrometric rather than densitometric in nature. Second, we wanted our system to be relatively fast so that we could image a live model. Third, we wanted to minimize the number of moving parts to reduce calibration and registration concerns. Fourth and finally, we needed to build our system out of components easily obtainable allowing us to complete our project within the six month time frame we allocated ourselves. We satisfied all four criteria with the second, the speed of our image capture, being our most questionable achievement whereas subjects needed to sit perfectly still for four to five minutes as we sequenced through our exposures.

We were provided with a C.R.I. Varispec solid state liquid crystal tunable filter (LCTF)[8] by Professor Zoran Ninkov of the Center for Imaging Science. This filter is manufactured by Cambridge Research and Instrumentation, Inc. (C.R.I) (See Figure 2 (c)). The filter has no moving parts. Selection of spectral bandpass occurs through a change in electric field. Our filter was a high contrast model with a nominal band pass of 10nm. High contrast specifies average transmission of less than 0.1% of out of band wavelengths.

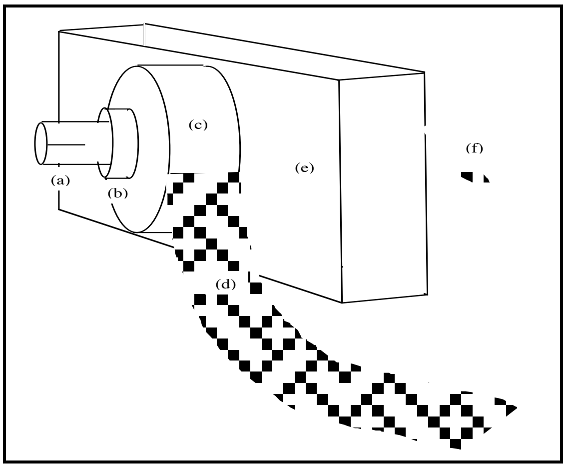

Fig. 2. Camera setup. (a) Enlarger lens (focused by manually pushing or pulling through lens sleeve), (b) lens sleeve made from Mylar and electrical tape, (c) C. R. I. tunable filter, (d) tunable filter connection to computer, (e) Canon A-1 filmback with auto-wind, (f) cable release.

Professor Andrew Davidhazy of the R. I. T. College of Imaging Arts and Sciences lent us a Canon A-1 film back with an auto-wind mechanism (Figure 2 (e)) and an enlarger lens (Figure 2 (a)) for the front of our system. The tunable filter was compatible with the camera lens mount, but there was no mounting capability on the scene side of the filter. We fashioned a lens sleeve out of Mylar and electrical tape (Figure 2 (b)). The enlarger lens was focused by pulling or pushing into the sleeve. Once the system was focused, the solid state aspect of the filter ensured nothing moved between exposures except for the film. The auto-wind mechanism and cable release ensured that any vibrations due to taking the image or moving the film were minimized. We chose Kodak Tmax p3200 black and white negative film as our detector. Except for the high red wavelengths the film has a relatively flat spectral response throughout the visible spectrum. (See Figure 3).

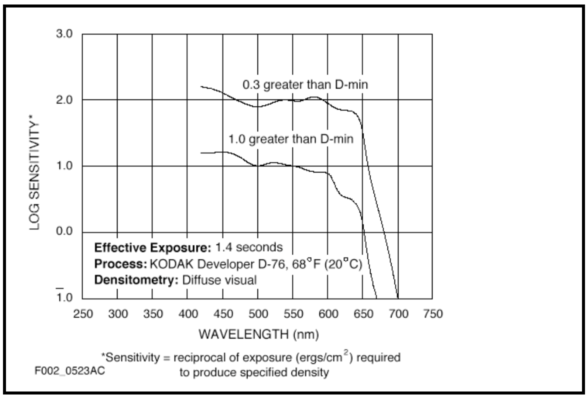

Fig. 3. Sensitivity curves for Kodak Tmax p3200 black and white film.[9] Note the severe loss of sensitivity in the wavelengths above 650. (Graph used courtesy of Eastman Kodak Company).

Our spectral images consist of 16 exposures each. (See figure 4). Nominal center wavelengths for tunable filter bandpasses were sequenced between 410nm and 710nm in 20nm increments. To prevent problems arising from processing differences between rolls of film, we imaged our characterization target (See Figure 5) on the first 16 exposures on each 36 frame roll. The next 16 exposures received our subject exposures. Previously we

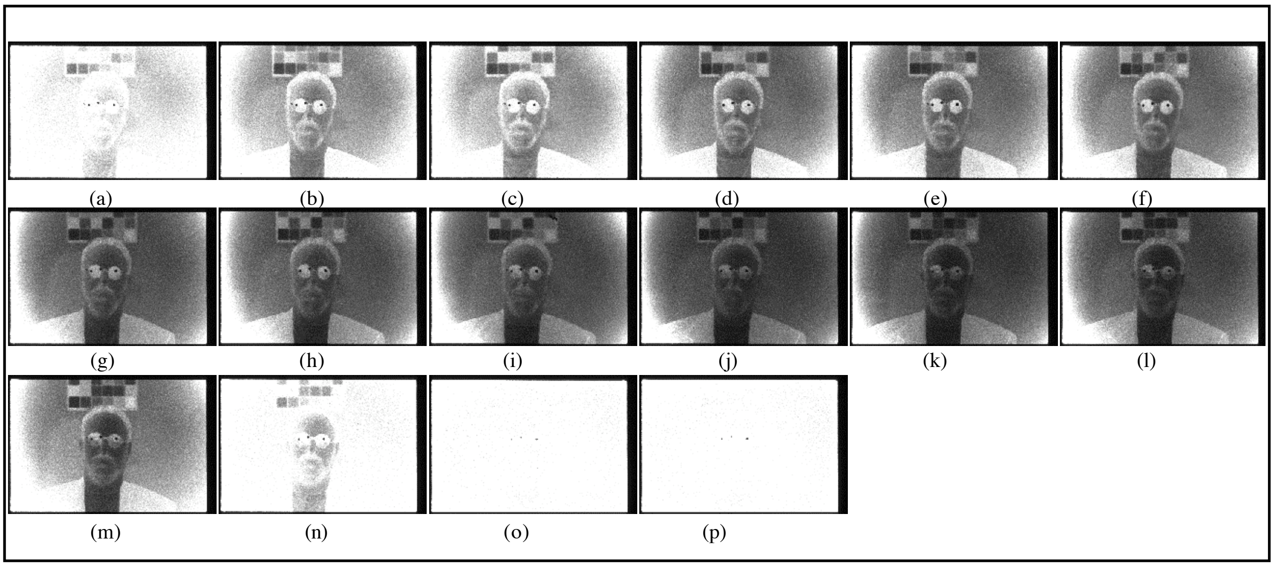

Fig. 4. Our model, Professor Roy Berns, sits for 16 separate exposures. He does a remarkably good job at not moving. His head is braced by a converted golf bag cart. To accommodate flash recharge, approximately 15-25 seconds lapses between exposures. Flash intensity has been calibrated to the combination of filter efficiency and film sensitivity for each filter bandpass. Nominal center wavelengths passed by the tunable filter: (a) 410nm, (b) 430nm, (c) 450nm, (d) 470nm, (e) 490nm, (f) 510nm, (g) 530nm, (h) 550nm, (i) 570nm, (j) 590nm, (k) 610nm, (l) 630nm, (m) 650nm, (n) 670nm, (o) 690nm, (p) 710nm. Film sensitivity and filter efficiency plummet at approximately 670nm. Last three frames (longest wavelengths) flash intensity turned to maximum giving Professor Berns a suntan. 12-bit scans of negatives produce usable data in long wavelengths. Bright spots on sunglasses can be seen in the illustrations of exposures (o) and (p) above.

had characterized the relationship between available flash intensity levels and film sensitivity at each of our filter settings. The higher the flash intensity level, the longer we had to wait between exposures for recharge.

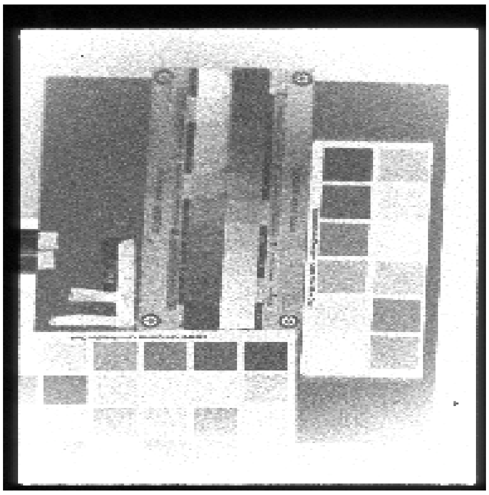

Fig. 5. System characterization target. Two gray step targets and two Macbeth gray scale. Target was imaged at each of 16 bandpasses.

Professor Roy Berns of the Munsell Color Science Laboratory agreed to be our first model. We thought it appropriate to invite him given his pioneering work in spectral imaging. He sat for us several days before departing for a sabbatical at the National Gallery of Art where he will be investigating the spectral reproduction of artwork. As this paper is prepared to coincide with a poster presentation at the International Symposium on Multispectral Imaging and Color Reproduction for Digital Archives where Dr. Berns is an invited speaker,[1] our choice of him enables Symposium participants to compare his actual face to our reproduction which will be part of the poster presentation.

To prevent our subject from inadvertently moving his head between exposures, we took apart a conventional golf bag cart and found that the main backbone provided a comfortable stabilizer. This backbone, when taped at the correct height onto a small wooden chair fit very well the back of the head and was not visible from the front. (See Figure 6). We asked our subject to relax his face and not to smile. Due to fact that the multiple high intensity exposures would be very uncomfortable to anyone even with their eyes closed, our subject wore sunglasses, but chose to keep his eyes open. We provided an ‘x’ on the wall in front of him for him to concentrate his eyes. To minimize time between exposures, three of us participated. One participant read off our previously determined flash intensity levels and took notes. Another set the flash intensity levels and executed the exposures via cable release. The third stayed at the computer incrementing the filter bandpass settings.

Fig. 6. Converted golf bag cart used as brace for head during 16 exposures.

4. CONVERTING FILM DENSITY TO SPECTRAL REFLECTANCE

Our exposed rolls of negative film were processed at a local black and white photofinisher. To the amusement of the technicians, we made the special request to have our negatives mounted in slide holders. To scan the negatives we used the Nikon SuperCoolScan LS-2000 which has a very nice setup for automatically scanning a set of slides. By mounting our negatives in slide holders we were able to take advantage of this feature. The LS-2000 provided us with 12-bit Tiff files. We discovered that the scratch removal feature known as Digital Ice introduced an artifact in our very underexposed negatives. From such negatives, areas of no exposure were unaffected, but areas of very slight exposure were interpreted as scratches and “removed.” We found it necessary to turn off the scratch removal feature. Our Tiff files were converted to 16 bit raw files in Adobe PhotoShop on our Macintosh and transferred to a Windows NT machine where we converted from Motorola byte ordering to Intel byte ordering in IDL. Another IDL routine was invoked to gather average 12-bit data from our characterization patches.

We associated the 12-bit averaged digital counts with the nominal center wavelength setting for the tunable filter. Previous spectrophotometric measurements were made of the individual patches on the gray step targets and the Macbeth gray scales (See Figure 5). This provided us with a reflectance to digital count relationship for each nominal wavelength. We found that a very simple model fit most of our data well: reflectance to film density represented as logarithmic, followed by a gain and a gamma as applied by the 12-bit scanner. In order to take advantage of our scanned negatives, we needed the inverse of this relationship, namely digital count to reflectance. The inverse model looked as follows :

$$R_{\square} = e^{\square(DC_{\square}/4095)^{\square} * G}$$

where R□ is the reflectance of a characterization patch at a particular wavelenght, DC□ is the scanner digital count for the same patch and the same nominal center wavelength, □ is the gamma applied by the scanner and G is the gain applied by the scanner . A MATLAB program was used to minimize the error between a derived □and G and the actual measured relationships. Figure 7 demonstrates the quality of our model for our portrait setup.

5. SPECTRAL REPRODUCTION

Our output approach was based upon the work of Koichi Iino and Roy Berns,[10] and Di-Yuan Tzeng[3]. The combination of these two works describes a spectral model for n-ink printing systems where no more than 4 inks are printed on any single pixel. We were given access to the MatchPrint proofing system at the College of Imaging Arts and Sciences. Although technicians who run the MatchPrint had no experience at printing more than four colors at a time, they agreed to make 6-ink prints for us. We chose a custom blue and green in addition to the standard commercial cyan, magenta, yellow and black. Tzeng's algorithms, implemented in MATLAB, were fairly complex and had only been exercised on small numbers of colors at a time. We needed to process large images and thus needed to make the approach reasonably efficient. We had 2000x2000 pixel 16-band spectral images from our camera which we wished to convert into 6 band images for our MatchPrint output. Processing each pixel in our image using Tzeng's implementation was out of the question given the slowness of the MATLAB code. Even more prohibitive would be producing directly a 16-band to 6-band lookup table with any reasonable resolution.

Our solution involved the following offline steps:

1) Build 10 lookup tables based on the following. A composite spectra is defined by summing 6 basis spectra weighted by 6 weight variables. The Iino-Berns-Tzeng model is used to derive digital counts associated with any 4 of our 6 MatchPrint inks minimizing spectral error between a MatchPrint print of those digital counts and the composite spectra. The model requires that one of the inks be black. There are 10 combinations of 4 inks chosen from our set of 6 inks where one is black ink. Thus, build 10 lookup tables, each associated with a specific set of 4 inks from our 6 MatchPrint inks, one of which is always black. Each lookup table maps from the 6 weight variables to digital counts for the

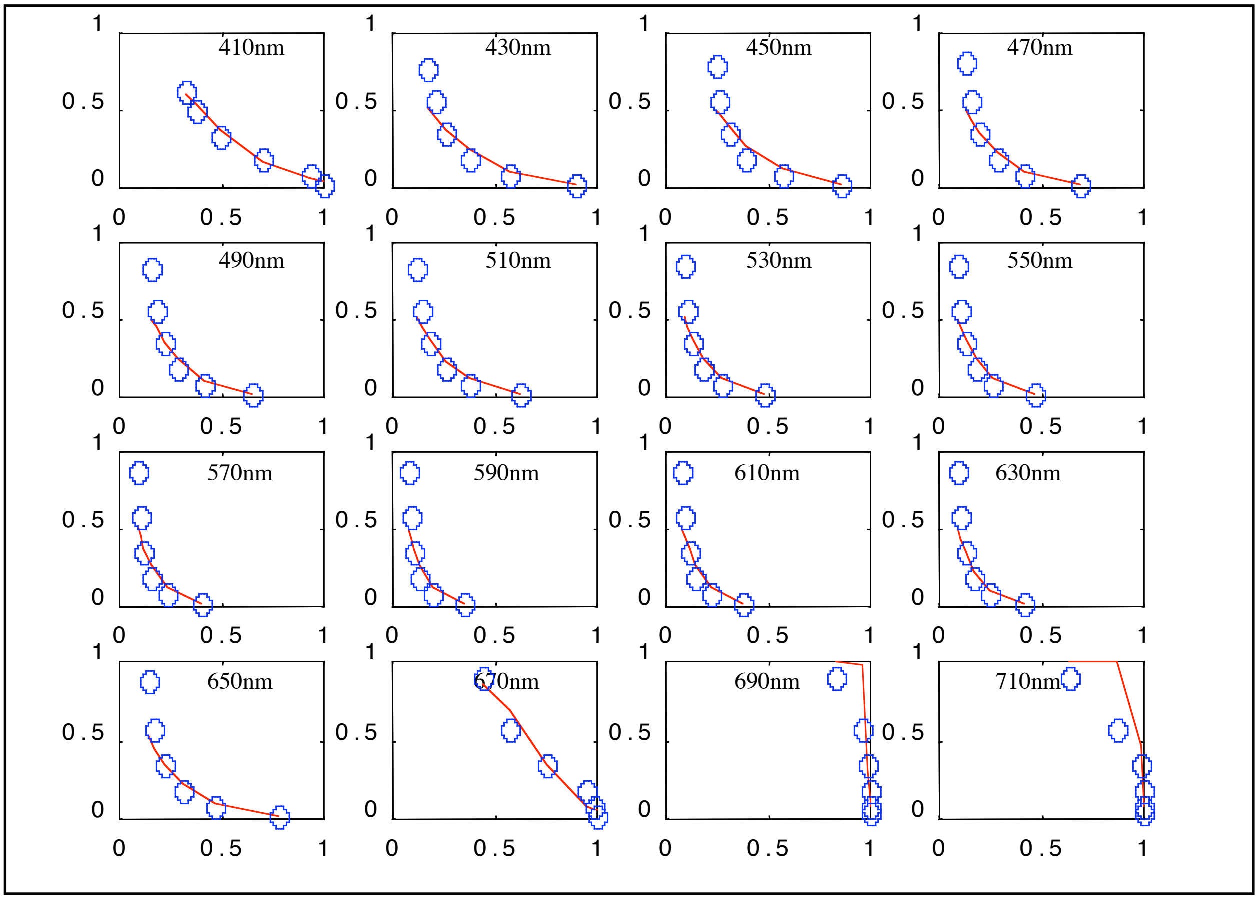

Fig. 7. Digital count (x axis) vs. reflectance (y axis). Broken lines are measured spectral data of the Macbeth gray scale. Solid lines are results of applying the model.

associated 4 MatchPrint inks.

2) Choose, for convenience and to minimize error, spectral descriptions of our 6 MatchPrint inks as our basis spectra.

Image processing was then implemented through exercising the following steps on each pixel in the image:

1) Use the psudoinverse capability of MATLAB to determine which 4 of the MATLAB inks are the most dominant for the pixel. Choose the lookup table associated with the dominant 4 (or dominant 3 if black is not one of the top 4).
2) Evaluate the pixel spectrum deriving weight variables for the 6 basis spectra. Interpolate the resultant weight variables through the lookup table delivering 4 MatchPrint digital counts.
3) Pad the 4 MatchPrint digital counts appropriately producing a 6-ink digital count.

These 6-band images were then printed on the MatchPrint proofer yielding our spectral reproductions.

6. LIPMANN2000 DATABASE

As expertise in spectral capture and spectral simulation grow in the Munsell Color Science Laboratory, our Lippmann2000 database will grow. We expect to utilize the HDF[11] image format for these many-channel images. We look forward to collaborating with others in the field who are interested in making their spectral images accessible to the public. To discuss such a possibility, please contact the main author at the email or postal address listed below.

Look on the Munsell Laboratory home page for a link to the Lippmann2000 site under the heading "Online Resources." The Munsell Color Science Laboratory home page is at http://www.cis.rit.edu/mcsl.

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Biography

Mitchell R. Rosen is a Senior Color Scientist at the Munsell Color Science Laboratory, Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology, as well as a Ph.D. candidate in the Center for Imaging Science's program in Imaging Science. He is currently on leave as a Senior Scientist at the Image Science Laboratory, Polaroid Corporation. He joined the staff of the Munsell Laboratory in September 1998 when he began his leave-of-absence during his 10th year in the Polaroid Image Science Laboratory. He received his B. S. degree in 1984 in computer science from Tufts University, Medford Massachusetts and his M. S. in 1993 in Imaging Science from R.I.T.. Prior to his master's work, he spent several years as staff programmer in the Visible Language Workshop, Media Laboratory, Massachusetts Institute of Technology. During his years at Polaroid he worked in image quality evaluation, imaging system specification and algorithm development. He has been active in industry-wide efforts to standardize desktop color management. His work in the Munsell Laboratory is focused upon development of spectral imaging infrastructure. He is a member of IS&T.

Xiao-Yun (Willie) Jiang is a Ph.D. candidate in the Imaging Science Program in the Center for Imaging Science at Rochester Institute of Technology. From 1996 to 1998 she was an Assistant Engineer with the Institute of Mechanics at the Chinese Academy of Science where she worked with lasers and optics. She received both her M. S. in 1996 and her B. S. in 1993 from the Department of Optical Engineering, Beijing Institute of Technology.

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