Recognition of small color differences with computer vision devices

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Abstract. It is experimentally shown that a digital atlas of monochromatic color stimuli with a controlled width of the spectrum can be constructed by using the monochromator. A method for testing the spectral sensitivity of the camera's *RGB* sensors and measuring its color gamut is presented. For detection and quantitative characterization of small color differences of the image elements, it is proposed to divide the objective analysis of the image into blocks of the color segmentation and the evaluation of the color tone and the color difference.

Keywords: digital image, color, dominant wavelength, saturation, digital color atlas, small color difference.

1 Introduction

At the moment, the estimation of color and color differences of images are most often performed with the use of three-color colorimeters [1], which involve the optical lighting system and the optical imaging system providing the high spatial resolution. In such colorimeters, images are captured by photomatrices with three-color Bayer filters, which may be popular imaging systems, such as digital cameras or scanners.

The recognition and the quantification of small color differences are needed in printing industry [2], development of devices using temperature-sensitive paints [3], criminal science [4, 5, 6,], expertise of documents, differentiation of strokes of document details, etc.

Problems solved with the use of computer vision are so versatile that almost each particular case requires the development of specialized algorithms for the digital image processing [7, 8].

Therefore, it is important to consider specific features of a design of illuminating blocks of colorimeters, to study the color rendering of digital cameras (or photomatrices) and the quality of their color grading, and to develop appropriate algorithms and software.

The present paper describes the method of determining the spectral sensitivity of RGB-sensors of the camera with the use of monochromatic stimuli. The experimental setup and the method of creating a digital atlas of monochromatic stimuli are discussed. It is proposed to perform objective estimation of the color difference in similar stimuli (or strokes of document details) by means of the mathematical processing of digital images of stimuli by using developed algorithms including the calculation of the chart of color characteristics of stimulus images, its color segmentation, and statistical analysis of data in the domains of interest.

2 Methods and results

For creating the monochromatic stimuli and studying the spectral dependence of the response of camera channels, we developed an experimental setup consisting of a light source (the halogen lamp), a condenser, an universal monochromator *UM-2* (including the following elements: lens, comparison prism, variable-width input slot, collimator objective, dispersing Abbe prism with a connected wavelength drum, telescope objective, and variable-width output slot), a multichannel fiber spectrometer *Kolibri-2* (*VMK-Optoelektronika*, *Novosibirsk*, *Russia*), and camera *Canon EOS 500D* (*Canon Inc.*, *Japan*) with the objective.

The light generated by the source is directed by the condenser through the lens to the input slot of the monochromator, which is located at the focal point of the collimator objective; after that, the light passes through the Abbe prism and is decomposed into a spectrum. The telescope objective produces the input slot image confocally with the output slot of the monochromator, which is captured by the camera objective and is retained as a digital image. The output slot of *UM-2* serves as a source of a monochromatic radiation. The light spectrum was monitored by the *Kolibri-2* fiber spectrometer; the spectrum was captured with drum rotation and wavelength changing by 1 nm.

For obtaining the digital color atlas, the images of the output slot of *UM-2* were captured by the motionless (with respect to the setup) digital mirror camera simultaneously with spectrum measurement by *Kolibri-2*. The camera operated in the "user" mode, which was described in much detail in [5]. This regime does not allow image preprocessing by a built-in processor of the camera at its disposal.

In the visible spectrum, we obtained 168 images of spectral stimuli, i.e., digital atlas elements with a step of 1 nm. The half-tone region in the each atlas element is removed. The resultant monochromatic stimuli allow the camera to be tested and the spectral responses of the photomatrix to be constructed. The spectral response of the photomatrix is a convolution of the spectral sensitivity function of the photomatrix itself with the function of the spectral distribution of energy in the light source. Figure 1 shows the spectral sensitivity of the *RGB* elements of the photomatrix after deconvolution with the lamp spectrum. The resultant curves are the transmission spectrum of the Bayer filter at the photomatrix.

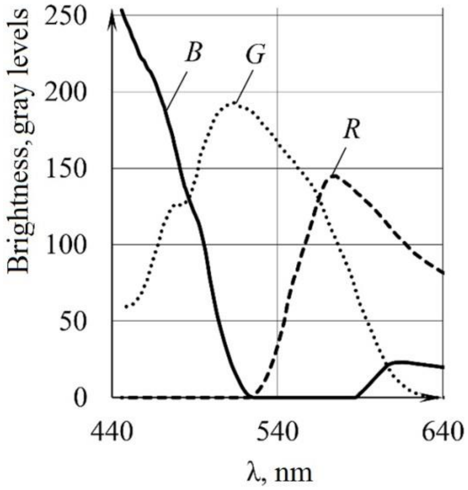


Figure 1. Spectral response of *RGB* channels after deconvolution with the lamp spectrum. The curves are plotted for the mean values of brightness.

Based on the monochromatic stimuli, we calculated the corresponding dominant wavelengths (DWLs); the DWL values were averaged over the entire image of the stimulus. The stimuli coordinates were plotted on the chromaticity diagram (*x*,*y*); thus, the color gamut of the camera was obtained, as is shown in Figure 2, where the solid bold curve is presented for the mean values of the coordinates (*x*,*y*) on each stimulus, and the dotted and dashed curves are given for the root-mean-square (RMS) deviations to the negative and positive sides, respectively. The resultant shape is noticeably different from a triangle. The color gamut of the camera is located within the locus, where the wavelengths of monochromatic stimuli are indicated.

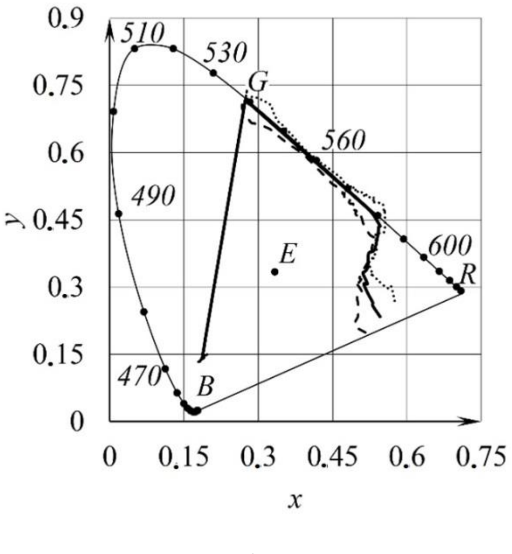


Figure 2. Experimentally determined color gamut of the digital camera in the chromaticity diagram (*x*,*y*). The wavelengths of monochromatic stimuli (in nm) are indicated in the locus.

Thus, the method is proposed for testing the color rendering of digital cameras with the use of experimentally obtained monochromatic stimuli. The method was tested by an example of the *Canon EOS 500D* camera.

A correctly calibrated camera makes it possible to detect and quantify small color differences. Color discrimination and quantification of color differences were performed in [2] in the color space CIE LAB. The total color difference ΔE^*_{ab} is calculated as the Euclidean distance between two color points

$$(\Delta E^*_{ab})^2 = (L^*_T - L^*_R)^2 + (a^*_T - a^*_R)^2 + (b^*_T - b^*_R)^2,$$

where the subscripts mean the tested stimulus (T) and the reference stimulus (R).

In many applications [9], the value $\Delta E^*_{ab} = 3$ is taken as a threshold of a visual color discrimination, which means that colors with the total color difference smaller than three cannot be reliably visually discriminated by the observer.

Barinova O.A. and Palchikova I.G. [4] reported the results of their experiments aimed to detecting adscripts with the use of the *VideoTool-M* (*TDISIE Sb RAS, Novosibirsk, Russia*) three-color colorimeter [1]. The experiments [4] showed that the fact of changing the original writing in a document without document destruction can be established by means of the differentiation of dyes with visually similar color characteristics by using their quantitative characteristics, namely, a color saturation (CS) (or DWL) and a total color difference between two colors ΔE^*_{ab} of certain selected image regions. The problem in this approach is the necessity of identifying colored regions. Usually dyes cannot be applied onto the paper surface homogeneously, and the stroke image always contains non-colored spots, as is shown in Figure 3. Moreover, it is not always possible to identify the domain of interest exactly within the stroke image because some part of the paper image is also captured. Because of all these factors, the image becomes noisy, it is difficult to estimate the DWL difference, CS, and ΔE^*_{ab} , and it is rather problematic to detect adscripts in marginal cases (ΔE^*_{ab} ~4).

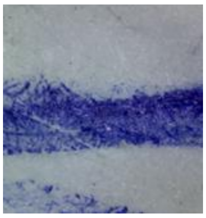


Figure 3. Microphotograph of the stroke on the paper.

We developed and tested a new algorithm for the detection and quantification of adscripts on the basis of the digital photo image of the inscription made on. It is proposed to perform the objective analysis of the image by means of dividing it into blocks of the color segmentation and estimation of the color tone and color difference. In this case, the color segmentation block performs the preprocessing function, i.e., defines the chart of the boundaries of differently colored classes for subsequent computations.

To eliminate the influence of illumination inhomogeneity and objective vignetting, the white background is first captured and the matrix of coefficients for the image normalization is calculated.

2.1 Color segmentation

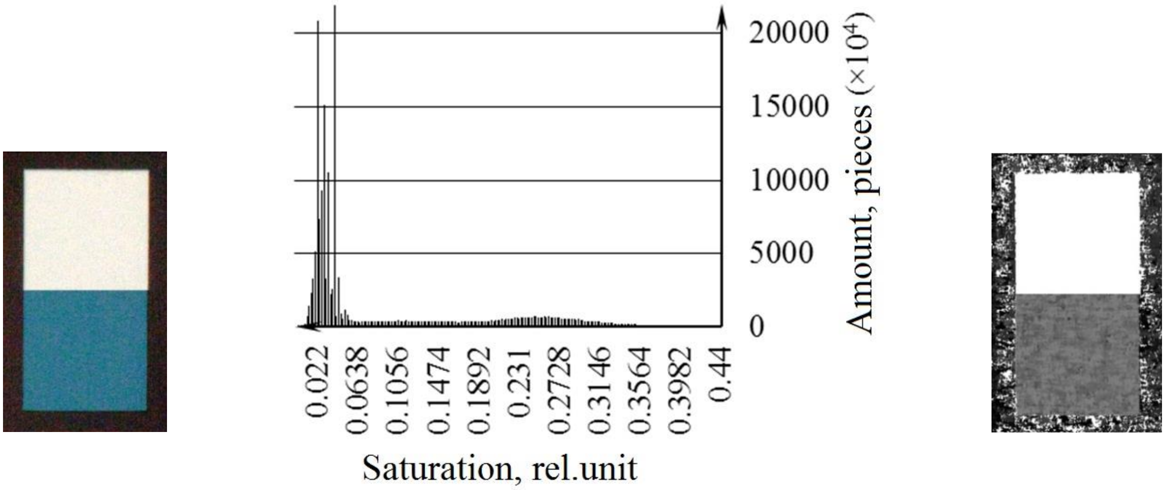
In the problems considered, we have to separate the image area related to the paper from the colored areas, and colors are very close to each other. Thus, all pixels have to be classified into two classes. Methods of threshold segmentation of images based on their brightness are well known and have been developed in sufficient detail [8, 10]. In the present study, Otsu's method [8] of the optimal global thresholding was modified as applied to the problem of the image segmentation in terms of a color.

Segmentation is performed on the basis of one of the quantitative parameters of color, namely, CS (or DWL). *RGB*- matrices of the color image are used to calculate the matrix of CS values, which can contain values from 0 to 1. Each pixel has a unique real value of CS; therefore, the CS histogram is a set of columns of unit height, but the columns are not uniformly distributed along the abscissa axis from 0 to 1. Otsu's algorithm does not allow finding the segmentation threshold for such histogram of unique CS values. Otsu's algorithm is usually applied to the histogram of the monochromatic image brightness, where the brightness values are integers in the interval from 0 to 255 levels of the gray scale. It is proposed to transform the CS histogram by means of rounding the values or division of the CS range (from 0 to 1) into even parts. In our case, the CS range is divided into 200 parts, and the normalized CS histogram for the inscription image is calculated. The proposed design of the CS histogram is the first step of the modified Otsu's algorithm for determining the segmentation threshold of the image on the basis of color saturation. Other steps are the same as in the original algorithm [8, p. 863].

The segmentation threshold is chosen by analyzing the histogram of the distribution of CS values in digital image pixels. If the histogram contains two clearly discernible regions so that each region is the most compact one, then the boundary between these regions in the histogram is the best threshold between the background and the inscription in the image. The algorithm searches for the threshold so that the maximum dispersion of two regions between the classes is reached. Based on the chosen CS threshold, the segmentation is performed: strokes having a greater CS are separated from a paper having a smaller CS.

The proposed color segmentation method was software implemented and the correctness of the software operation was tested by an example of segmentation of images of the elements of the color atlas *Macbeth ColorChecker chart* [10].

The main stages of the color segmentation are illustrated in Figure 4.



a *b* *c*

Figure 4. Basic stages of the color segmentation: *a* – the image of two elements of the atlas; *b* – CS histogram of the image; *c* – CS- diagram of the image obtained by means of image processing with the modified Otsu's method.

2.2 Estimation of the color tone and color difference

The chosen CS threshold defines the boundaries of differently colored classes of the image for subsequent computations. The chosen pixels that refer to dyes serve as data for calculating the values of (*R*,*G*,*B*) and (*x*,*y*) coordinates in each pixel, and also the mean values of ⟨*R*,*G*,*B*⟩ over the domain of interest (along the stroke) and the root mean square (RMS) values. Based on the (*R*,*G*,*B*) values, one can calculate the matrices of the CS and DWL values, color differences, and also matrices of any recalculated values of the parameters. Such quantitative characterization allows the domains of interest in the stroke images to be compared with each other. It can be assumed that, if some strokes are performed with two different dyes, then the general set of the values of color angles of the entire inscription will contain two normal distributions (in accordance with the number of dyes). To evaluate whether the data distribution is consistent with the standard normal distribution, the block for the color difference estimation was supplemented with the normal plot construction *QQ*-plot.

The algorithm was tested by examples of detecting adscripts whose dyes could not be discriminated by Selivanov's color guide [12], and the high efficiency of the algorithm in solving expertise problems was confirmed.

When processing the digital image data for monitoring the natural and man-made processes, one of the important characteristics is the color of plants. The developed software were tested by an example of detection and quantification of small color differences of dahlia leaves grown in spring on the southern (S) and northern (N) windows (three containers on each window). Seventy four photos of plants on a white paper background were captured and processed. When shooting, the same camera settings and then the same digital image processing algorithm were used.

The algorithm includes normalization of the original photo image to the image of the white background near the plant image. For each container, the averaged color coordinates (*x*,*y*) and the mean DWL and CS values were calculated. The coordinates of six points (in accordance with the number of containers) were plotted in the chromaticity diagram (*x*,*y*). (Figure 5a). The dotted line in Figure 5a separating the S and N points is parallel to the locus line; the direction of increasing saturation is indicated by the arrow. The samples had practically identical colors. The difference in the mean group DWL values was slightly greater than 0.5 nm, whereas the RMS value was ±1.3 nm.

It is seen in Figure 5a that the chromaticity points S and N are located almost along one CS line consecutively: first there follows the point S (southern) and then the point N (northern) as the CS increases. Using the CS value, we separated the groups from the southern and northern windows; the difference was approximately 2.8% (Figure 5b). The northern samples displayed more saturated hues. The RMS values for the southern samples were 7% greater than those for the northern samples. The mean value of the total color difference between the compared groups was $\Delta E^*_{ab} = 4$. Thus, the groups were almost indiscernible visually. The use of the camera operating as a three-color colorimeter revealed the difference in the growing conditions of plants of the same type and made it possible to estimate the fine difference in the dahlia leaf color.

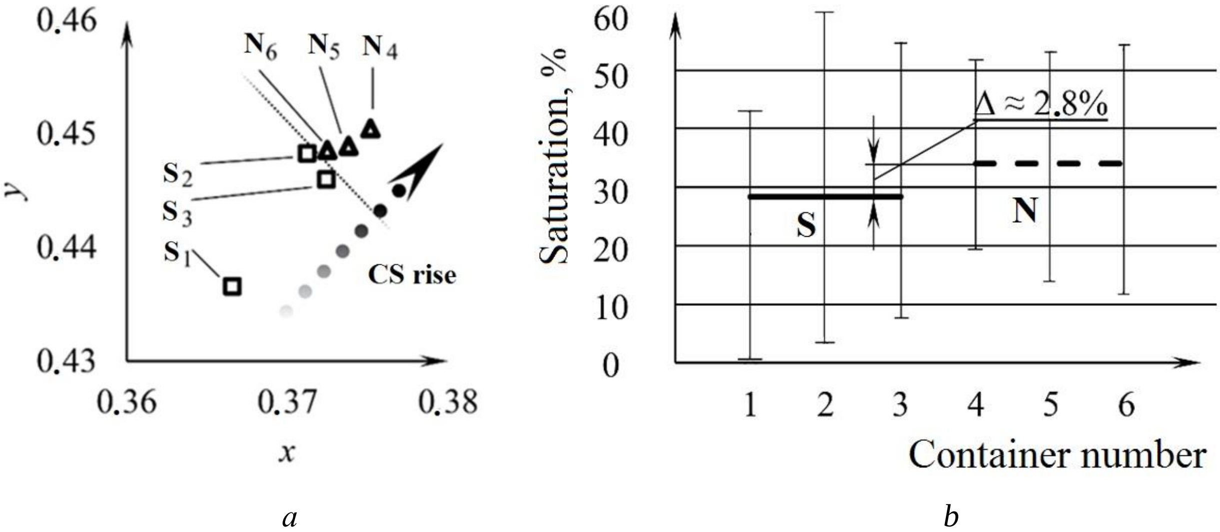


Figure 5. The color contrast between the plant groups: *a* – arrangement of the color points of the containers in the chromaticity diagram (*x*,*y*); *b* – mean values of saturation and their RMS values (indicated by the bars I) versus the container number.

3 Conclusions

The unique experimental setup on the basis of the *UM-2* monochromator was developed for obtaining the monochromatic color stimuli with the controlled spectrum width. It was demonstrated that the spectral sensitivity of the *RGB*-sensors and the color gamut of the camera could be tested with the use of monochromatic stimuli.

The new algorithm was developed for detection and quantification of adscripts in the inscription photo image. It is proposed to divide the objective analysis of the image into blocks of the color segmentation and the estimation of the color background and the color difference. In this problem formulation, the block of color segmentation performs the preprocessing function and defines the chart of the boundaries between differently colored classes for subsequent computation of the color differences.

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