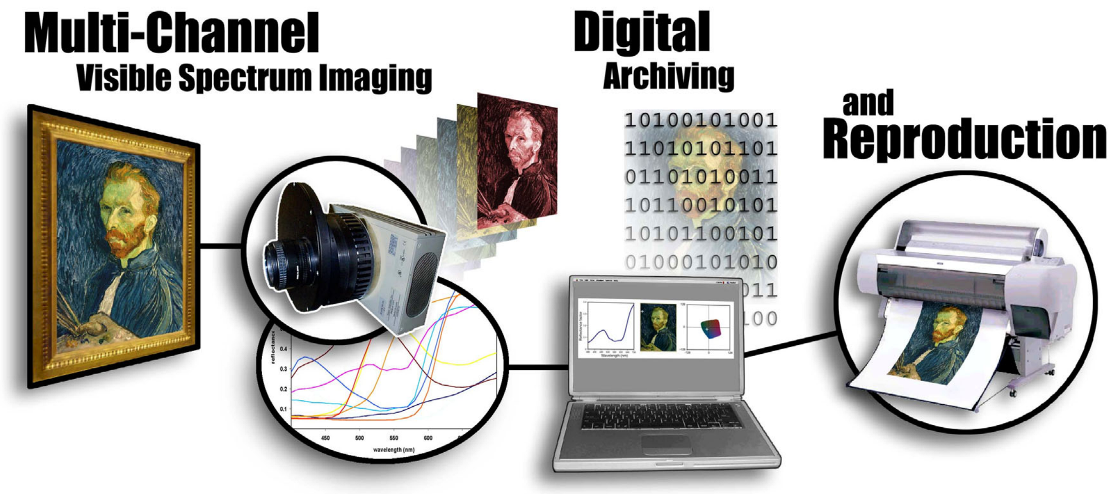
Phase I Final Report
to the
National Gallery of Art, Washington



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Art-si.org
art spectral imaging

The phase I anticipated activities and outcomes, as described in the original research contract, are as follows:

> Phase I is concerned with the development of a research-grade low-resolution imaging system that can measure the spectral properties of objects and a thorough testing of the camera's performance in terms of spectral, colorimeteric, and spatial quality. The majority of research will occur at RIT with periodic visits to the Gallery to test the practicality of the system in a museum setting. The anticipated outcome is a computer-controlled multi-spectral digital camera system and associated software. The software will be research oriented. A thorough understanding of the effects of image noise and the method or spectral estimation as it relates to estimation accuracy and image quality is also anticipated.

A camera system was constructed, shown below, in Figure 1. A Roper Scientific Quantix monochrome sensor was interfaced to a controlling computer system. Two different pre-filtration systems were used. The first was a six-position, computer-controlled filter wheel. The second was a computer-controlled liquid-crystal tunable filter. Illumination was provided by two tungsten lamps.

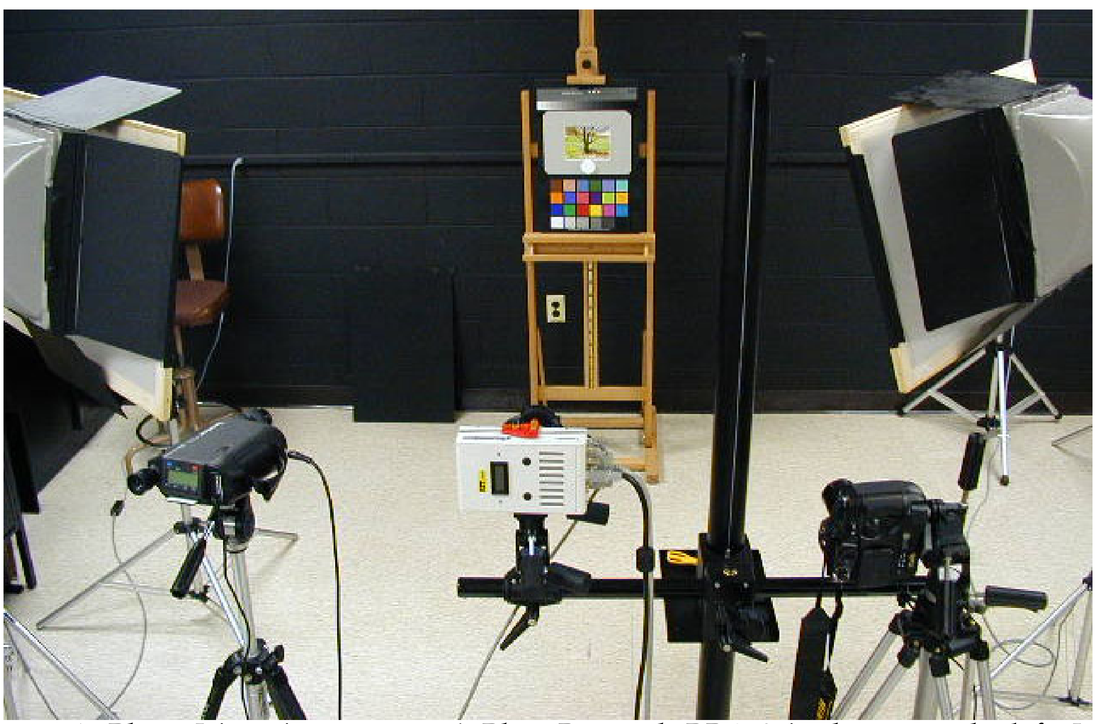

Figure 1. Phase I imaging system. A PhotoResearch PR650 is shown on the left. It is used to make direct measurement of the lighting system. In the center is the Quantix sensor. On the right is the Nikon D-1 digital camera, used to provide a benchmark.

The physical properties of the camera were characterized, described in the technical report, "*Characterization of a Roper Scientific Quantix monochrome camera*," authored by Ellen Day, Francisco H. Imai, Lawrence Taplin, and Shuxue Quan. This step is necessary in order to use the camera for scientific imaging.

An important consideration is the type of lighting when performing scientific imaging. The tungsten lamps are already owned by the Munsell Color Science Laboratory (MCSL). Before testing alternative lamps such as HMI or compact fluorescent, a computational analysis was performed to evaluate the effect of source spectral power distribution on spectral estimation accuracy. The study indicated that although tungsten has the best performance, the choice of lighting is not a significant factor. The study is described the technical report, *Simulation of spectral estimation of an oil-paint target under different illuminants*," written by Francisco H. Imai.

A viewing environment was created, consisting of a computer-controlled LCD and viewing booth, shown in Figure 2. The spectral radiance of the booth was adjusted to have similar luminance to the LCD. Using spectral and colorimetric instrumentation, the color properties of the LCD and booth were characterized. An article describing the colorimetric characterization of the LCD is near completion titled, "*Characterization of an Apple Cinema Liquid Crystal Display*," authored by Ellen Day, Lawrence Taplin, and Roy S. Berns. The manuscript will be submitted to Color, Research, and Application. We have also characterized a CRT display in support of this research. A technical report titled, "Characterization of an SGI CRT monitor," authored by Ellen Day. This environment is shown in Figure 3. These type of characterizations are required in order to eliminate visual editing using software such as Adobe Photoshop from the image archiving workflow.

An extensive experiment was performed to test various methods of spectral estimation using the Quantix camera and both filter systems. The first spectral image from the system is shown in Figure 4, along with Francisco Imai and Lawrence Taplin. The report is titled, "*Comparison of the accuracy of various transformations from multi-band images to reflectance spectra as part of end-to-end color reproduction from scene to reproduction using spectral imaging*," authored by Francisco H. Imai, Lawrence Taplin, and Ellen Day. One of the main results is summarized in Table I (Table XV of the report). A paint target was created using the Gamblin Conservation Colors. Each pigment was mixed with white at two different concentrations; the 30 chromatic colorants resulted in 60 target colors. The estimation accuracy is summarized in this table comparing the liquid-crystal tunable filter (LCTF), a six-filter approach using filters optimized at the Munsell Color Science Laboratory, and a multi-filter RGB approach patented by Imai and Berns. Two different mathematical transforms were tested, principal component analysis (PCA) and pseudo-inverse (PINV). It is important to note that these are independent data; often, only the calibration target performance statistics are published. It is very interesting that the wide-band approaches yielded results very similar to the 31-band spectral approach. Given that this approach is an approximation, it may be possible to achieve reasonable spectral performance using commercial color-array sensors.

Table I. Spectral estimation evaluation result for the Gamblin paint target using pixel-based approach.

Filtering method		31 Narrow-band channels by LCTF			6 Wide-band channels using MCSL optimized Schott Glass filters			6 Wide-band channels RGB glass filters with and without Wratten (Imai and Berns patent pending)		
Transform	Metric	ΔE^*_{00} (D65, 2°)	RMS (%)	Metamerism Index (D65, A, 2°, ΔE^*_{00})	ΔE^*_{00} (D65, 2°)	RMS (%)	Metamerism Index (D65, A, 2°, ΔE^*_{00})	ΔE^*_{00} (D65, 2°)	RMS (%)	Metamerism Index (D65, A, 2°, ΔE^*_{00})
PCA	Average				2.2	3.7	0.9	2.6	4.3	1.0
	Max/Min(GFC)				4.9	11.8	3.7	5.4	15.3	3.9
	Std Dev				0.9	1.9	0.7	1.1	2.9	0.7
PINV	Average	1.9	2.3	0.4	2.2	3.5	0.8	2.7	4.2	1.0
	Max/Min(GFC)	4.7	7.5	1.4	5.1	10.9	2.8	5.5	15.3	3.7
	Std Dev	0.8	1.2	0.3	1.0	1.9	0.5	1.2	3.0	0.7

Different spectral-estimation techniques yield different spectral and colorimetric performance, as shown above in Table I. Ellen Day is completing a visual experiment in which observers judge images generated using these techniques with original objects viewed in a light booth. Observers are judging both color accuracy and spatial image quality. This experiment is Ellen's Color Science M.S. research thesis requirement. This will be completed with the next two months. An image from the liquid-crystal tunable filter is shown in Figure 5: 31 bands were combined to yield a colorimetric image for the LCD assuming that the viewing illuminant was simulated daylight and the observer was the 1931 CIE standard observer. Preliminary analyses indicate that all the techniques yield images indistinguishable from one another. This is further evidence that commercial color-array sensors may be an excellent compromise between cost, complexity, perceived color quality, and spectral estimation accuracy.

Figure 2. Viewing environment for evaluating color and spatial image quality. Image pairs are shown on an Apple Cinema Display via the Matlab software environment. Various test targets are placed in the Macbeth light booth.

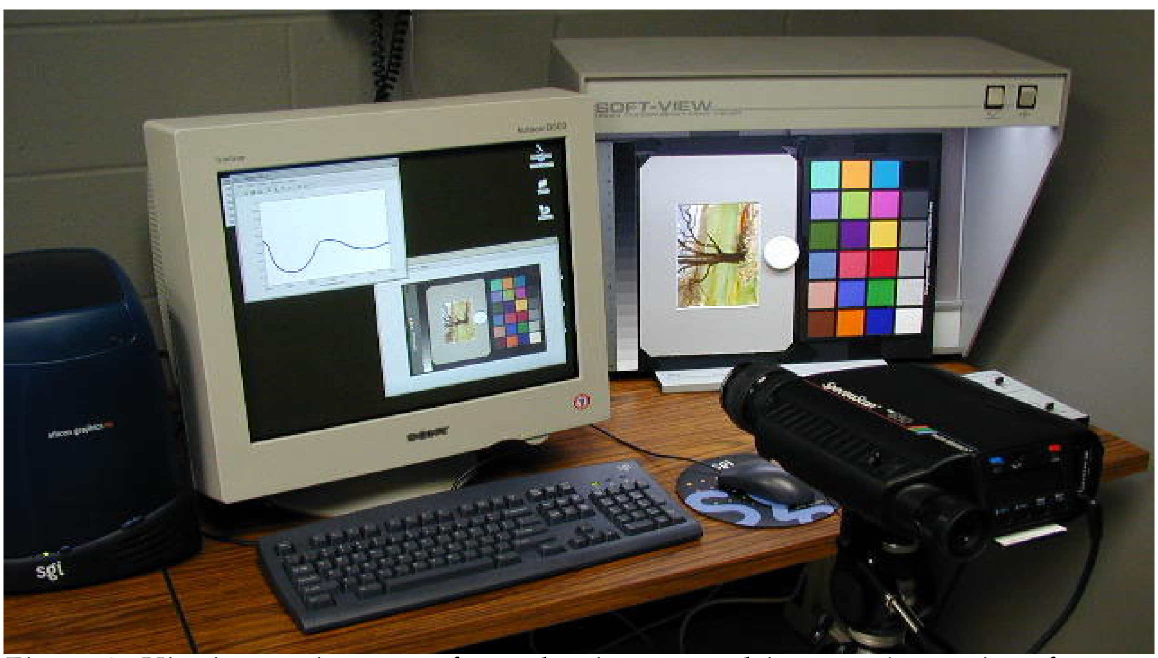

Figure 3. Viewing environment for evaluating spectral images. A user interface was created so that the spectral reflectance factor of the imaged object can be seen while rolling over the image. The spectroradiometer, shown in the foreground, is used to measure both the display and viewing environment.

Figure 4. Lawrence Taplin (left) and Francisco Imai along with our first spectral image rendered for a display using the imaging system shown in Figure 1. The particular display shown here is the IBM 200 ppi LCD.

Figure 5. Image rendered for the LCD display shown in Figure 2 based on a liquid-crystal tunable filter.

During Phase I, we received significant funding from the Andrew W. Mellon foundation. One of our goals is to provide leadership for the American museum, archive, and library communities with respect to scientific imagine of cultural heritage. A new web site was created for information access, www.art-si.org, standing for art spectral imaging.

In the near future, our plans are to evaluate the Kodak KAF-16801 color sensor. This sensor is available in Sinar products that incorporate micro- and macro-positioning. We will be looking at different transformations for estimating spectral reflectance factor. We are performing a computational analysis to define a set of artist materials for target manufacture. Finally, we are repeating our imaging experiments using upgraded lighting and better stray-light rejection, shown in Figure 6.

Figure 6. Phase I updated imaging system. On the easel is the GretagMacbeth ColorCheckerDC, used to calibrate the imaging system. Below it is an oil-paint target.

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