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An Optimal Combination of Illumination Intensity and Lens Aperture for Color Image Analysis

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Abstract: The spectral color resolution of an image is very important in color image analysis. Two factors influencing the spectral color resolution of an image are illumination intensity and lens aperture for a selected vision system. An optimal combination of illumination intensity and lens aperture for color image analysis was determined in the study. The method was based on a model of dynamic range defined as the absolute difference between digital values of selected foreground and background color in the image. The role of illumination intensity in machine vision was also described and a computer program for simulating the optimal combination of two factors was implemented for verifying the related algorithm. It was possible to estimate the non-saturating range of the illumination intensity (input voltage in the study) and the lens aperture by using a model of dynamic range. The method provided an optimal combination of the illumination intensity and the lens aperture, maximizing the color resolution between colors of interest in color analysis, and the estimated color resolution at the combination for a given vision system configuration.

Keywords: Color image, Dynamic range, Lens aperture, Illumination intensity, Machine vision

Introduction

An important consideration in color image analysis is to maximize the spectral color resolution of an image. Several previous studies for color machine vision applications have indicated that the spectral color resolution of color images was not great enough (Krutz and Precetti, 1991; Tao et al., 1990).

Two factors influencing the spectral color resolution of an image for a selected vision system are illumination intensity and lens aperture. A color image is represented by RGB values sensitive to the amount of reflected light reaching the image sensors. It is common practice to decide on lens aperture and image intensity by observing color images on a monitor. However, the human visual system adjusts to reduce the dependence of color appearances on the variations of illumination (Brainard and Wandell, 1990). Therefore, the human visual criterion is not reliable for deciding the illumination intensity and the lens aperture. An objective criterion for determining these factors needs to be established for color image analysis.

For intensity images, Wittels and Zisk (1986) suggested that the optimum illumination should produce an image on which the brightest area is just below the sensor's saturation level and the darkest area is just above noise level of the vision system. They measured the usable contrast of a camera expressed by the ratio of the maximum output voltage to the minimum. Their strategy for illumination was to select the illumination level that maximized the scene contrast, while placing the luminance of the darkest and the brightest area within the bounds calculated by the measured maximum and minimum output voltages.

Ruzhitsky and Ling (1992) noted that the lens aperture influenced the successful classification of leaves. Cowan and Bergman (1989) studied techniques for calculating the three-dimensional region for acceptable locations of vision sensors and illumination sources. An acceptable range of lens apertures satisfying the requirements of image resolution, field of view and objects visibility in the image was also estimated in their study. However, they suggested that the specific selection of the lens aperture and the location of the illumination source should be based on the dynamic range of the camera defined as the allowable intervals of irradiance at the camera sensor. Throop et al. (1993) tried to optimize lighting and lens aperture for maximum contrast between bruised and unbruised apple tissue for various commercial vision

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cameras. Parkkinen et al. (1988) suggested a color image representation to preserve color information in images, and to accurately analyze color images in the spectral manner.

The dynamic range (the usable contrast) of a color image can be considered as the absolute difference between the digital values of a selected foreground and a selected background color in an image. Using this interpretation, the dynamic range represents the spectral color resolution between the selected foreground and background colors. For the machine vision system using an 8-bit digitizer, the maximum value of dynamic range would be 255 for each color channel. However, the selection of a foreground and a background color in the image depends on the colors of interest in image analysis.

This research assumed that the desired illumination condition for color image analysis maximized the spectral color resolution of the image below the saturation level of image sensors. For a selected light source and sensor, this illumination condition is practically obtained by adjustment of illumination intensity and lens aperture. This study modeled the dynamic range in terms of the illumination intensity and the lens aperture and developed an objective method for determining an optimal combination of the illumination intensity and the lens aperture for color image analysis.

Materials and Methods

1. A Model of Dynamic Range

(1) The role of illumination intensity in machine vision

Assuming uniform diffuse illumination, let $I(\lambda)$ be the spectral power distribution (SPD) of illumination incident over the surface of objects. Let $\mu_{Ri}(\lambda)$ and $\sigma_{Ri}(\lambda)$ be the average diffuse spectral reflectance of an object and its standard deviation, where the subscript, i, represents objects in an image. Similarly, let $\mu_{Ei}(\lambda)$ and $\sigma_{Ei}(\lambda)$ be the average SPD of the reflected light and its standard deviation, reaching the image sensors through the lens. Then, $\mu_{Ei}(\lambda)$ and $\sigma_{Ei}(\lambda)$ for an object form a certain statistical distribution in the histogram of the image. It should be noted that there are three statistical distributions for RGB color channels in a color image represented by RGB values.

For the objects m and n on an image, $\mu_{Ei}(\lambda)$ can be expressed as:

$$\mu_{Em}(\lambda) = LF_m \cdot I(\lambda) \cdot \mu_{Rm}(\lambda) \qquad \text{for object m} \qquad (1)$$

$$\mu_{En}(\lambda) = LF_n \cdot I(\lambda) \cdot \mu_{Rn}(\lambda) \qquad \text{for object n} \qquad (2)$$

where LF_i is the attenuation multiple factor of $\mu_{Ei}(\lambda)$ controlled by the lens aperture. Also, $\sigma_{Ei}(\lambda)$ are :

$$\sigma_{Em}(\lambda) = LF_m \cdot I(\lambda) \cdot \sigma_{Rm}(\lambda) \qquad \text{for object m} \qquad (3)$$

$$\sigma_{En}(\lambda) = LF_n \cdot I(\lambda) \cdot \sigma_{Rn}(\lambda) \qquad \text{for object n} \qquad (4)$$

From the equations (1) and (2), the difference of δ_{Emn} between $\mu_{Em}(\lambda)$ and $\mu_{En}(\lambda)$ is:

$$\begin{aligned}\delta_{Emn} &= \mu_{Em}(\lambda) - \mu_{En}(\lambda)\\ &= I(\lambda) \cdot [LF_m \cdot \mu_{Rm}(\lambda) - LF_n \cdot \mu_{Rn}(\lambda)] \qquad (5)\end{aligned}$$

δ_{Emn} represents the spectral color resolution (the dynamic range) between objects m and n.

When LF_i and $I(\lambda)$ are, respectively, changed to $LF_i' = k_1 \cdot LF_i$ and $I'(\lambda) \approx k_2 \cdot I(\lambda)$ by adjusting the lens aperture and the illumination intensity for a selected light source and sensor, $\mu'_{Em}(\lambda)$ and $\mu'_{En}(\lambda)$ at the changed condition are :

$$\begin{aligned}\mu'_{Em}(\lambda) &= LF_m' \cdot I'(\lambda) \cdot \mu_{Rm}(\lambda)\\ &= k \cdot LF_m \cdot I(\lambda) \cdot \mu_{Rm}(\lambda) \qquad (6)\\ \mu'_{En}(\lambda) &= LF_n' \cdot I'(\lambda) \cdot \mu_{Rn}(\lambda)\\ &= k \cdot LF_n \cdot I(\lambda) \cdot \mu_{Rn}(\lambda) \qquad (7)\end{aligned}$$

where k is the multiplication of k_1 and k_2. Similarly, $\sigma'_{Em}(\lambda)$ and $\sigma'_{En}(\lambda)$ from the equations (3) and (4) are:

$$\sigma'_{Em}(\lambda) = k \cdot LF_m \cdot I(\lambda) \cdot \sigma_{Rm}(\lambda) = k \cdot \sigma_{Em}(\lambda) \qquad (8)$$

$$\sigma'_{En}(\lambda) = k \cdot LF_n \cdot I(\lambda) \cdot \sigma_{Rn}(\lambda) = k \cdot \sigma_{En}(\lambda) \qquad (9)$$

Thus, the difference of δ'_{Emn} between $\mu'_{Em}(\lambda)$ and $\mu'_{En}(\lambda)$ at the changed condition is:

$$\begin{aligned}\delta'_{Emn} &= \mu'_{Em}(\lambda) - \mu'_{En}(\lambda)\\ &= k \cdot I(\lambda) \cdot [LF_m \cdot \mu_{Rm}(\lambda) - LF_n \cdot \mu_{Rn}(\lambda)]\\ &= k \cdot \delta_{Emn} \qquad (10)\end{aligned}$$

The above equations indicate that when the factor k increases by changing the illumination intensity or the lens aperture, the statistics for the objects m and n also increase by the factor of k. These equations correspond to stretching the histogram of the image. However, one would expect from the equation (10) that the valleys of the histogram would get deeper due to the increase in spectral resolution between the objects m and n. Ruzhitsky and Ling (1992) proved this fact experimentally.

In the above simplified model for the role of illumination intensity, it was assumed that the effect of the lens aperture on $\mu_{Ei}(\lambda)$ is similar to that of the illumination intensity. However, the lens aperture only controls the amount of reflected light reaching the image sensors while the illumination intensity in the scene is related to very complicated reflection process (Bajcsy et al., 1990). Also, the saturation of image sensors limits the improvement of the spectral resolution obtained by increasing factor k. As a result, there exists an optimal combination of illumination intensity and lens aperture that maximizes the spectral resolution of an image for a given system configuration.

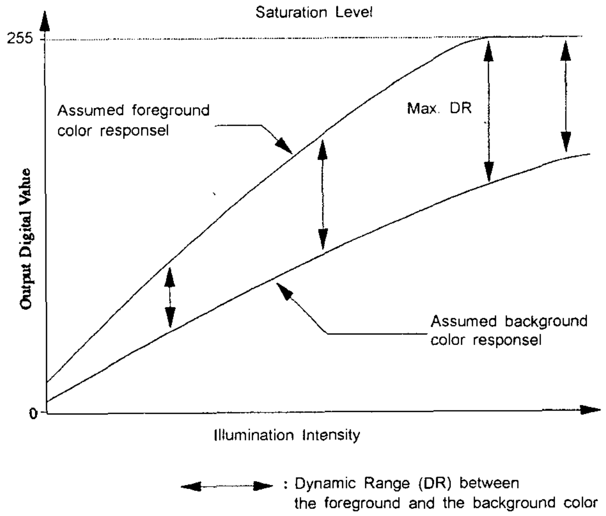


Fig. 1 the relationship between the dynamic range and illumination intensity at a fixed lens aperture.

(2) An optimal selection of illumination intensity and lens aperture

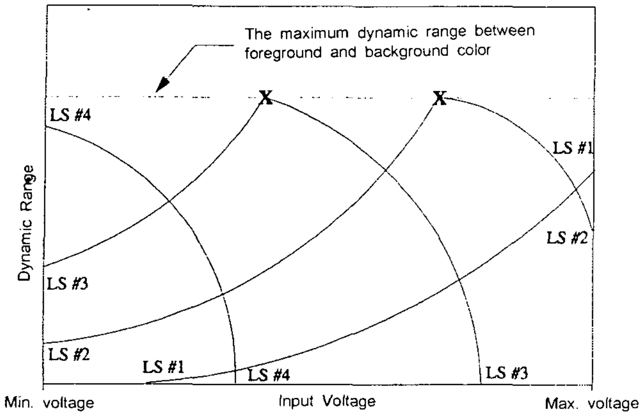
There are three dynamic ranges (DRs) for red, green and blue color channels in a color image represented by RGB values. Fig. 1 illustrates the relationship between the DR and illumination intensity at a fixed lens aperture for one color channel. It is assumed in Fig. 1 that the spectral reflectance of a foreground color is greater than that of a background color. Thus, the output digital value of the foreground color reaches to the saturation level faster than that of the background color. For the selected foreground and background color, the DR would increase with increasing the illumination intensity, as shown in the figure.

When the output digital value of foreground color, however, reaches the saturation level, the DR would decrease and eventually approach zero. Hence, the maximum DR at a fixed lens aperture occurs at an illumination intensity just generating the saturation of foreground color, where the spectral resolution of the image would be also the maximum. At different lens apertures, the illumination intensity can not produce the maximum DR. If the lens aperture changes, the amount of reflected light reaching image sensors also changes. The amount of reflected light producing the maximum DR of the image is determined by a combination of illumination intensity and lens aperture, as shown in the equation (10).

For a given system configuration, the intensity of the reflected light at the image sensor is controlled by lens aperture adjustment and, generally, the input voltage, or the number of bulbs in the illumination system. In this study, the magnitude of input voltage represents the illumination intensity. For other illumination configurations, however, the factor of input voltage would be replaced by another criteria, such as input current or the distance between the illumination source and the objects in the scene, etc. Also, the illumination intensity could be represented by step changes in input voltage or current.

Fig. 2 illustrates the relationship between the DR and the input voltage at several lens apertures for one color channel. The minimum and the maximum voltage represent the usable range of input voltage on the designed illumination system. Based on the equation (10), the DR is proportional to the intensity of the reflected light at image sensors. Because the intensity of the reflected light is approximately proportional to the square of input voltage, the relationship between the DR and the input voltage is quadratic. The optimal input voltage maximizing the DR at a given lens aperture is designated by 'X'.

In Fig. 2, the maximum DR at the point 'X' is represented to be same at every possible lens aperture. This might not be true for an illumination system having a spectral shift of illumination due to the change in color temperature with input voltage. However, the relationship between the DR and the input voltage does not change because the spectral



X : The optimum input voltae at the given lens aperture
LS : Lens Aperture (LS#1 > LS#2 > LS#3 > LS#4)

Fig. 2 The relationship between dynamic range and input voltage at several lens aperture.

shift of illumination could not be large for a given system configuration. At each lens aperture, the input voltages beyond 'X' generate saturation of the foreground color. As shown in Fig. 2, the characteristic of the curve changes significantly around point, 'X'.

The effect of the reciprocal of the lens aperture on the DR is similar to that of input voltage because the intensity of the reflected light at the image sensors is also proportional to the square of the reciprocal of lens aperture. Thus, the DR can be modelled as a quadratic form of the input voltage and the lens aperture. The $DR_{i,j}$ is :

$$DR_{i,j} = a_{i,j} \cdot V^2/LS^2 + b_{i,j} \cdot V/LS^2 + c_{i,j} \cdot V^2/LS + d_{i,j} \cdot V/LS + e_{i,j} \qquad (11)$$

where the subscript i represents saturating and non-saturating region (S and N), the subscript j represents red, green and blue color channel (R, G and B), LS is the lens aperture and V is the input voltage. The coefficients in the equation (11) are determined by applying the least squares method to actual DR data obtained at selected combinations of the input voltage and the lens aperture.

One specific combination of the input voltage and the lens aperture determines simultaneously three DRs for RGB color channels. An optimal combination for one color channel might not be optimal for the other channels. When the DR model is obtained for each color channel, an optimal combination of the input voltage and the lens aperture for color image analysis, (LS,V)optimal is :

$$(LS,V)_{optimal} = (LS,V) \text{ at } \max(DR_{N,R} \cdot DR_{N,G} \cdot DR_{N,B}) \qquad (12)$$

This is because the maximum spectral resolution in RGB color domain occurs when the multiplication of three DRs for RGB color channels reaches its maximum.

In applying the criterion in the equation of (12), the saturation of image sensors is an important limitation. A particular combination of input voltage and lens aperture maximizing the spectral resolution in RGB color domain might cause the saturation of image sensors in any color channel. Therefore, an optimal combination of the input voltage and the lens aperture should be determined within the common set of three non-saturating ranges for RGB channels.

Equation (11) provides the non-saturating range of the input voltage and lens aperture for each color channel. The maximum DR occurs when the digital value of foreground color is at its saturation level. Thus, the input voltage at the maximum DR, designated by 'X' in Fig. 2, indicates the upper bound of its non-saturating range at the given lens aperture. The input voltage (or the lens aperture) at 'X' is obtained by equating $DR_{N,j}$ to $DR_{S,j}$ for each color channel and selecting the solution of the resulting quadratic equation within its usable range.

2. An Experimental Simulation for an Optimal Combination of Illumination and Lens Aperture

A lighting chamber with four 50 W DC halogen lamps and four white reflectors was designed for diffuse illumination. Fig. 3 shows the schematic diagram of the illumination and vision system utilized in the study. The input DC voltage was controlled by a variable DC-12A, 24 V voltage regulator. The DC-voltage regulator had a voltage indicator with 0.5 V intervals and its usable voltage range was approximately 10 V to 23 V for the designed lighting chamber. The distance between illumination sources and objects was fixed to 1 m, based on the size of objects in the image. A camera lens with a focal length of 24 mm, a Sony XC-711 CCD color camera and an ATvista color image board (Truevision Inc., Indianapolis, IN) were used for the study. The lens

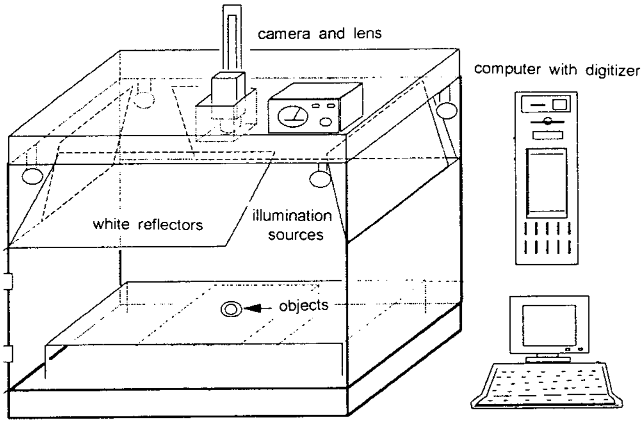


Fig. 3 A schematic diagram of the illumination and vision system in the study.

aperture ranged from f2 to f16 with 7 steps.

The color rendition chart developed by McCamy et al. (1976) was selected as a reflectance object for the study. One frame of the chart was made up of 24 matte patches characterized by different spectral reflectance (equivalently, different visual colors). Six patches (No. 19 ~ No. 24) were different colors of neutral gray. The spectral reflectance of these patches differed only by a scalar multiplier in the visible spectrum. The optimal combination of the input voltage and the lens aperture was tested for some pairs of foreground and background colors selected from the color chart.

Based upon the described model, a program for determining an optimal combination of the input voltage and the lens aperture was written in Microsoft 6.0 C language (Microsoft Corp., Redmond, WA). The program steps were as follows :

(1) The usable range (or step) of the input voltage and the lens aperture for the given system configuration was specified.

(2) The actual DRs between the foreground and the background color selected from the image were collected at several arbitrary combinations of input voltages and lens apertures.

(3) Based on the digital value of the foreground color, the actual DRs for each channel were sorted into saturating and non-saturating groups. When the digital value of foreground color is 255, the DR at the particular combination belongs to the saturating group.

(4) The saturating and non-saturating DR models for each color channel were evaluated by the least-squares method.

(5) The non-saturating range of the input voltage and the lens aperture for each color channel were estimated using the evaluated DR models.

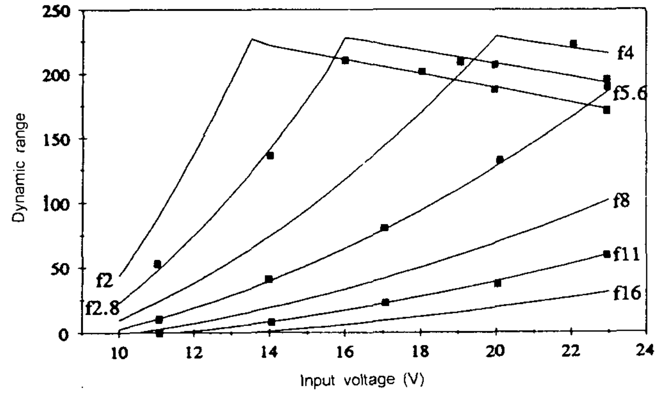
Results and Discussion

The DR model was first tested for a pair of white and black patches on the color chart. Table 1 shows the DR models of RGB color channels for the pair. The actual DRs for the least-squares fit of DR model were collected at 20 arbitrary combinations of the input voltage and the lens aperture (12 in the non-saturating region and 8 in the saturating region). As R^2-values in Table 1 shows, the DR model expressed by the equation (11) accurately represented the actual DRs.

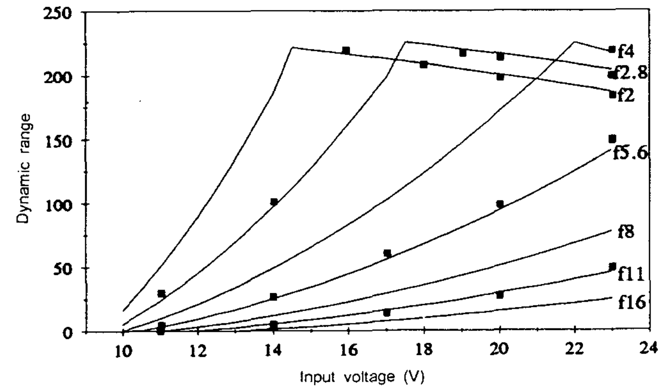
Based on the estimated DR models, the change of DR in the usable range of input voltage at specific lens apertures was plotted in Fig. 4. The points in the figure represent the actual DRs at the specific

Table 1 The coefficients of dynamic range models for a pair of white and black patches

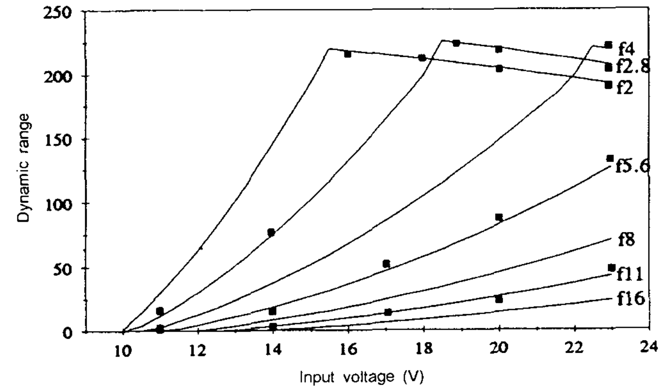
Color Channel		Coefficients of DR model					R^2
		V^2/LS^2	V/LS^2	V^2/LS	V/LS	Const	
Red	Non-Sat.	11.95	-109.43	0.97	-3.92	-10.61	0.993
	Sat.	0.42	2.51	-0.24	-11.21	294.37	0.968
Green	Non-Sat.	9.62	-86.69	0.92	-9.91	-3.82	0.987
	Sat.	0.82	-18.5	-0.6	8.18	249.1	0.993
Blue	Non-Sat.	7.9	-72.56	1.12	-13.43	-4.16	0.972
	Sat.	1.42	-30.83	-0.86	13.85	250.03	0.991



(a) Red channel



(b) Green channel



(c) Blue channel

Fig. 4 The change of dynamic range in the usable range of input voltages at specific lens apertures for a pair of white and black patches.

combinations. In Fig. 4, the portion of the curve where the DR was increasing represented the non-saturating range of input voltage at the particular lens aperture. There was no saturation of image sensors in the usable range of input voltage at the lens apertures of f5.6 through f16 in the illumination system used for the study.

Table 2 shows the maximum non-saturating input voltages at specific lens apertures for RGB color channels. The maximum non-saturating input voltages estimated by using the DR models were matched to the measured ones within 0.5 V range. Note that the input voltage could be adjusted by 0.5 V intervals with the voltage regulator used for the study. As shown in Table 2, the estimated maximum non-saturating input voltages at lens apertures of f5.6 through f16 were over the usable range of input voltage (10 V to 23 V). Such results were coincident with the fact that there was no saturation of image sensors at those lens apertures in the usable range of input voltage.

For the pair of white and black patches, an input voltage of 20 V at a lens aperture of f4 was the combination maximizing the color resolution in the non-saturating range. Table 3 shows the DRs in RGB color channels at the first five combinations that generated the relatively high color resolution. The color resolution in the table represents the theoretical number of colors to be distinguished in RGB color domain. Though the measured DRs for RGB color channels was somewhat smaller than the DRs estimated by the DR models, the result of experiment also showed that the combination of 20 V at f4 was optimal. In fact, the optimal combination for a pair of white and black patches would be optimal for color analysis where all 24 color patches should be contained, since the spectral characteristics of other 22 patches in the color chart would lie between those of white and black patches.

Table 3 suggests another important fact in determining an optimal combination of input voltage and lens aperture. The maximum non- saturating input voltage estimated by the DR models may not be exactly the same as the experiment measurements. As shown in Table 2, the first two combinations of 20 V at f4 and 16 V at f2.8, and the fourth combination of 13.5 V at f2 were close to the saturating range. If there is a discrepancy between the estimated and the measured maximum non-saturating input voltages, the saturation of image sensors might occur at those combinations. Table 3, however, implies that an optimal combination could be determined within a certain boundary of the one suggested by the DR model. Therefore, when the saturation of image sensors

Table 2 The maximum non-saturating input voltages at specific lens apertures for a pair of white and black patches

Lens Aperture (F-No)	Maximum non-saturating input voltage(V)					
	Red		Green		Blue	
	Estimated1)	Measured	Estimated	Measured	Estimated	Measured
2	13.5	13.5	14.6	15	15.5	16
2.8	16.1	16.5	17.7	18	18.7	19
4	20.0	20.5	21.9	22	22.8	22.5
5.6	24.9	N/A2)	26.8	N/A	27.5	N/A
8	31.7	N/A	33.3	N/A	33.4	N/A
11	39.3	N/A	40.2	N/A	39.6	N/A
16	50.5	N/A	49.9	N/A	48	N/A

1) The estimated maximum input voltage was calculated by equating the saturating and the non-saturating DR model for each color channel.

2) Non-applicable(over the usable range of input voltage).

Table 3 The dynamic ranges in RGB color channels at some particular combinations of input voltage and lens aperture for a pair of white and black patches

Lens aperture	Input voltage	Color channel	Dynamic range(DR)			Color resolution ($DR_R \cdot DR_G \cdot DR_B$)
			Red	Green	Blue	
f4	20V	Estimated	229	171	147	5756373
		Measured	220	168	142	5248320
f2.8	16V	Estimated	223	161	131	4703293
		Measured	221	158	130	4539340
f4	19.5V	Estimated	213	158	136	4576944
		Measured	207	156	133	4294836
f2	13.5V	Estimated	226	159	122	4383948
		Measured	221	157	120	4163640
f4	19V	Estimated	198	146	125	3613500
		Measured	194	145	123	3459990

occurs at the suggested optimal combination, the next smaller input voltage at the same lens aperture (in this case, 19.5 V at f4) could be selected as a possible optimal combination.

The DR model was also applied for some different pairs of foreground and background colors. Table 4 lists the optimal combinations of the input voltage and the lens aperture obtained by using the DR model. Each pair contained two patches selected from the color chart that were similar in hue. For each pair, one patch having smaller RGB values than the other (No. 1, No. 3, No. 9 and No. 11) was chosen as a background color. As shown in Table 4, an optimal combination was dependent on the colors of interest in color analysis. It was difficult to visually determine the proper combinations of the input voltage and the lens aperture for all those pairs. However, the DR models provided the best combination maximizing the resolution between colors of interest in color analysis for the given system configuration. The values in parentheses represent the measured DRs at the suggested optimal combination. For pairs of No. 1 and No. 2, and No. 11 and No. 14, the foreground color was saturated at the suggested optimal combination. The next possible optimal combinations were 22 V at f4 for the pair of No. 1 and No. 2, and 20.5 V at

Table 4. The optimal combinations of input voltage and lens aperture for selected pairs os foreground and background colors

Color patches	Color names by ISCC / NBS	Optimal combination	Dynamic range			Color resolution
			Red	Green	Blue	
No. 1 vs. No. 2	moderate brown light reddish brown	22.5V at f4	133 (128	68 65	54 50)[1]	488376
No. 3 vs. No. 13	moderate blue vivid purplish biue	20V at f2	115 (115	118 118	56 56)[2]	759920
No. 11 vs. No. 14	string yellow green strong yellowish green	22V at f2.8	173 (163	105 101	24 22)[3]	435960
No. 9 vs. No. 15	moderate red strong red	19.5V at f2.8	41 (40	27 26	23 22)[4]	25461

[1] The dynamic ranges were measured at 22 V and f4 due to the saturation of foreground color at 22.5 V and f4.

[2] The dynamic ranges were measured at 20 V and f2 : No saturation.

[3] The dynamic ranges were measured at 20.5 V and f2.8 due to the saturation of foreground color at 22 V and f2.8.

[4] The dynamic ranges were measured at 19.5 V and f2.8 : No saturation.

f2.8 for the pair of No. 11 and No. 14, respectively.

This study focused on the selection of the optimal combinations for two visually similar colors because the color resolution between such colors was especially important in color analysis. However, an optimal combination for visually different colors could be selected by a similar procedure, based on the DR model. For example, the spectral reflectance of blue and red is respectively inclined to the blue and the red waveband. In such a case, a particular combination can saturate only a color for one color channel. The DR model independently estimates the non-saturating range for each color channel. Since an optimal combination is determined within the common set of three non-saturating ranges for RGB channels, the suggested combination is the one maximizing the color resolution between the visually different colors without the saturation of image sensors.

Conclusions

An objective method of determining an optimal combination of the illumination intensity and the lens aperture for color image analysis was described in this study.

An optimal combination was determined with respect to the spectral color resolution of an image. The method was based on a model of dynamic range defined as the absolute difference between digital values of a selected foreground and a background color in the image. An optimal combination of the illumination intensity and the lens aperture was assumed to be the combination that maximizes the spectral color resolution of the image below the saturation level of image sensors. The spectral color resolution of a color image in RGB domain was represented by the multiplication of three dynamic ranges for RGB color channels.

In the study, a computer program for simulating the optimal combination of two factors was implemented for verifying the related algorithm. It was possible to estimate the non-saturating range of the illumination intensity (input voltage) and the lens aperture for an illumination system by using a model of dynamic range. The method provided an optimal combination of the illumination intensity and the lens aperture, maximizing the color resolution between colors of interest in color analysis, and the estimated color resolution at the combination for a given vision system configuration.

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