

Relative Color Delineation Testing of Visible Camera Systems

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ABSTRACT

The human eye has the ability to distinguish millions of colors. Employing this attribute along with cognitive spatial cues a human being can differentiate between even the slightest color variations. The goal of any imager is to collect the maximum amount of information from a scene, both spatially and spectrally. Whether it is used for artistic reproduction or camouflage detection, a camera has the same ultimate specifications. While much sensor research and development has been conducted to improve both spatial and intensity resolution, less effort has been directed to color contrast delineation. This specification is not only difficult to define but complex to test. Most color testing is confined to print or display technology and is supported by a myriad of test equipment and standards. Typical camera color calibration may rely on color standards with defined illuminants but is ineffective in contrast resolution definition. This paper will discuss hardware and software developed by the authors that is utilized to project precise dual color controlled images to determine the color contrast resolution of an imager. Algorithmic challenges related to human-perceived versus machine-created color in conjunction with real-time color feedback loops will be addressed. Design issues including system stability, color resolution, channel matching, and target registration will also be discussed. Calibration routines and verification will be presented along with example results of the complete system.

Keywords: Color, Color Contrast, Visible, Collimator, Target, Integrating Sphere, Test Equipment

1. INTRODUCTION

There are a myriad of parameters commonly used to define the performance of an imager. Most consumer grade digital cameras tout spatial resolution as their imperative specification. Beyond the ubiquitous megapixel rating of the camera's sensor, sensitivity is the only other basic advertised key specification. For a monochrome system this may be all that is required to understand sensor performance - the number of active pixels and how sensitive they are to light. Along with spatial resolution and sensitivity, color camera specifications need to include color accuracy and resolution. Accuracy of an imager is mainly dependent on proper white balance and effective filter pattern processing routines. Color accuracy is typically established using a variety of test charts with known illuminants. Unfortunately it is not practical to verify color resolution in a similar manner. Instead of attempting to employ various controlled charts of millions of colors it is more efficient to use a calibrated color projector capable of reproducing dual color controlled images filling the full format of the camera under test.

While all current color cameras can benefit from color resolution testing, future broadband, or fused, systems will necessitate this type of analysis as well. Modern fused imagers typically employ both a monochrome sensor that has response in the visible wavelengths and one that is active in the infrared, fusing both of these signals into a meaningful false color image. Future broadband systems may employ multiple sensors, including color. Since these systems require temperature resolution testing of the infrared sensor it would be prudent to analyze the color resolution of the visible sensor as well.

Over 30 years ago, a standard was developed for human color perception. The CIE1976 mathematically transforms the colors humans perceive into the three axis CIE $L^*a^*b^*$ color space, where L^* is intensity, a^* is chromaticity, and b^* is saturation. Using these coordinates, color differences can be calculated and given the figure of merit ΔE . Human observers can differentiate ΔE values of 0.5 to 1.0, typical single sensor color cameras are capable of ΔE measurements of 3 to 6. In the man-machine interface this represents a loss of information; compare this to night vision sensors where the sensor provides more information than the naked eye. For critical applications, the minimum color contrast measurement is an important criteria in camera selection.

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The setup required to test the relative color delineation, or color resolution, of a camera consists of a single optical system fed by dual discrete color inputs and inverse target patterns. The hardware is controlled from a single software application that includes a series of test modules designed to establish the relative color resolution of the camera under test. Each color source is under closed loop control and the overall system output is calibrated.

2. COLOR SOURCES

In order to project a test image, a uniform source of energy is first required to fully illuminate an imaging plane. In this case there are two imaging planes each with their own color source. These sources are matched outside of the optical system and then calibrated through the full optical path. Each color source employs dual closed loop control ensuring that their outputs' luminance and spectral content are stable.

2.1 Color Generation

Discrete colors are generated in each of the two channels of the system using a set of subtractive filters fed by a Quartz Tungsten Halogen (QTH) lamp. QTH lamps are simple to control and readily commercially available making them an attractive system consumable. Each lamp is powered by a stable power supply, utilizing a motorized mechanical attenuator to control luminance. See Figure 1 for the typical spectral distribution of the lamps used in the system.

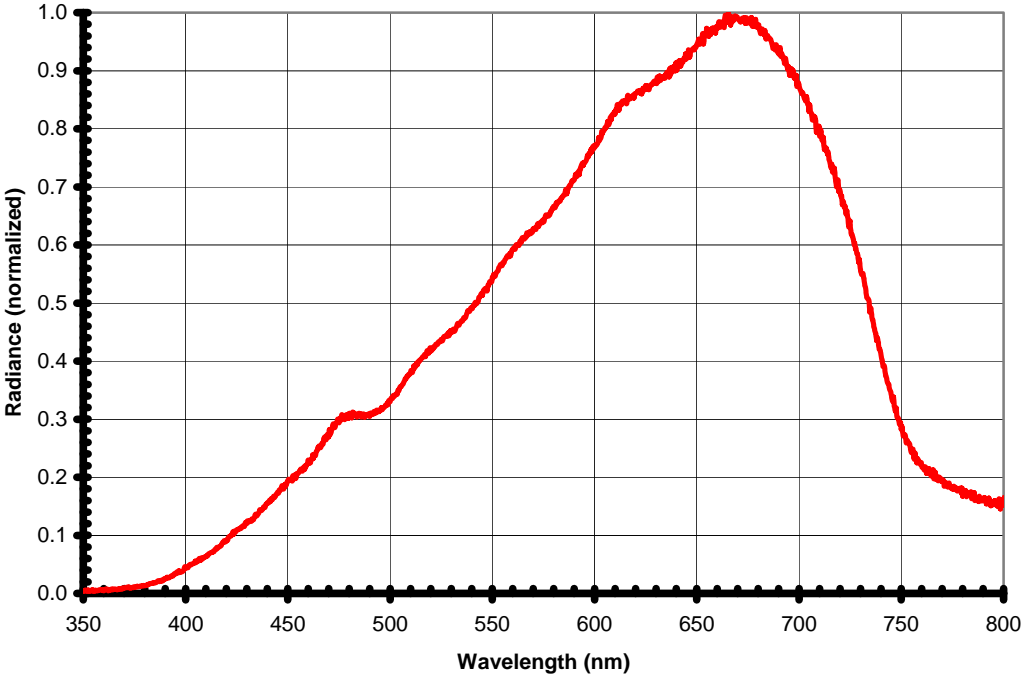


Figure 1. Color Generator QTH Lamp Normalized Spectral Radiance

A three piece matched subtractive filter set consisting of cyan, magenta, and yellow filters is used to shape the spectral output of the QTH lamp. See Figure 2 for typical filter spectral transmission. Each filter is mounted to a precisely controlled motorized arm which is used to position it in and out of the optical path, thus controlling its relative spectral influence.

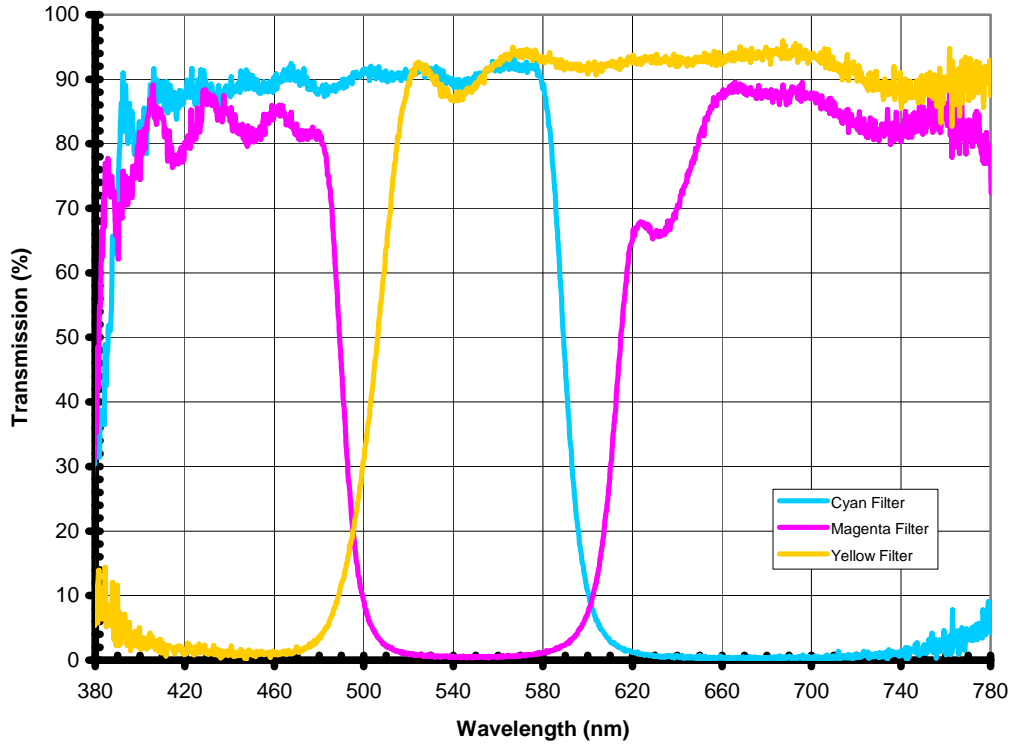


Figure 2. Color Generator Filter Set Spectral Transmission

2.2 Light Integration

Each color source employs a dual integrating sphere design to ensure that the spectrally shaped light is properly blended and uniform at the imaging plane. The QTH lamp is first fed through the attenuator and into the primary sphere. This sphere is responsible for integrating the output of the QTH so that it will be uniform when it reaches the filter plane. A method to select spectrally matched lamp pairs was developed to make the light generation consistent among both channels. The primary sphere is fed into the secondary sphere through the filter plane coupling. The secondary sphere integrates the effects of the relative filter positions to blend the shaped color into a uniform continuous output at the imaging plane. See Figure 3 for a diagram of the dual sphere design.

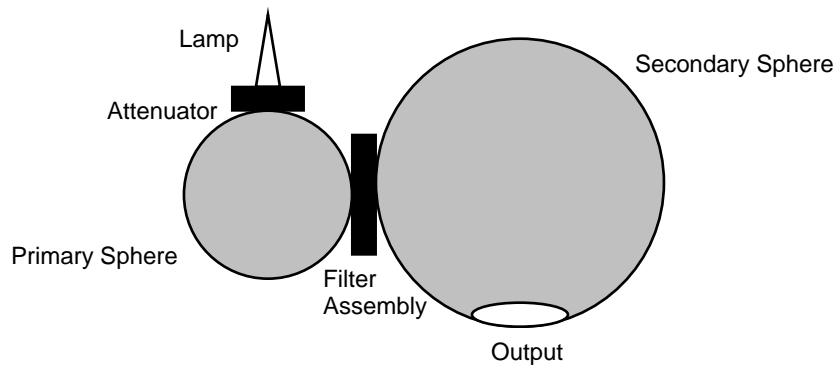


Figure 3. Color Generator Dual Sphere Design

2.3 Control

Each color source employs dual closed loop control by means of discrete sensors in both the primary and secondary spheres. A silicon based detector is located in the primary sphere and is the source of the luminance feedback. A spectrometer is installed within the secondary sphere providing spectral feedback. See Figure 4 for a diagram of the sensor and feedback loops.

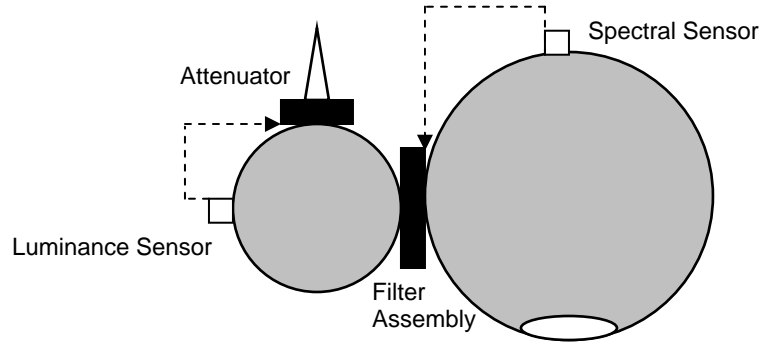


Figure 4. Color Generator Control Loop Design

3. TEST TARGETS

At the heart of any image analysis system is the test target. The radiation source shines through the target and the projection optics present the target to the sensor under test. The target pattern defines the test image and much of the subsequent analysis.

3.1 Target Design

In order to present a dual color controlled image the targets were designed in pairs, one to represent the foreground of the image and the other for the background. The foreground targets appear as a negative impression where all of the target is opaque only allowing light through the desired feature and its corresponding background target is the inverse, or positive impression, of the same pattern. See Figure 5 for a captured sample target image set to an exaggerated color disparity.

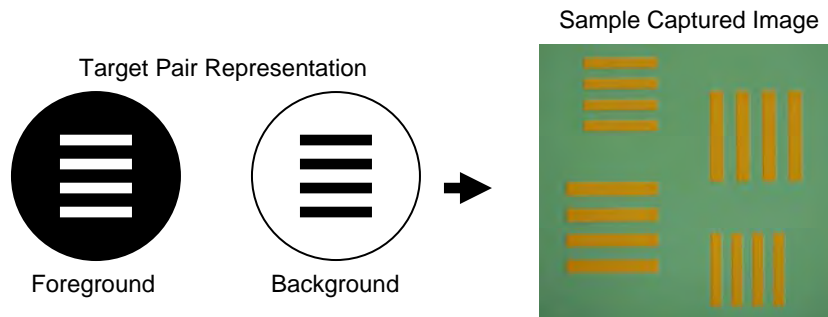


Figure 5. Sample Target Image with Exaggerated Color Disparity

3.2 Target Construction

Each target assembly consists of a glass inlay fixed into a metal holder which is installed in a multi position motorized target wheel. See Figure 6 for a system photo showing the location of the target wheel assembly. The target pattern is imaged onto its glass substrate using a black chrome photo etching process and finished with an anti-reflection coating on both sides. Each glass inlay is mounted into a metal frame to facilitate handling, mounting, and adjusting. The foreground and background channels each employ a single target wheel, thus allowing up to twelve target pairs. Target position is under closed loop control by means of a high resolution encoder mounted to the target wheel rotational axis. In addition to the fine angular adjustment provided by the hub encoder, each target frame allows for precise X-Y-Z alignment by means of a series of set screws.

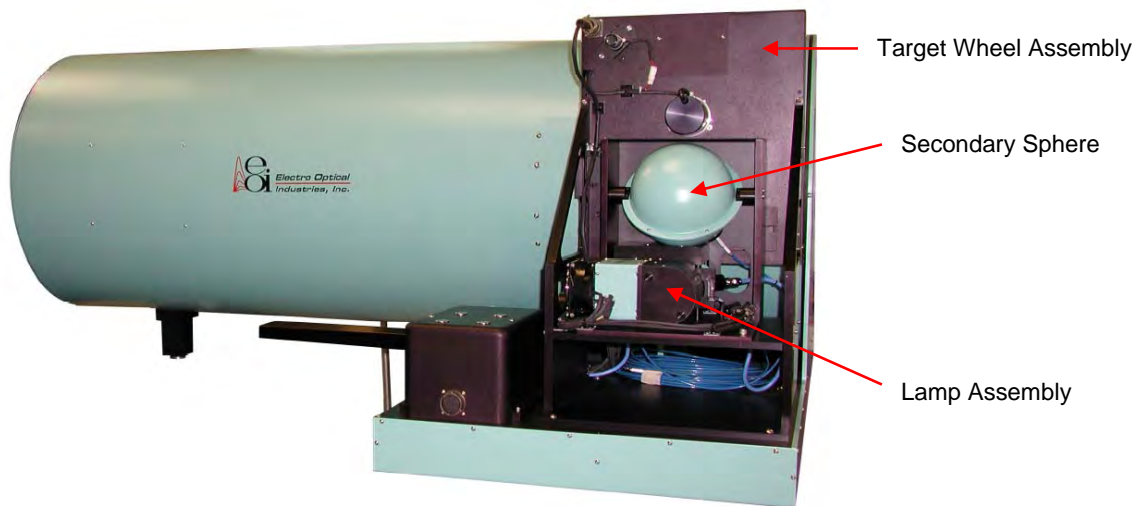


Figure 6. Color Contrast Projector System

4. OPTICS

The projector is designed to test a color camera, including optics, thus an optical system with collimated output is preferred. In an effort to maintain spectral fidelity it is ideal to employ an all reflective optical system, although in some applications it is simply not practical. Since this collimator includes two discrete input channels, foreground and background, a refractive beam splitting element is utilized in collaboration with the rest of the all reflective system.

4.1 Collimator

Typical reflective collimators can consist of merely one fold mirror and one off-axis parabolic mirror. This simple design can be used in most all systems that contain a single image plane and single output aperture. Unfortunately the collimator required for relative color delineation testing requires two imaging planes and a single output aperture. The design of this system utilizes one fold mirror, one off-axis parabolic mirror, and one refractive beam splitting element. See Figure 7 for a diagram of the optical system.

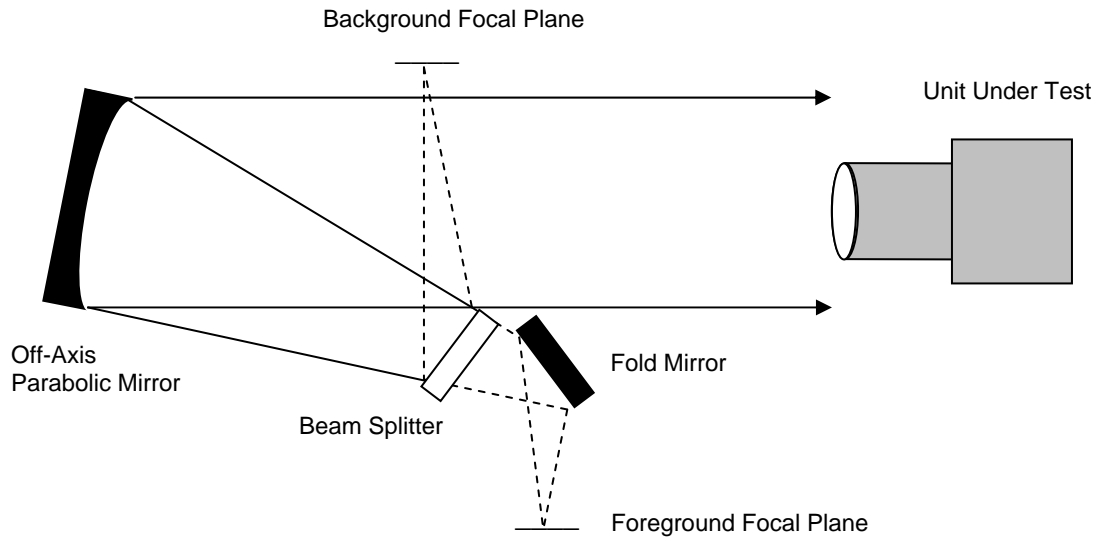


Figure 7. Optical System Diagram

4.2 Beam Splitter

The refractive beam splitting element is required to combine foreground and background channels both spectrally and spatially. Imperfections in the spectral distribution were effectively calibrated out via the absolute color calibration that was performed at the exit aperture of the collimator, through the complete optical system. Spatial effects proved more difficult to mitigate. Positional registration was improved by carefully aligning the matched target pairs once installed in the wheel. Other imaging artifacts proved inherent to various beam splitter substrates and required an iterative solution approach.

5. SOFTWARE

The application software for the system encompasses direct control of each channel including luminance, color, target position, and neutral density filter attenuation. In addition to hardware control the application includes a set of defined imaging tests designed to establish the relative color delineation specifications of the camera under test.

5.1 Calibration

CIE $L^*a^*b^*$ was chosen as the color space to work within for its expansive range and its inherent design to approximate human vision. The a^* and b^* terms are Cartesian coordinates for the color map and the L^* term corresponds closely to the human perception of “lightness”. In order for an absolute color to be specified in CIE $L^*a^*b^*$ a whitepoint must also be defined. Before completing any color testing the system software prompts the user to validate the color references for improved accuracy. This automated task runs simultaneously on each channel placing all color filters, one by one, into the full optical path to collect spectral readings and concludes by removing all filters and recording a whitepoint value. See Figure 8 for a screenshot of the application window. This calibration routine effectively incorporates any spectral aging effects of the lamps and filters. Changes in the lamps can affect the whitepoint and thus the CIE $L^*a^*b^*$ absolute color. Aging of the filters can degrade the efficiency of the calculation routines required for translating CIE $L^*a^*b^*$ into relative filter position.

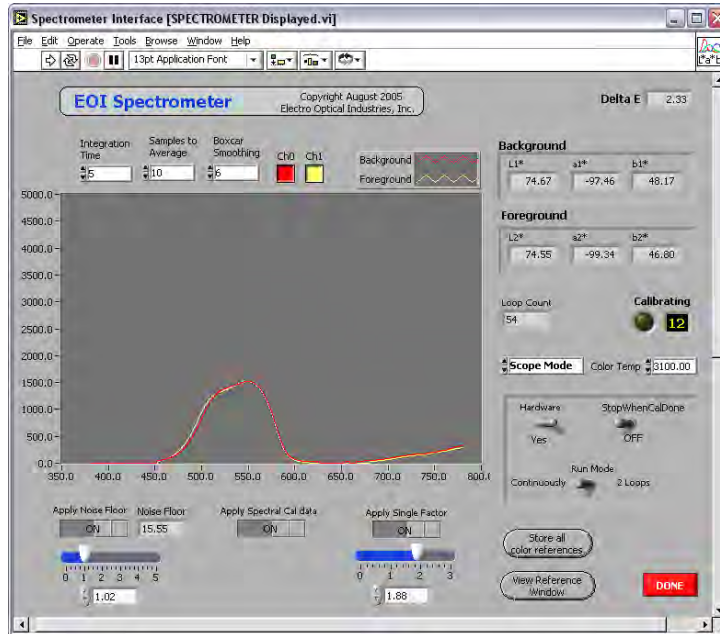


Figure 8. Color Reference Validation Window

The figure of merit used to describe color difference is called Delta E, or more specifically ΔE^*_{ab} as it is defined in CIE76. See Equation 1 for color difference in terms of Delta E between $L_1^*a_1^*b_1^*$ and $L_2^*a_2^*b_2^*$.

$$\Delta E^*_{ab} = [(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2]^{1/2} \quad (1)$$

5.2 Control

The control capability of the application software comprises options for setting target position, neutral density filter attenuation, luminance, and color. See Figure 9 for a screenshot of the main control window. Target position can be set to one of any of the twelve predefined positions and include an option for offsetting by single encoder counts for trimming alignment. Neutral density filter attenuation is a simple three option menu that essentially includes settings for filter A, B, or none. The luminance control is used to define the setpoint of the closed loop lamp attenuator control. Colors are set in the CIE $L^*a^*b^*$ color space by discrete L^* , a^* , and b^* inputs and are available for preview.

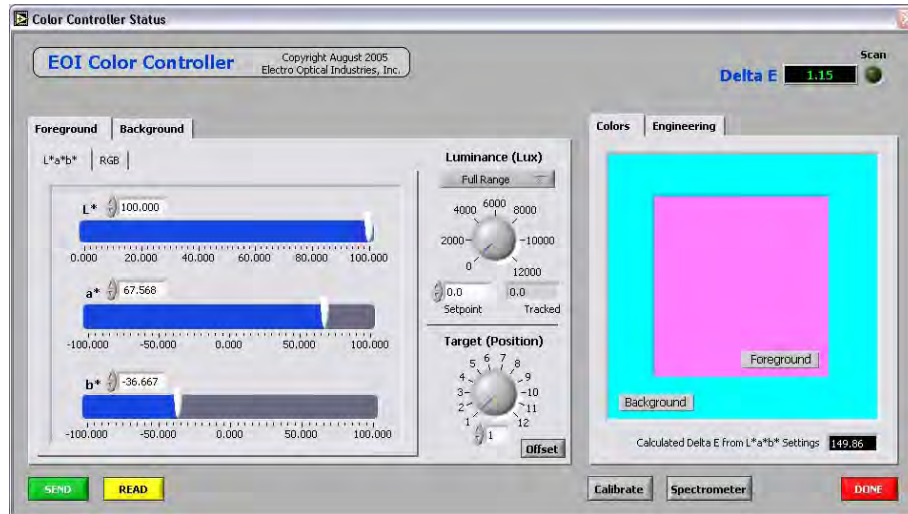


Figure 9. Main Control Window

It was determined that the most efficient control algorithm was greatly dependent on color space region thus various algorithms were developed. These included Open Loop, CMY Closed Loop, CMY-L Closed Loop, Logic Closed Loop, and H-Array Closed Loop. For added flexibility $L^*a^*b^*$ result priority can be set to equal (default), L^* , a^* , b^* , or a^*b^* . See Figure 10 for a screenshot of the main control window advanced options tab.

The Open Loop control scheme, which sets the color filter positions one time, is based on the theoretical $L^*a^*b^*$ to CMY conversion. The CMY Closed Loop control option initially sets the color filters by an open loop approximation and then moves into a one-half closing-in loop until the defined number of iterations has been reached. CMY-L Closed Loop control is identical to CMY Closed Loop with the exception that luminance is also adjusted during the closing-in iterations. Logic Closed Loop employs an empirically derived proprietary logic tree to reach the desired setpoint in the defined number of iterations. The H-Array Closed Loop is an expansion of the Logic Closed Loop as it initially employs the same logic tree but adds an additional step of complexity by compiling a historical array of iteration setpoints and results then uses them to tune the output of the logic tree design. Typically the best results were achieved using the proprietary H-Array Closed Loop Control algorithm.

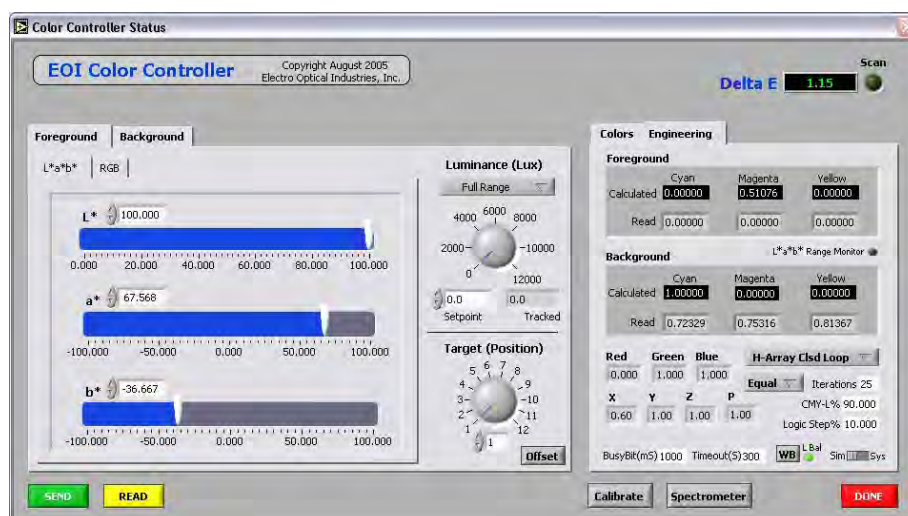


Figure 10. Main Control Window Advanced Options

5.3 Analysis

The image analysis section of the application software includes three individual test modules dependent on Delta E color difference and are designed to ascertain the relative color delineation of the camera under test. Minimum Detectable E Difference (MDED) is used to quantify the minimum color difference that is detectable by a trained operator in a test image of two colors. The result of the MDED test is a plot of measured Delta E recorded for at least three pinhole array targets, of various spatial frequencies, that the operator was able to detect. See Figure 11 for a screenshot of a sample MDED result window.

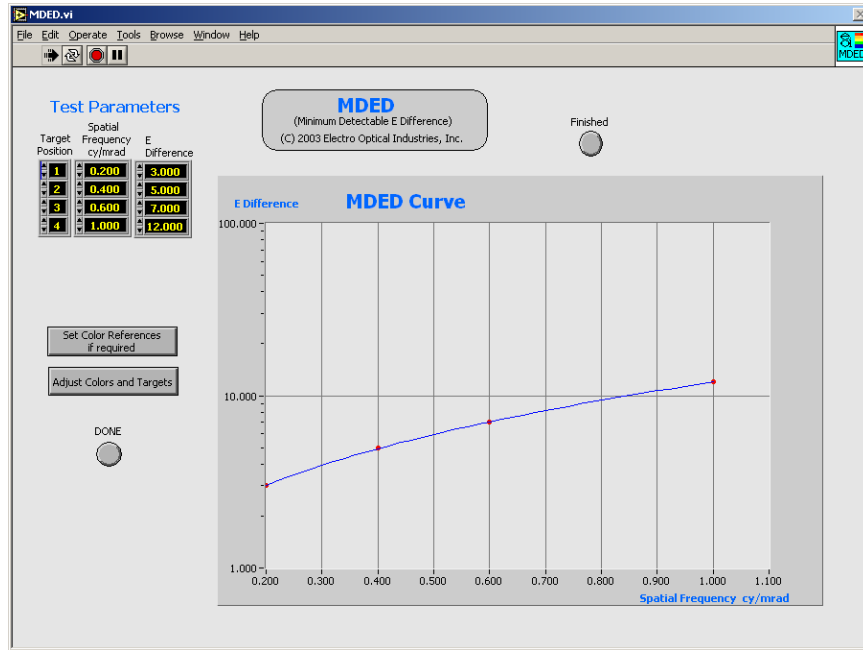


Figure 11. Minimum Detectable E Difference Test Result Window

Minimum Resolvable E Difference (MRED) is used to quantify the minimum color difference that is resolvable by a trained operator in a test image of two colors. The result of the MRED test is a plot of measured Delta E recorded for at least three 4-Bar targets, of various spatial frequencies, that the operator was able to resolve. The result window is very similar to the MDED sample shown in Figure 10.

Noise Equivalent E Difference (NEED) is a color sensitivity figure of merit defined by Equation 2.

$$NEED = (\Delta E) / (\text{Signal/Noise}) \quad (2)$$

Using a square target image with a color difference that is perceivable by a trained operator, areas of signal and background are defined and signal to noise ratio is calculated. See Figure 12 for a screenshot of the NEED test window.

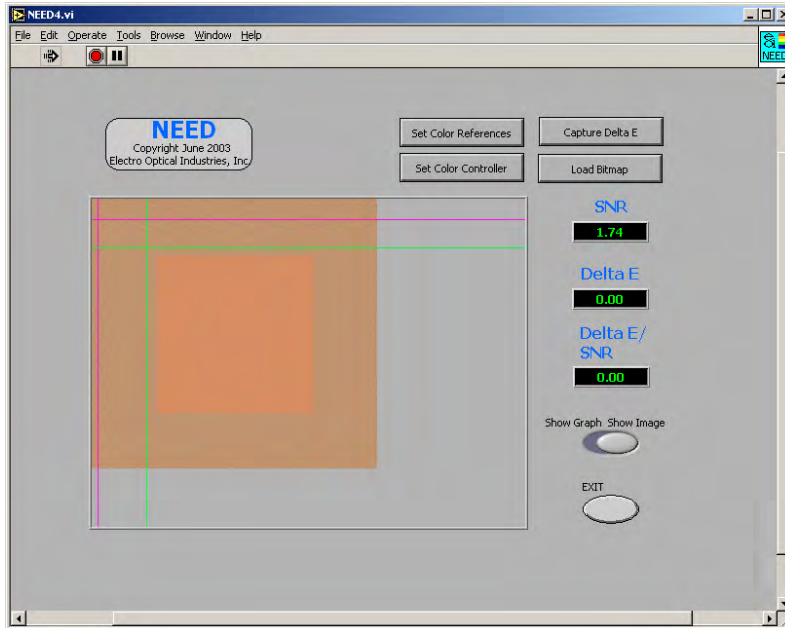


Figure 12. Noise Equivalent E Difference Test Window

6. RESULTS

The fully completed color contrast projector was run through a myriad of performance tests to establish operating specifications. Testing spanned all components of the system including lamps, attenuators, filters, targets, optics, and software. Of the comprehensive testing outline three main specifications serve to summarize system capability: color resolution, output stability, and image registration.

6.1 Resolution

Absolute color resolution of each channel is theoretically limited by the precision of filter positioning within the active optical path. The filter encoders on the current system allow for 3350 discrete positions. Given three filters this translates to 3350^3 or 37,595,375,000 possible colors.

Another, possibly more meaningful, measure of color resolution is that of minimum projection contrast between the foreground and background channels. Given the system operates in the CIE $L^*a^*b^*$ color space, contrast measurements are reported in CIE76 ΔE^*_{ab} or Delta E. See Equation 1. As was mentioned in section 5.2 efficient color control algorithms vary greatly depending on color space region. For this reason minimum projection contrast is not a constant value. See Tables 1 and 2 for Delta E results at various chosen colors for high and low light levels, respectively.

Table 1. High Light Level Foreground-Background Delta E

L*	Set Point			Lux	ΔE
	a*	b*			
50.73	0.17	-0.12	5000	5.40	
48.18	64.51	72.83	5000	2.67	
49.73	-68.11	54.89	5000	6.54	
44.45	-5.15	-2.84	5000	7.61	
48.17	-0.82	-2.69	5000	5.48	
50.13	1.59	1.41	5000	6.96	
88.34	0.12	2.66	10000	6.92	

Table 2. Low Light Level Foreground-Background Delta E

L*	Set Point			Lux	ΔE
	a*	b*			
50.73	0.17	-0.12	100	5.65	
48.18	64.51	72.83	100	7.00	
49.73	-68.11	54.89	100	1.51	
44.45	-5.15	-2.84	100	4.97	
48.17	-0.82	-2.69	100	5.45	
50.13	1.59	1.41	100	5.58	
100	0	0	100	8.93	

6.2 Stability

Luminance stability proved critical to maintaining accurate projection contrast and absolute color. After the lamp warmed up to operating temperature luminance was controlled via a closed loop between the light detector in the primary sphere and a mechanical attenuator on the lamp assembly. The attenuator was also driven closed loop by means of feedback from an encoder on the positioning mechanism. Both of these control loops were managed by software that was tuned for maximum luminance stability. See Figure 13 for luminance stability results.

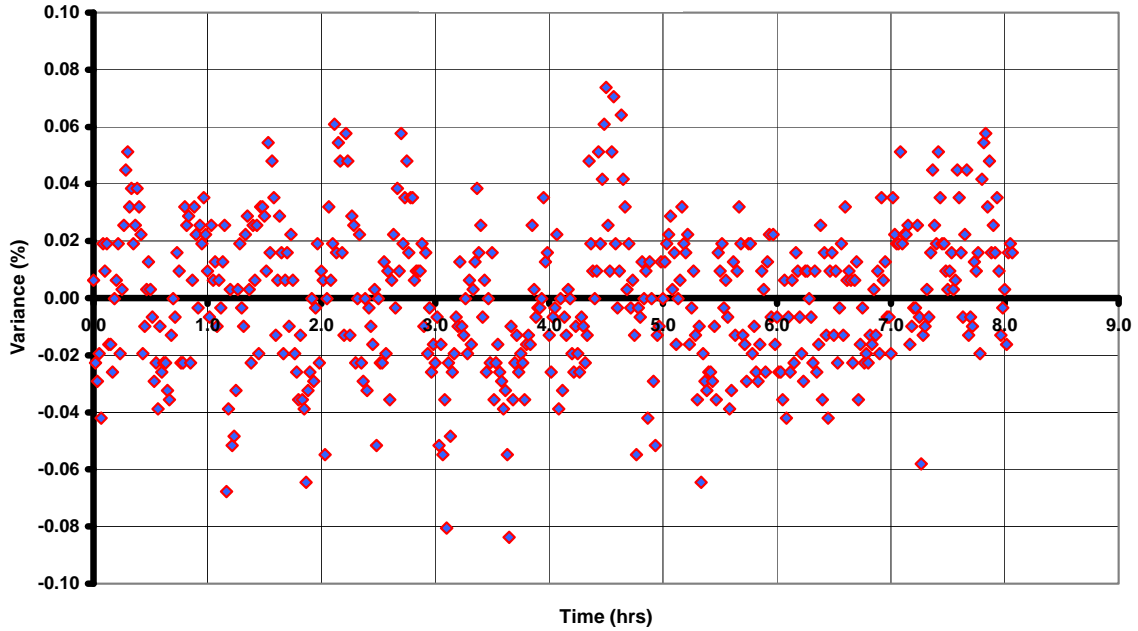


Figure 13. Luminance Stability

6.3 Registration

Since the projected dual color controlled image is actually a fusion of foreground and background channels, target registration is imperative to imaging performance. The target mounting hardware and positioning system allow for numerous axes of automated and manual target adjustment yet it still proved difficult to match each target pair precisely. Given the foreground astigmatism introduced by refraction through the beam splitter, target alignment data is difficult to quantify by means of image analysis. See Table 3 for an approximation of spatial target registration error.

Table 3. Target Registration Error

Target	Alignment		
	Linear X (mm)	Linear Y (mm)	Angular (mrad)
1	0.015	0.015	0.5
2	0.030	0.015	0.8
3	0.015	0.015	0.4
4	0.030	0.015	0.3
5	0.030	0.015	1.2
7	0.030	0.015	0.3
8	0.030	0.030	0.4
9	0.030	0.015	1.3
10	0.030	0.030	1.5
11	0.030	0.030	1.5

7. IMPROVEMENTS

During the performance testing of the system many aspects of the original design were scrutinized in an effort to maximize performance of subsequent proposals. Although time and budget did not allow for exploration of the ideas for enhancements, based on the extensive testing of the current system we are confident that the changes will affect the system positively.

Much of the proposed design modifications revolve around the color filter assembly. As is shown in Figure 2 the matched filter set left gaps in spectral coverage that required compensation elsewhere in the system, often in the software driven color making algorithms. With a customized filter set the system will be more efficient and be able to reproduce a broader range of minimum contrast colors. While under manual control, the current design was able to accomplish Delta E values as low as 0.3, incorporating planned changes should enable the system to meet this consistently while driven programmatically. In addition, by increasing the resolution of the filter positioning encoders we can expect to increase the theoretical discrete number of possible colors from over 37 billion to almost 154 trillion.

Luminance control was also an area of significant design discussion. The three main areas to investigate for improvement in the light control include: providing tighter control of the attenuator, enhancement of the stability of the lamp power supply, and improving the stability and lowering the noise of the detector. Additionally the lamp itself comes under scrutiny since it is the permutation of the filter set and the white light source responsible for accurate color making. A higher color temperature lamp closer to the noon sun spectral such as a Xenon Arc may prove more effective than the current QTH design, especially in the blue end of the color space.

8. CONCLUSION

There is currently a need to characterize the relative color delineation of color camera systems. The main obstacle preventing the pervasiveness of this type of analysis is the test equipment itself. This equipment is not simple in design and encompasses many design challenges ranging throughout the system including the color sources, targets, optics, and software. These challenges, though, have been met and have even progressed towards future designs addressing current issues as well as those that are still undergoing definition. Color contrast performance is a complex specification but so are the imaging systems that could benefit from its classification. Digitally fused sensor systems comprised of color cameras are still in their early stages but they will shortly become common place and will require methods for performance verification. The ability to evaluate color contrast over a wide range in the color space will be a key criterion in selecting which camera to include in multispectral imagers. Spatial resolution and general sensitivity may be enough for consumer grade cameras of today but users will soon demand meaningful color performance specifications.

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