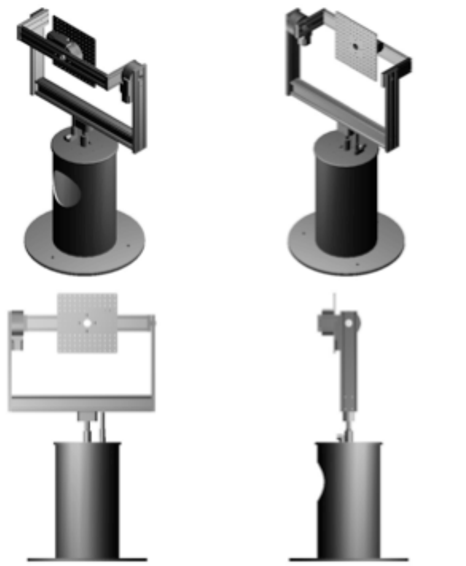
Munsell Color Science Laboratory Imaging Goniospectrometer



Technical Report
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MCSL
MUNSELL COLOR SCIENCE LAB

The mission of the Munsell Color Science Laboratory is to advance the science, understanding, and technology of color and appearance through education, research, and outreach

* Note that this report was excerpted from a December 2009 Final Report for the Andrew W. Mellon Foundation.

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Overview

Imaging artwork for documentation and reproduction has a long and rich history. The vast majority of such imaging reduces an illuminated three-dimensional object onto a two-dimensional plane, rendering a specific observing experience. For this reason, successful museum photographers have backgrounds in art history and aesthetics enabling them to produce images that convey important appearance phenomena about the object. The drawback to this practice is a need for reshooting when the appearance criteria change. It would be ideal if we can separate the image capture and rendering. In this manner, the object can be re-rendered for various criteria. In other words, we first image the artwork to define its physical characteristics, or total appearance. Then computer graphics techniques are used to produce an image for specific lighting, observing or publishing criteria.

For artwork such as paintings and drawings, a complete physical description would include spatially varying spectral reflectance factor, surface macrostructure (depth), and surface microstructure (bi-directional reflectance distribution function, BRDF). Spectral reflectance factor and BRDF can be measured with a spectral camera and a single light source positioned about the object (or multiple light sources). Depth can be measured with a variety of techniques including laser scanning, confocal microscopy, and structured light. An alternative to measuring depth is to measure surface normal, which is a vector direction perpendicular to the surface. Measurements of spectral reflectance factor, BRDF, and surface normal can be accomplished with a single imaging system.

Beginning in 2006 a research program was initiated to develop an abridged approach to measuring the total appearance of paintings. The first step was building an imaging goniospectrometer, the subject of this technical report.

Preliminary Instrument Design

We initiated this activity by studying current systems. This included a literature review and study of BRDF instruments worldwide, summarized within the M.S. thesis of Y. Chen, a visit to Cornell University during 2006 including discussions with 3D imaging pioneer Professor Torrance, and a visit to the National Institute of Standards and Technology (NIST) in 2007 (see Figure 1). This resulted in a preliminary design for an imaging system that can measure spectral reflectance as a function of illumination and collection angle, known as the bi-directional reflectance distribution function or BRDF. A local engineering firm, Lightforce Technology, Inc., was subcontracted to design a system (see Figure 2). The results were published as a technical report. The design process revealed that a system similar to the Cornell University system was impractical for use in a museum and in MCSL. In particular, we recognized that the lighting, camera, and object positioning systems should be separated rather than integrated as a single instrument. Thus, we designed a three-axis computer-controlled positioning system, a computer-controlled translation stage for various detectors mounted on a commercial camera stand, and installed a commercial track lighting system sold by Sinar.

Figure 1. NIST gonio-spectrophotometer. Left, Dr. Maria Nadal, NIST. Right, Dr. David Wyble, MCSL.

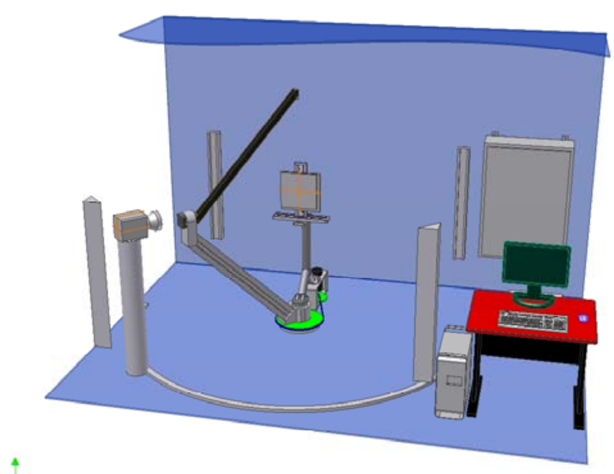

Figure 2. 2007 concept drawing of our BRDF system.

Shown in Figure 3 are various configurations and degrees of freedom of instruments designed to measure BRDF, both imaging and non-imaging. Each configuration shows how the light, detector and sample can be moved in different ways to achieve full (NIST, MCSL, and Stanford/Cornell) and partial (Murakami) access to all possible BRDF measurement-angle configurations. It is clear that there are many ways with varying complexity and cost to capture 3D data.

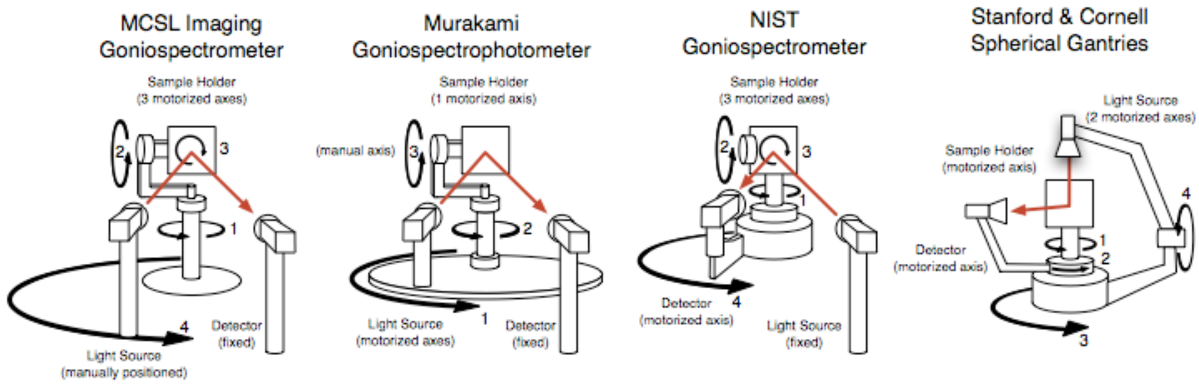

Figure 3. Degrees of freedom in (from left to right) the MCSL Imaging Goniospectrometer, a commercial instrument made by Murakami, NIST's Goniospectrometer, and the Spherical Gantries at Stanford and Cornell.

Spectral Imaging Laboratory Dark Room

The Spectral Imaging Laboratory developed in our last project was modified to have a light-tight sub-space in the back half of the laboratory so that measurements could be performed in the dark while other activities were taking place in the adjacent lit space, shown in Figure 4.

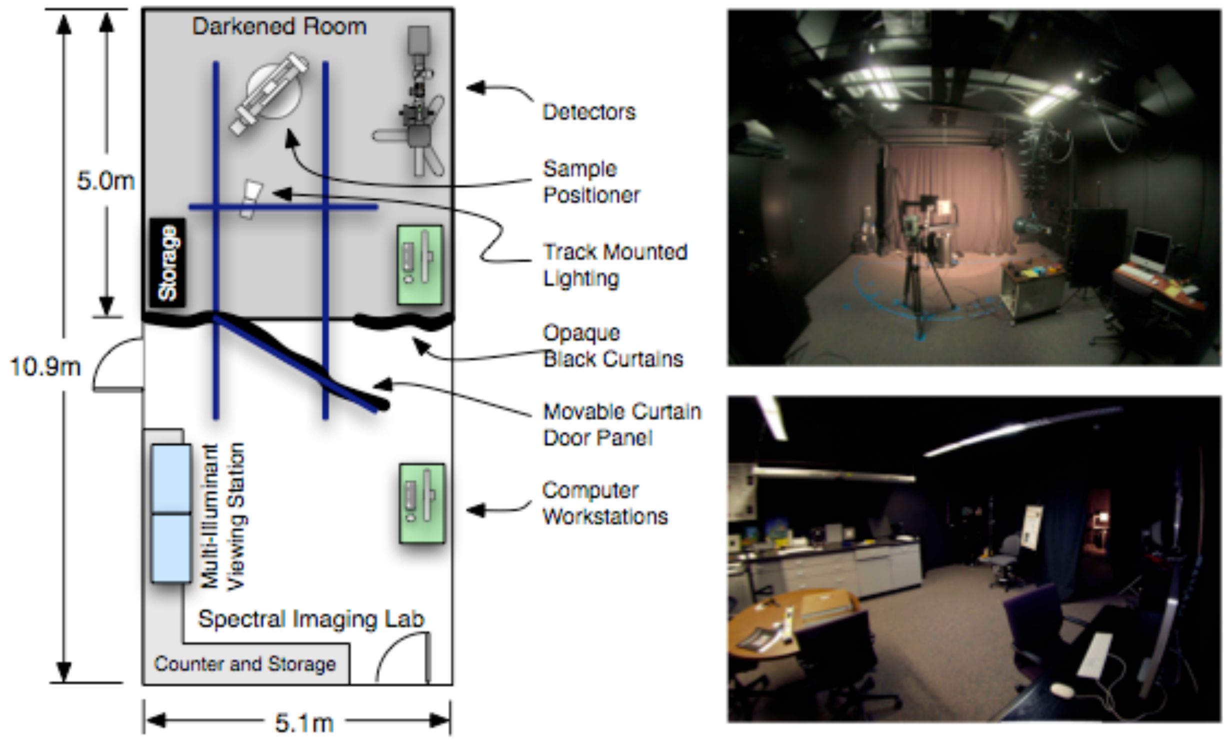

Figure 4. Light-tight sub-space.

Detectors and Translating Camera Stand

Three detectors have been included in the MCSL Imaging Goniospectrometer. They are mounted on a small optical breadboard attached to a modified Foba Studio camera stand, shown in Figure 5. The cross arm of the camera stand can be moved using a Velmex motorized linear positioner to allow each detector to be sequentially placed at the same viewpoint, Figure 6. The MCSL-Sinar Multispectral Camera is mounted closest to the vertical post of the camera stand and is used to capture high-resolution multi-spectral images that do not require color pattern interpolation. An off-the-shelf Canon 5D with a 135mm lens is used for fast acquisition of RGB images. Lastly, a Konica Minolta CS-2000 Spectroradiometer is mounted at the end of the arm and can be used to take full spectral spot measurements. Furthermore, the spectroradiometer can be aimed at any point on the sample surface or at a fixed white-reference for light source monitoring via a front surface mirror affixed to a motorized pan-tilt positoner made by Directed Perception. A summary of the detectors is listed in Table I.

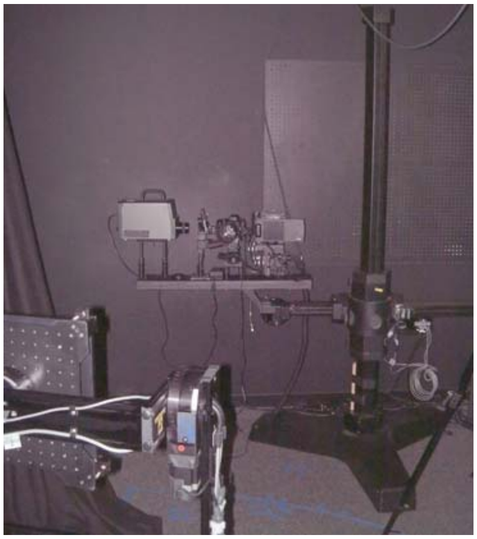

Figure 5. Camera stand (back right) and imaging detectors (center) for MCSL Imaging Goniospectrometer. The three-axis sample positioner is visible in the foreground. Room and devices have been blackened to reduce flare and inter-reflections in the imaging system.

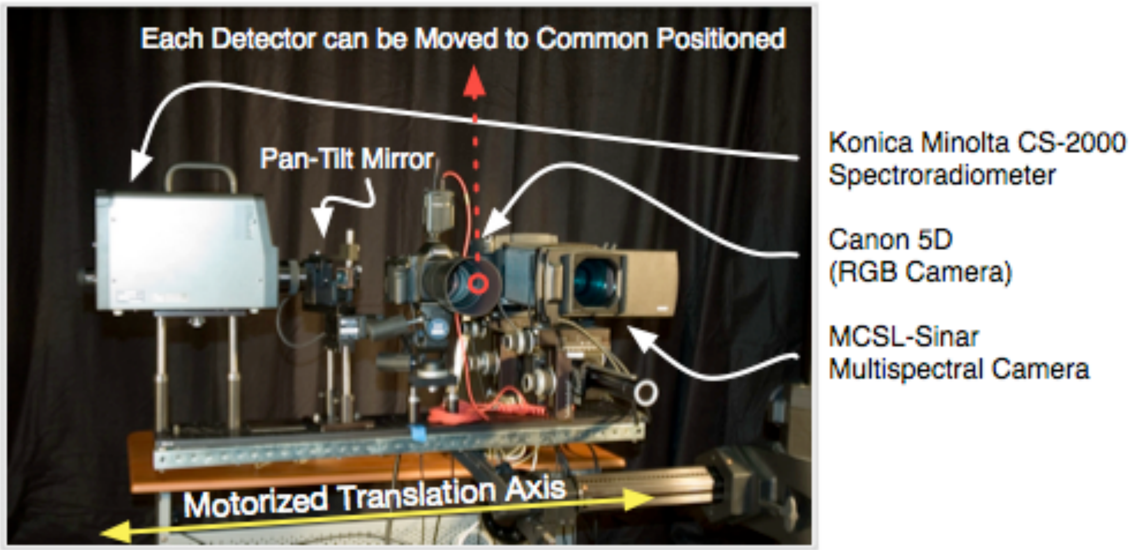

Figure 6. Three detectors of the MCSL Imaging Goniospectrometer mounted on a motorized camera stand to allow them to sequentially collect data from the same vantage point.

Table I. MCSL Imaging Goniospectrometer detector summary.

Detector	**Konica Minolta CS-2000**	**Canon 5D**	**MCSL-Sinar Multispectral Camera**
Sensor Resolution	Spot-measurement	4368 x 2912 (12MP)	5440 x 4080 (22MP)
Sensor Size	1.0, 0.1 and 0.2 degree spot size	36 x 24 mm	38.8 x 50 mm
Lens	Mfr. Standard	Canon EF 135mm f/2L USM	Sinar Digital 210mm f/5.6 CAB Lens
Spectral	380-780nm (1nm steps)	RGB	Multispectral (6ch)

Three-Axis Computer-Controlled Positioning System

After completing the preliminary instrument design review by Lightforce Technology, it was determined that the simplest and most economic option for achieving a four-degree of freedom imaging goniospectrometric system was to assign three axes of rotation to the sample itself. This configuration also has advantages for system accuracy and stability as the rotation occurs close to the sample's center of mass. Velmex, Inc. was contracted to design, fabricate and deliver a three-axis sample positioner. Their design (Figure 7) allows a target painting, sample panel, or other object, weighing up to 10Lbs, to be rotated in three dimensions around a fixed point in space. The geared stepper-motor driven rotary positioner at the top of the pedestal base has a resolution of 0.01125 and a speed of 11.25 degrees per second (~1000 Steps/Sec). The other two positioners have resolutions of 0.0125 degrees and speeds of 12.5 degrees per second.

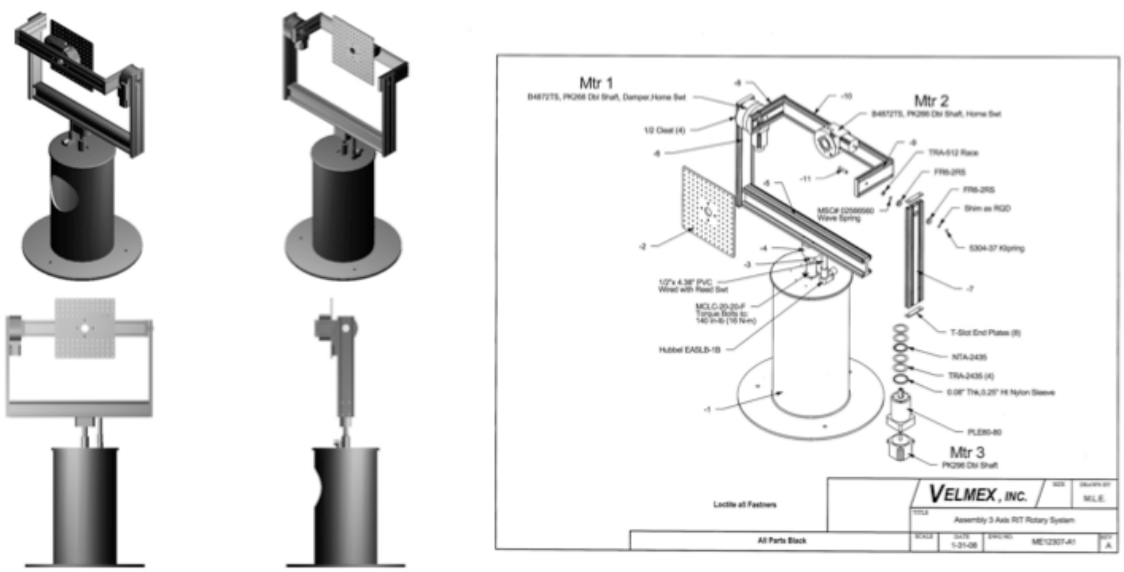

Figure 7. Computer renderings of Three-Axis Sample Positioner (left) and exploded view of its components (right).

The completed sample positioner is shown in Figure 8 as installed into the imaging system. On the sample stage is a large white reference made of Fluorilon that serves as a calibration standard in the system. Mounting the standard and other rectangular samples to sample positioner was first accomplished by using the clamping system shown in Figure 9. These clamps were designed to push samples forward and secure them at the system's plane of rotation located 2.75" in front of the square mounting plate. Experience in using this system led to the conclusion that mounting samples in a repeatable fashion was quite difficult. A second clamping system was created, designed, and fabricated specifically for the 10"x10" panels onto which the artist material samples were produced. As shown in Figure 10, it also includes fiducial markers that are used to locate the sample holder's position for automatic rectification and sub-pixel registration during image processing.

Figure 8. Three-Axis Sample Positioner as installed in the MCSL Spectral Imaging System. A 12x12" Fluorilon white reference has been mounted on the positioner; the round white pressed Halon reference used for illumination monitoring is at the top of the base and the two Velmex motor controllers are visible on the floor.

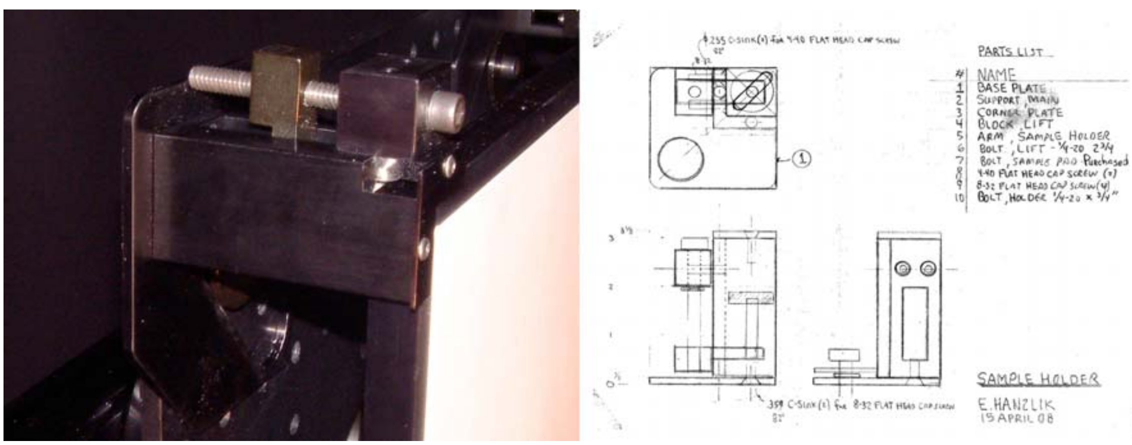

Figure 9. Clamping system designed to accommodate rectangular samples up to 12x12x2" and align their front surface to the plane of rotation of the sample positioner.

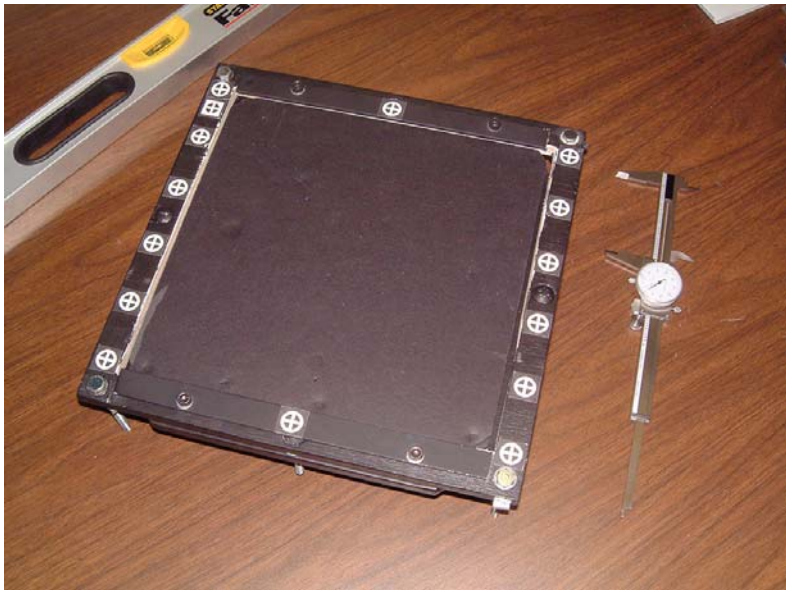

Figure 10. Alternate sample clamping system that simplifies mounting of 10x10" panels and includes integrated fiducial markers (white circles and crosses) for automated image rectification and registration.

Controlling Software

All aspects of the MCSL Imaging Goniospectrometer are currently controlled from within the MATLAB programming environment on an Apple iMac computer. The computer is interfaced to the various system components via USB, Firewire and Serial connections as shown in Figure 11. These connections allow the real-time control over each instrument's settings, allow the exchange of data, and the collection of measurements and images. Class based libraries were written within MATLAB to ultimately control and access each instrument with just a few lines of code. Currently, manual intervention in data collection is required only to mount the samples to the sample positioner and when the light source position needs to be changed. Future enhancements to the system hardware will eliminate the need for the latter by motorizing the carriages that the lighting rides on in the ceiling tracks.

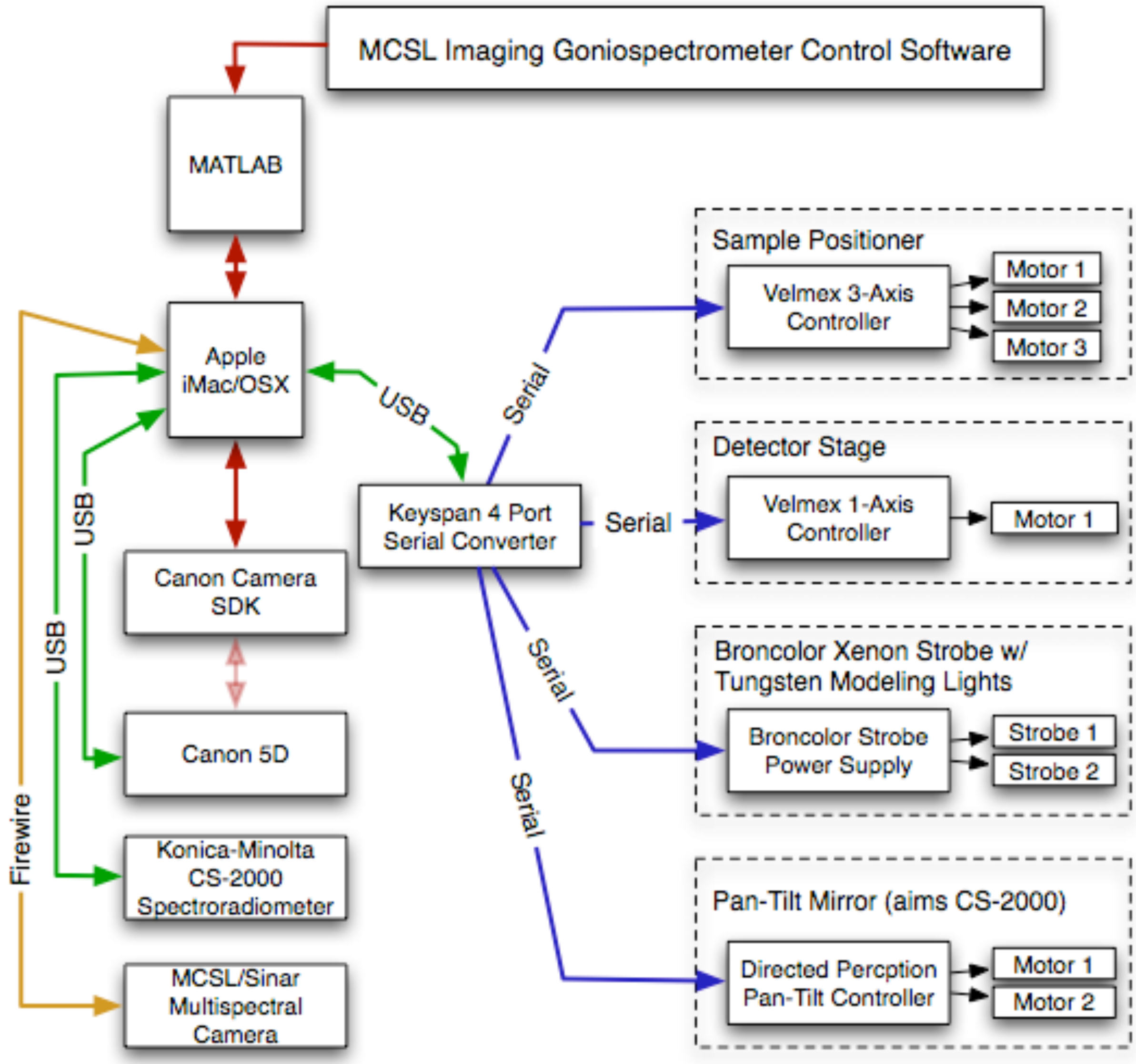

Figure 11. MCSL Imaging Goniospectrometer control software connections between hardware and software. Red arrows represent software connections (note that the Canon SDK is a software library that communications indirectly with the camera via the USB link).

System Calibration

The MCSL Imaging Goniospectrometer uses polytetrafluoroethlene (PTFE) pressed to a density of 1g/cc as a physical realization of a perfect reflecting diffuser. This scale is transferred to sintered PTFE, trade name of Fluorilon. Angle settings are calibrated using a front-surface mirror. System verification is performed using the cyan tile from the BCRA Series II tiles. This tile is used to verify specific BRDF values and model parameters estimated using the Cook-Torrance model. Spectral and colorimetric data, optical flare, and photometric linearity are calibrated and verified using color targets made from reflecting materials that have good spatial uniformity.

Project Sponsor

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