Report #17-UR-049

NSTSCE

National Surface Transportation
Safety Center for Excellence

Color Camera

Jason E. Meyer • Ronald B. Gibbons • Caroline A. Connell

Submitted: February 28, 2017

Impairment
Technology
Infrastructure
Mobility

Housed at the Virginia Tech Transportation Institute
3500 Transportation Research Plaza • Blacksburg, Virginia 24061

ACKNOWLEDGMENTS

The authors of this report would like to acknowledge the support of the stakeholders of the National Surface Transportation Safety Center for Excellence (NSTSCE): Tom Dingus from the Virginia Tech Transportation Institute, John Capp from General Motors Corporation, Chris Hayes from Travelers Insurance, Martin Walker from the Federal Motor Carrier Safety Administration, Lincoln Cobb from the Federal Highway Administration, and Cathy McGhee from the Virginia Department of Transportation and the Virginia Transportation Research Council.

The NSTSCE stakeholders have jointly funded this research for the purpose of developing and disseminating advanced transportation safety techniques and innovations.

EXECUTIVE SUMMARY

Background

Under the sponsorship of the National Surface Transportation Safety Center for Excellence (NSTSCE), a research team at the Virginia Tech Transportation Institute (VTTI) developed a color camera system that can collect naturalistic video data with accurate color rendering.

Photometric devices can accurately measure color but cannot record the video data necessary for understanding visibility in dynamic environments like nighttime driving. Video recorders can take video data but are inaccurate with respect to color measurement. To measure color and its effects on visibility in naturalistic settings, a color camera system was developed that can record video data with color rendering similar to what humans perceive. This system includes a calibrated color camera and image analysis software.

Methods

The camera system was selected and calibrated in different lighting scenarios using a standard color chart. Custom MATLAB programs were used for this calibration. These calibration files were compared for color-rendering accuracy, and the best file, based on calibration in daylight, was selected for further analysis. Researchers then used the color camera system, calibrated with the daylight file, to collect data in a variety of naturalistic settings. The color space coordinates from the color camera's images were compared with those taken with a color meter and a digital photometer.

Results

When the camera was calibrated to daylight, it produced the most-accurate images, even when taking images in artificial lighting. Shorter exposure times produced darker images but more-accurate color space coordinates. After calibration and exposure adjustment, the color camera's chromaticity coordinates (x, y) had about 10% error with respect to the color meter. The color camera's luminance value (Y) had less than 5% error with respect to the color meter. The calibration file produced can be used with multiple cameras.

A new image analysis method was developed. It and its accompanying custom MATLAB programs allow researchers to select portions of an image and analyze their three-dimensional color space coordinates. This capability will be useful in future work; for example, comparing photometric equipment, and analyzing naturalistic video data.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

CIE	International Commission of Illumination
HPS	high pressure sodium
LED	light-emitting diode
NSTSCE	National Surface Transportation Safety Center for Excellence
VTTI	Virginia Tech Transportation Institute

CHAPTER 1. INTRODUCTION

With the sponsorship of the National Surface Transportation Safety Center for Excellence (NSTSCE), a research team at the Virginia Tech Transportation Institute (VTTI) developed an image capture system to record and analyze accurate color video data gathered in naturalistic driving research.

Color measurement is important when studying visibility, especially visibility in nighttime driving scenarios; color perception changes with the ambient lighting level, affecting color contrast and visibility. This project addressed a deficiency in naturalistic driving research, where data-collection instruments must continuously record data while being as unobtrusive as possible. However, devices that measure color, like handheld color meters and digital photometers, are unwieldy and do not take video data. While many cameras record video in color, they do not necessarily render color data accurately, in a manner congruent with human color vision.

The purpose of this project was to develop a color camera system that accurately records color video data of nighttime driving scenarios. The system developed includes a calibrated camera to collect images and a subsystem to accurately analyze and report the images' color data. The remainder of this report provides technical background on measuring color and describes the system, the selection of camera hardware, the calibration procedure, and the comparison that was performed between the color camera and other color measurement devices.

QUANTIFYING COLOR

Color is a multidimensional construct. The hue of an object is the dominant wavelength of light reflected from the object. Color saturation is the extent that a color is composed of a single wavelength of light. Hue and color saturation together form the chromaticity of a color. Luminance is the brightness of an object as perceived by a human; it is not equivalent to radiance, or absolute brightness. Luminance, hue, and color saturation all factor in to how humans perceive color.

Two methods to quantify color were used when calibrating and testing the color camera for this project. The first method was based on the International Commission of Illumination (CIE) 1931 XYZ color space,(1) where X is a combination of the different cone response curves, Y is luminance, and Z is analogous to blue cone stimulation. Together, X, Y, and Z are analogous to the eye's cone response. Here, the CIE xyY color space was used, where x and y are chromaticity coordinates derived from the X, Y, and Z values of a color, and range from zero to one, and Y is luminance (Figure 1).

The second color quantification method used was the CIE 1976 Lab (L*a*b*) (CIELAB) color space.(2) In this color space, color values are also calculated using X, Y, and Z values but are more perceptually uniform that the 1931 XYZ color space, so a change of color value for any color corresponds to the same perceived change in color. In the CIELAB color space, L represents lightness, calculated from relative luminance, and a and b are chromaticity coordinates, similar to x and y in the CIE xyY color space.

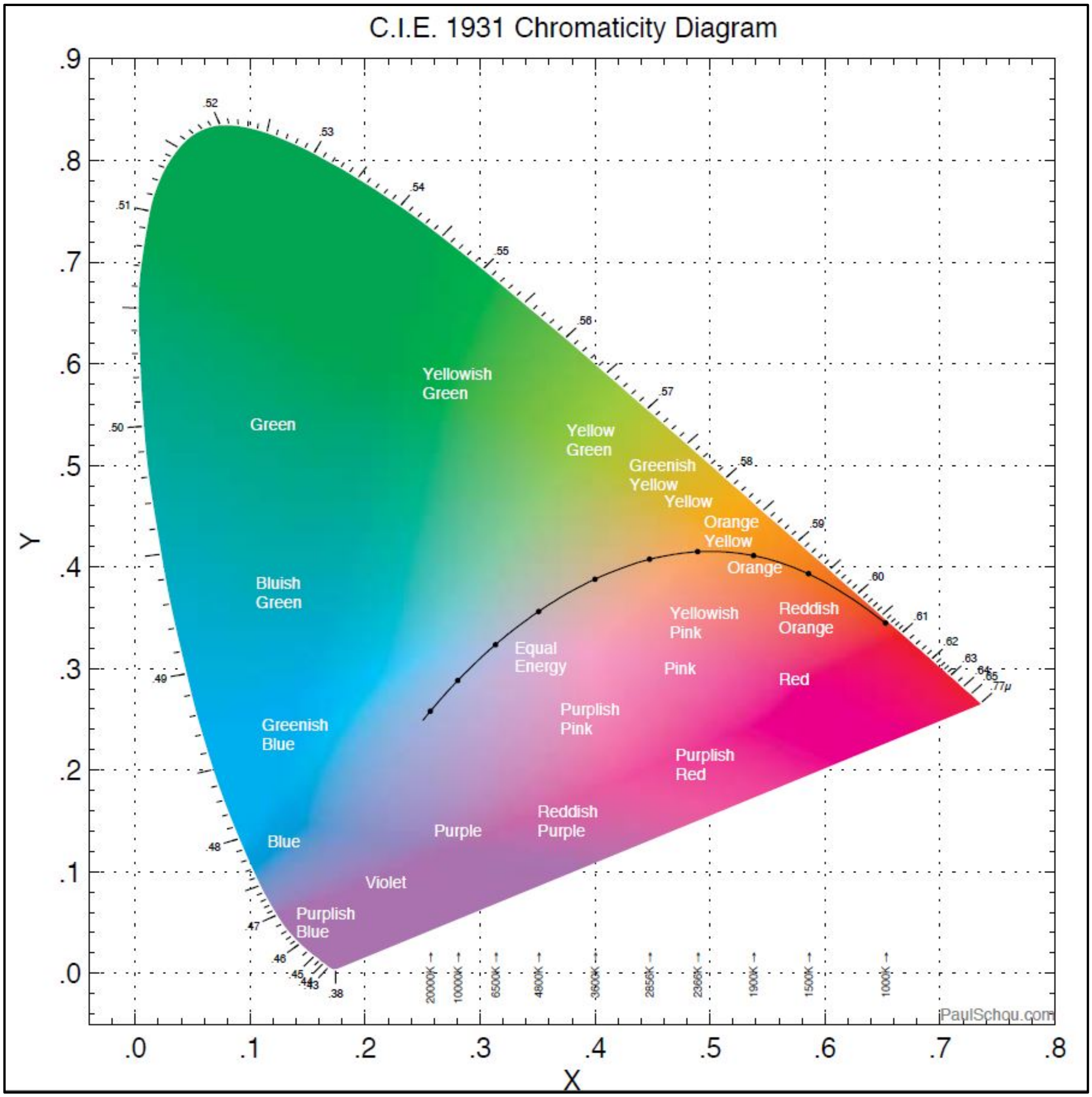


Figure 1. Diagram. CIE 1931 xy chromaticity chart.

MEASURING COLOR

The human eye has cones specialized to detect red, green, and blue light. Cameras capture color in a similar way by using three color channels in red, green, and blue. Each pixel detects one of those colors. The three images, one from each channel per set of pixels, are run through a de-mosaicking algorithm that combines the color values of a pixel and its eight neighbors to create a full 24-bit color value for that pixel. This processing, however, can take time as three images are required. This does not work for moving application as the three images will not be compatible as the vehicle moves.

The major effort of this project was to use a single image with color data and develop an algorithm combining the color values of the camera as similarly as possible to how humans perceive color, and then apply the algorithm to naturalistic video data.

CHAPTER 2. SYSTEM OVERVIEW

HARDWARE

The color camera system included a Point Grey Flea2 (FL2) color camera (Figure 2). This camera was an appropriate size for mounting inside the windshield, was compatible with the camera currently used by VTTI for luminance measurements, and provided the resolution and sensitivity required for the application.

Figure 2. Photo. Point Grey Flea2 camera.

The camera was connected to a laptop computer using a 9-pin 1394b (Firewire 800) serial bus cable and a PCMCIA (PC) card that enabled communication between the computer and camera. The laptop was a Dell E6400 with an Intel Core 2 Duo processor running at 2.26 GHz. The PC card was a LaCie (16 or 32 bit) card with multiple 6-pin or 9-pin Firewire jacks, allowing multiple cameras to use it to connect to a laptop. The system was powered using standard Dell power supplies: a 120-V AC power supply for working outside a vehicle and a 12-V DC power supply for working inside the test vehicle.

SOFTWARE

The research team created two custom programs for this project. The calibration program was custom MATLAB code that calibrates the color camera for different lighting scenarios, and is described in the next chapter. The analysis program, also a custom MATLAB program, allows researchers to select regions of an image to compare how different color measurement devices report the region’s color.

CHAPTER 3. CALIBRATION METHODOLOGY

After the hardware was selected and set up, the color camera system was calibrated to take color video data that aligned as closely as possible with human vision. Calibration was performed using a white surface and a multi-color test chart.

CALIBRATION EQUIPMENT

The white surface, an 85% reflective projection screen mounted on a stand, was the starting point for color calculations. The diffuse screen ensured that light was uniformly reflected.

The color calibration was performed using a GretagMacbeth ColorChecker chart that allowed the system's color processing to be compared to human color vision. Both calibration tools are shown in Figure 3.

Figure 3. Images. Camera calibration equipment: diffuse white surface (left) and GretagMacbeth ColorChecker (right).

CALIBRATION PROCEDURE

The camera was set up facing the calibration equipment. The ColorChecker chart was placed in front of the diffuse white screen. Targets typically used in visibility experiments at VTTI were also placed in the scene because researchers were interested in how the color camera would measure their color. An example of the calibration scene is shown in Figure 4.

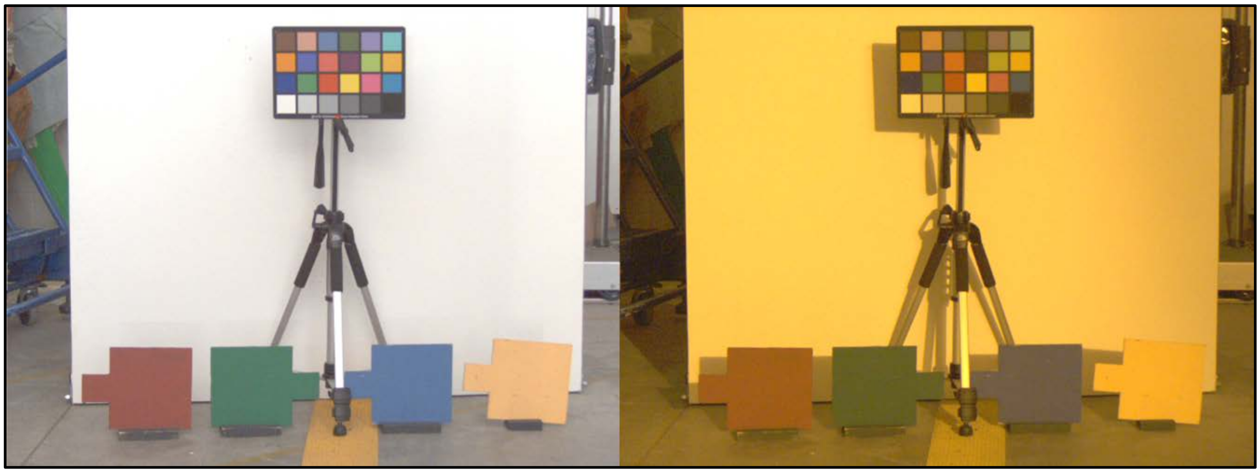


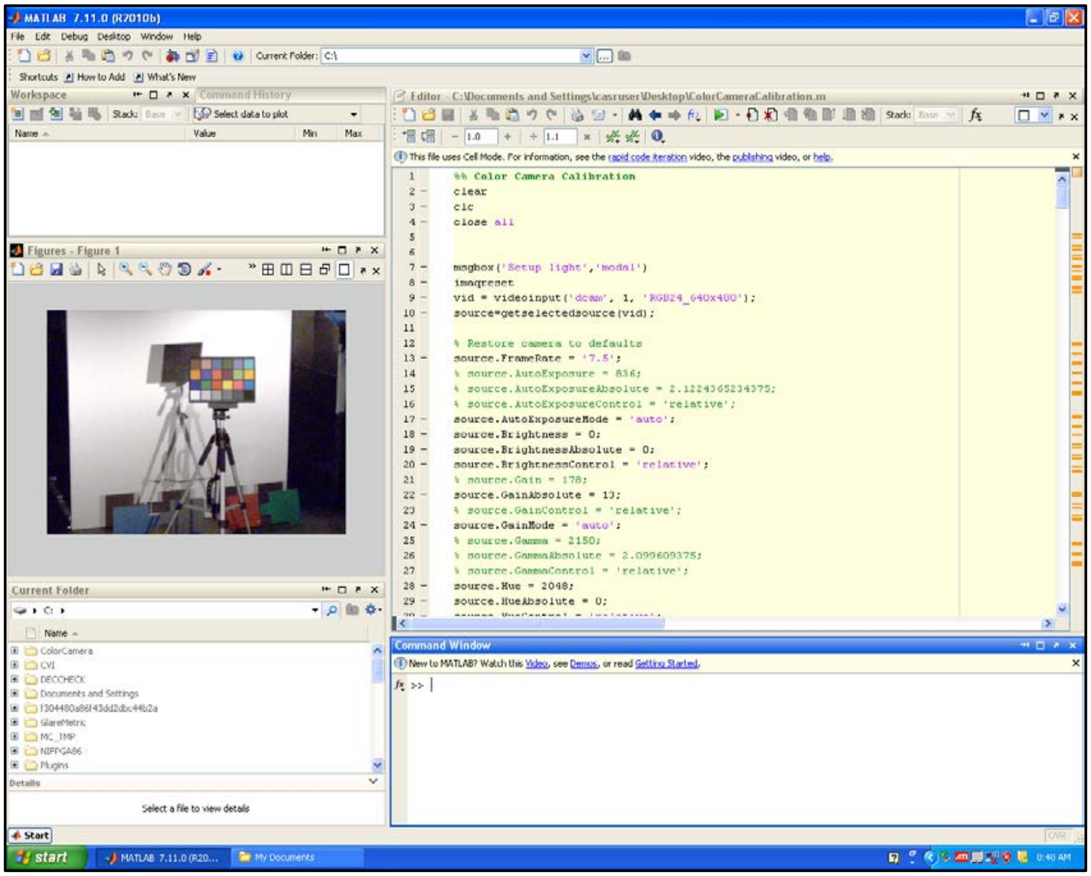
Figure 4. Photo. Calibration scene with daylight (left) and HPS lighting (right).

Once the scene was set up and the camera positioned to take images of all the items, images of the scene were taken with a several different light sources, which are listed in Table 1.

Table 1. Calibration light sources.

Calibration Light Sources
Daylight
High pressure sodium (HPS)
Metal halide
Light-emitting diode (LED) (3500K)
LED (6000K)
Tungsten halogen headlamps

The calibration procedure began with analyzing a “white” image to establish a baseline for determining and defining color. The diffuse white screen was used primarily for this purpose. Following this, multiple images were taken of the multiple colors composing the color chart. Next, a calibration program analyzed the red-, green-, and blue-colored squares. A screenshot of that program is shown in Figure 5.



This file uses Cell Mode. For information, see the rapid code iteration video, the publishing video, or help.

```
%% Color Camera Calibration
clear
clc
close all


msgbox('Setup light','modal')
imaqreset
vid = videoinput('dcam', 1, 'RGB24_640x480');
source=getselectedsource(vid);

% Restore camera to defaults
source.FrameRate = '7.5';
% source.AutoExposure = 836;
% source.AutoExposureAbsolute = 2.1224365234375;
% source.AutoExposureControl = 'relative';
source.AutoExposureMode = 'auto';
source.Brightness = 0;
source.BrightnessAbsolute = 0;
source.BrightnessControl = 'relative';
% source.Gain = 178;
source.GainAbsolute = 13;
% source.GainControl = 'relative';
source.GainMode = 'auto';
% source.Gamma = 2150;
% source.GammaAbsolute = 2.099609375;
% source.GammaControl = 'relative';
source.Hue = 2048;
source.HueAbsolute = 0;
```

New to MATLAB? Watch this Video, see Demos, or read Getting Started.

```
>> 
```

Figure 5. Screenshot. Calibration program.

The camera's CIELAB values for the red, green, and blue squares were compared with the values given by the chart manufacturers. The program then adjusted the camera control variables so that the camera's CIELAB values matched the chart's values. The control variables adjusted by the program are listed in Table 2.

Table 2. Camera control variables.

Camera Control Variable	Description
Exposure	Increment of time that the camera's electronic shutter stays open
Gamma	Defines the function between incoming light level and output picture level. Used primarily in emphasizing details in the darkest and/or brightest regions of the image.
Brightness (%)	The level of black in an image. A high brightness will result in a low amount of black in the image.
Saturation (%)	How far a color is from a gray image of the same intensity. For example, red is highly saturated, whereas a pale pink is not.
Gain (dB)	Amount of amplification applied to a pixel
White Balance	A method to enable white areas of an image to appear correctly by modifying the gain of the red and blue channels relative to the green

A calibration file containing the camera control variables (exposure, gain, white balance, etc.) for each lighting condition was generated. Those calibration files were tested by comparing the camera's performance with that of two other color measurement devices, a color meter and digital photometer, as described in the next chapter.

CHAPTER 4. DYNAMIC ROADWAY COMPARISON

In order to evaluate the efficacy and practicality of the color camera system, multiple comparisons were performed:

1. Automatic control of color camera to manually set and calibrated values
2. Calibrated values under multiple lighting types or colors
3. Color camera to color meter and digital photometer

The comparisons are described below. The results of the comparisons are presented in more detail in Chapter 5.

COMPARING THE COLOR CAMERA'S AUTOMATIC CONTROL MODE TO THE CALIBRATION FILES

The color camera is able to analyze ambient light and automatically adjusts its control variables using an automatic control mode. That automatic control mode was used as a baseline, and images using that mode were compared with those taken when the camera was operating in user control mode with the research team's calibration files. The baseline comparison was done as a proof-of-concept to show that the camera's automatic settings were not suitable for accurate chromaticity and luminance measurements.

COMPARING THE CALIBRATION FILES

To determine which calibration file produced an image most similar to what a typical driver sees, the color camera was programmed to take consecutive photos using the calibration files for daylight, 3500K LED overhead lighting, and 6000K LED overhead lighting. These images were then compared.

COMPARING THE COLOR CAMERA TO OTHER DEVICES

The color camera, calibrated using the different calibration files, was tested in a naturalistic multicolor environment to determine how the color and luminance values from the color camera compared with those from laboratory-standard photometric instruments, in this case a Radiant Imaging Model PM-9913E-1 digital photometer and a Minolta CS-100 luminance and color meter. To do so, all three pieces of test equipment were used inside a vehicle (Figure 6), and researchers used them simultaneously to capture similar images on routes with both multiple overhead lighting types and no overhead lighting.

Figure 6. Photo. Color camera evaluation setup.

Since the color camera’s exposure time affects luminance and chromaticity, images were taken using multiple exposure intervals to determine which exposure resulted in the least error compared to the other color measurement devices.

CHAPTER 5. RESULTS AND DISCUSSION

This chapter presents the results from the dynamic roadway comparison that was described in Chapter 4. Three comparisons were performed:

1. Automatic control of color camera to manually set and calibrated values
2. Calibrated values under multiple lighting types or colors
3. Color camera to color meter and digital photometer

COMPARING THE COLOR CAMERA’S AUTOMATIC CONTROL MODE WITH THE CALIBRATION FILES

Figure 7 shows a comparison the color camera’s automatic control mode with the daylight calibration file. The images from the camera in automatic control mode were blurry and oversaturated, whereas the images taken using the daylight calibration file were clearer, confirming that automatic control mode was not a viable option.

Figure 7. Photos. Images from color camera in automatic control mode (left) and using the daylight calibration file (right).

COMPARISON OF CALIBRATION FILES

Images of a scene with objects of different colors were captured with the color camera using the various calibration files. The color camera’s chromaticity coordinates for those colors were compared with the values obtained with the color meter. Images taken with the camera calibrated with 3500K LED lighting, 6000K LED lighting, and daylight are shown in Figure 8. The percentage error between the color camera and the color meter are shown in Figure 9 for five colors: red, orange, yellow, green, and blue.

Figure 8. Photos. Examples of color camera system calibrated to 3500K LED lighting (left), 6000K LED lighting (center), and daylight (right).

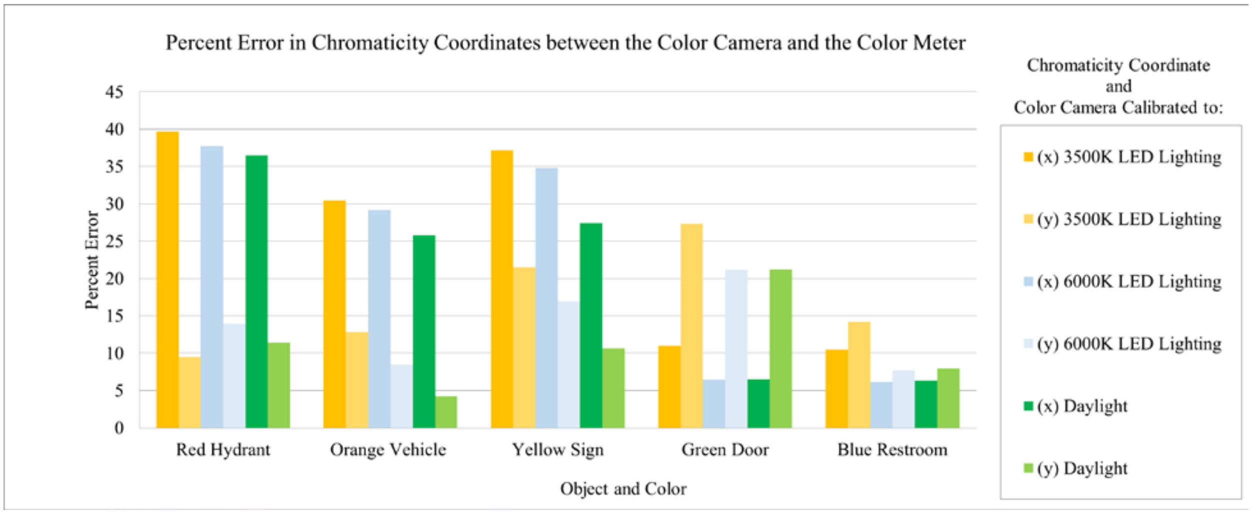


Figure 9. Chart. Comparison of color camera and color meter chromaticity coordinates.

When the color camera used the daylight calibration file, the percentage error between the color camera’s chromaticity coordinates and the color meter’s chromaticity coordinates was, in general, the lowest. Because the daylight calibration file generated the best results, subsequent evaluations only used images taken with that calibration file.

COMPARISON OF LUMINANCE VALUES

The color camera using the daylight calibration filter was compared with a color meter and digital photometer.

Color Camera Compared with Color Meter

Shutter speed and luminance were considerations in the comparison between the color camera and the color meter. Changes in exposure also change a scene’s color rendering, as shown in Figure 10, where the car in the image with the longer, 55-ms exposure (left) appears more red.

Figure 10. Photos. Scene with 55-ms exposure (left) and 33-ms exposure (right).

The red car’s chromaticity coordinates (*x* and *y*) and luminance value (*Y*) from the color camera were compared with those from the Minolta color meter. The results are shown in Figure 11.

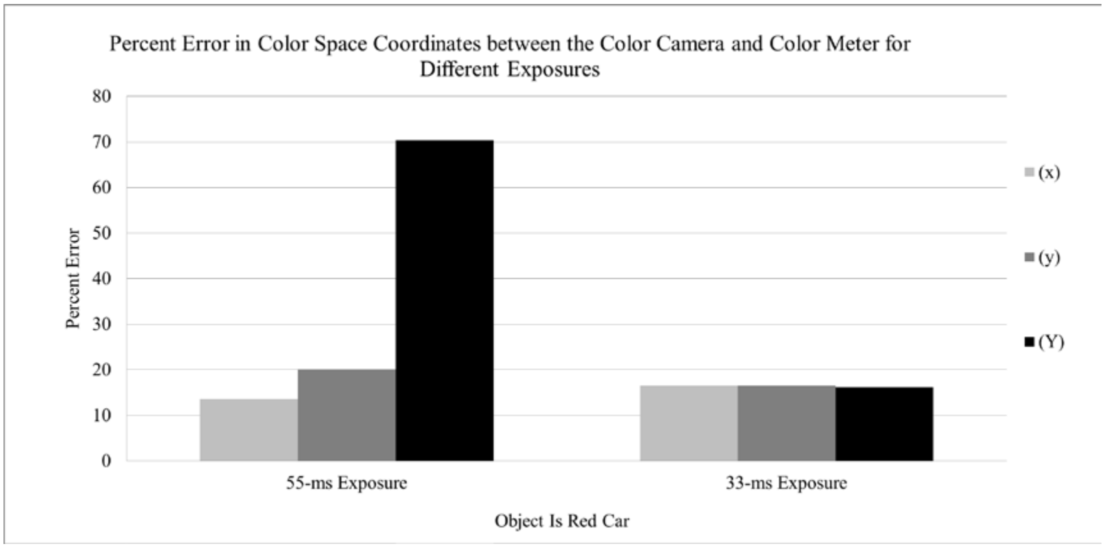


Figure 11. Chart. Impact of exposure on luminance measurement error for red car in Figure 10.

Although the image taken by the color camera with a 55-ms exposure appeared brighter, its percentage error for luminance, when compared with the color meter, was about 70%. The shorter exposure time, 33 ms, had a far lower error in luminance measurement, at about 17%. The chromaticity coordinates, *x* and *y*, had similar errors for the two exposures.

Color Camera Compared with Digital Photometer

A side-by-side comparison of images captured by the color camera and the digital photometer is shown in Figure 12. The color camera’s image (right) is darker because the exposure time was shortened to reduce error in luminance.

Figure 12. Photos. Comparison of images taken with digital photometer (left) and color camera (right).

The orange section of the images was selected to compare the color space coordinates (*x*, *y*, and *Y*) between the color camera, the color meter, and the digital photometer. The results are shown in Figure 13.

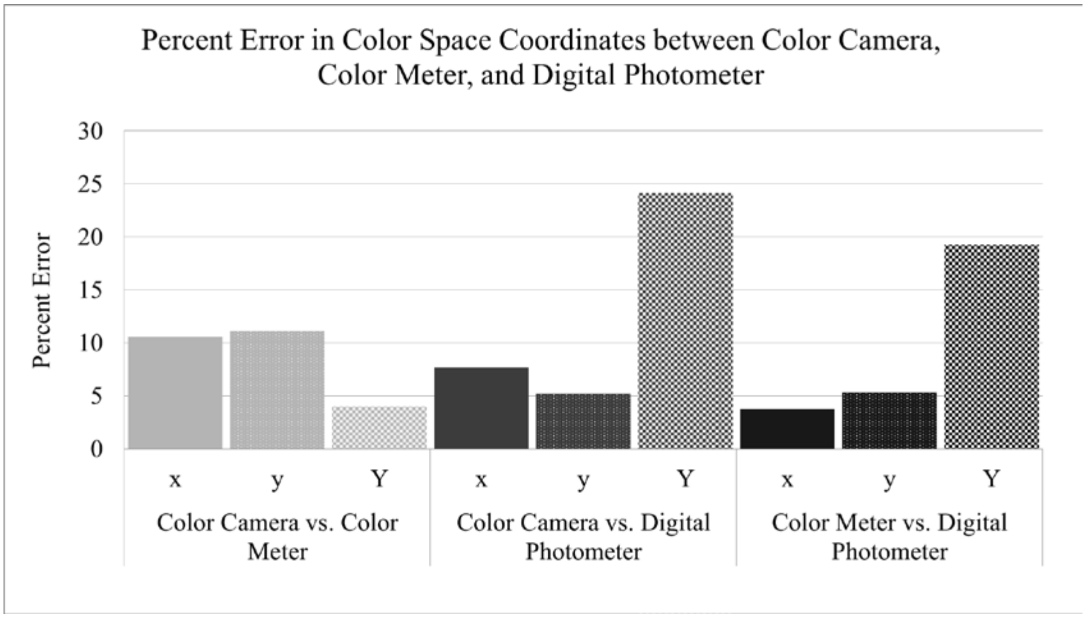


Figure 13. Chart. Comparison of color camera, color meter, and digital photometer color space coordinates.

The color camera had lower error in chromaticity when compared to the digital photometer (about 5%), and lower error in luminance when compared to the color meter (less than 5%). There is a large error between the color meter and the digital photometer, 5% to 7.5% in chromaticity and almost 25% in luminance, showing that finding a baseline for comparison is not a simple task.

SUMMARY

The color camera was calibrated using a color grid and various lighting types. After calibration, the color camera was compared for accuracy with a handheld Minolta color meter and a Radiant Imaging digital photometer by taking similar images with all three pieces of equipment in a number of naturalistic, nighttime settings and then comparing the images’ color space coordinates.

The calibration using daylight data produced the most accurate color space coordinates when compared with those from the color meter, even when the camera was used in darkness or with artificial lighting. Shorter exposure times produced darker images but more-accurate color space coordinates. The color camera was compared with both the color meter and digital photometer, but those two devices did not produce the same color space coordinates as each other, illustrating the error inherent in digital color measurement.

CHAPTER 6. CONCLUSIONS

The goal of this project was to develop a camera system that accurately records color video data of nighttime driving. This system included a calibrated camera to collect images and a method to analyze and report the images' color data. The new image analysis method and software were developed to allow researchers to select portions of an image and analyze their three-dimensional color space coordinates, which will find ready application in research on color and visibility.

The testing described above resulted in the development of a color camera system that can be calibrated to capture accurate chromaticity coordinates and luminance values in video data, combining capabilities that previously required using several different instruments. Multiple cameras can be calibrated using the same file. Video data can be taken at 7.5 frames per second in naturalistic settings. This is impossible with a handheld color meter, which has a small field of view, cannot be used while driving, and lacks a practical data logging method for a dynamic environment. It is also impossible with a digital photometer because the device is too unwieldy for long-term installation and it cannot capture rapid video images. The result of this research is a small, easily mounted color camera that is an accurate tool for measuring color in dynamic settings where visibility is crucial, such as nighttime driving scenarios.

This camera system will allow the complete color description of the visual field from a moving vehicle. These results will have a significant impact on the evaluation of a driver's behavior in a lighted environment. This will also have significant impact on the evaluation of the naturalistic environment.

REFERENCES

1. International Commission of Illumination (CIE). (1932). *Commission internationale de l'Eclairage proceedings, 1931*. Cambridge: Cambridge University Press.

2. International Commission of Illumination (CIE). (1978). *Recommendations on uniform color spaces, color-difference equations, psychometric color terms*. Supplement No. 2 to CIE publication No. 15.