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Comparative experiment on the accuracy evaluation of colorimetric measurements in software and hardware environments by implementing the scenario "The basis for comparison is a measurement standard"

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Abstract

The article demonstrates the results of a comparative experiment on the accuracy evaluation of the method developed by the author for measurements of the objects color characteristics by processing their digital images. The experiment was conducted on the basis of the Belarusian State Institute of Metrology (Minsk, Republic of Belarus) by comparing with reference values reproduced by the National Reference of chromaticity coordinates. The scheme of the experiment and the results are obtained. The scope of the method has been determined.

Keywords: digital image, colorimetry, chromaticity, precision

Introduction

Currently, digital images are widely used to study the geometric and optical properties of extended objects. The digital image is an information model of the registered object and a final link of the information and measuring channel including the illuminator, the illuminated surface of the object, the standard, the matrix photodetector, the software, the information display device. In this context, any registered object has an almost infinite number of realizations in the form of its digital images. Therefore, to obtain reliable results it is necessary to ensure metrological traceability of measurement results to international or national standards or reference measurement procedures. As a rule, such investigations involve the evaluation of properties on the nominal and ordinal quantity-value scales. To perform measurements it is necessary to use metric or conventional scales providing metrological traceability by reference to a measurement standards or reference measurement procedure. The Research Laboratory of Optoelectronic Instrument Engineering (Belarusian National Technical University, Minsk, Republic of Belarus) implements a research project “Development of Metrological Assurance of Measurements in Software and Hardware Environments” in cooperation with the National Academy of Sciences, within the framework of the Scientific Research State Program “Electronics and Photonics”. A comparative experiment was conducted on the basis of the production and research Department of Physical, Chemical and Optical measurements (Belarusian State Institute of Metrology). The National Standard of color units, spectral coefficients of the directed transmission and diffusion reflection in the range of waves lengths (0.2 - 2.5) microns was applied as a basis for comparison. In the conditions of repeatability and an intermediate precision the color coordinates of reference chromatic samples were defined, by means of their digital registration with the help of various technical vision systems. The purpose of this article is to demonstrate of comparative experiment results carried on for researches of accuracy indicators of colorimetric measurements in hardware and software environments.

Materials and Methods

Preparatory stage

The experiment purpose is an assessment of correctness and an accuracy determining coordinates of chromaticity of monochromatic samples (The National Standard of color units) by measurement with the help of the spectrophotometer and at the same time repeated registration by the systems of technical vision systems (digital cameras of a semi-professional class with existence of the TIFF or RAW formats) with step by step increasing exposure time and digital images processing. The National Standard of color units, spectral coefficients of the directed transmission and diffusion reflection in the range of lengths of waves (0.2 - 2.5) microns (http://www.belgim.by/1428/) represents a set of standard chromatic samples (reflecting measures of coordinates of X, Y, Z color and coordinates of chromaticity x, y). Color coordinates X, Y, Z and chromaticity coordinates x, y of the reflecting samples have ranges X = 2.5 … 109.0 color units; Y = 1.4 … 98.0 color units; Z=1.7 … 107.0 color units; x =0.0039 … 0.1000 chromaticity units; y =0.0048 … 0.1000 chromaticity units. Expanded uncertainty is 0.1 color units, 0.0070 chromaticity units. Each camera registered the object of measurement 3 times with the values of exposure time taken from some number of $T_1, \dots, T_i, \dots, T_m$ $(T_1 < \dots < T_i < \dots < T_m)$. The scheme of an experiment is provided on figure 1.

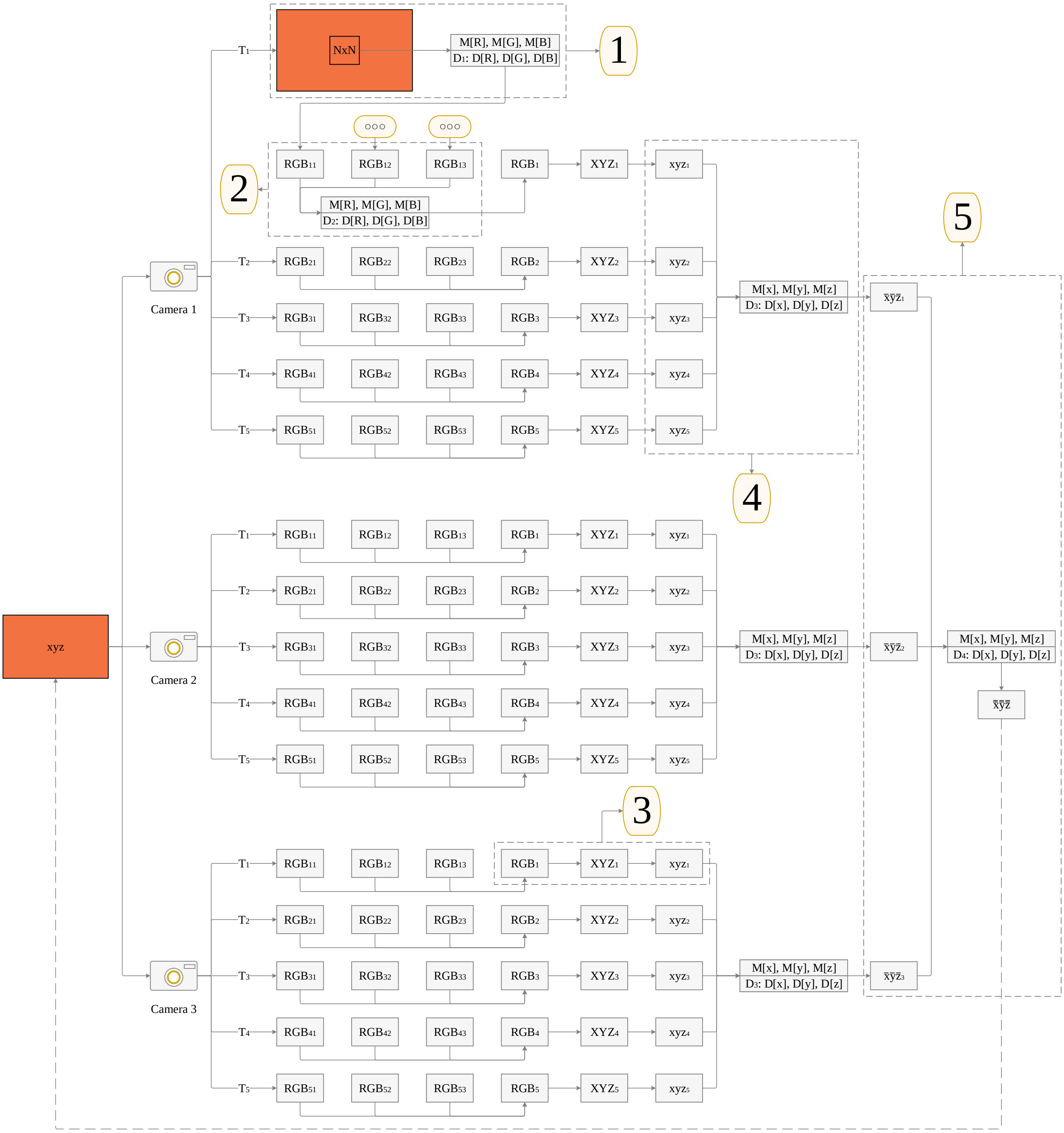


Fig 1: Hierarchical structure of an experiment with full group of factors

Since the digital image is an ordered a set of elements (pixels) the definition of objects brightness and colorimetric features involves averaging over a certain area of pixels. The authors [1] have developed a software product "Metrum" which allows to automate the process of determining the optimal size of the digital image. At the initial stage, it is necessary to determine the optimal size of the digital image area of *n* pixels for which the variance would be minimal. We chose a section of cloudless sky in the daytime as a test object and recorded it with a digital camera (Nikon D3200 with resolution of 6034×4012 pixels, a focal length of 42 mm, aperture of f/32, sensitivity (ISO) of 100, automatic white balance, RAW format (.NEF), Picture Control mode - "neutral") working color space Adobe RGB. The exposure time was *T*: 0.2 s, 0.3 s, 0.7 s, 1.0 s, 1.3 s, 4.0 s. Then we selected five areas (see figure 2) to more accurately determine the size of the active pixel areas by the intensities in red (R), green (G), and blue (B) color channels.

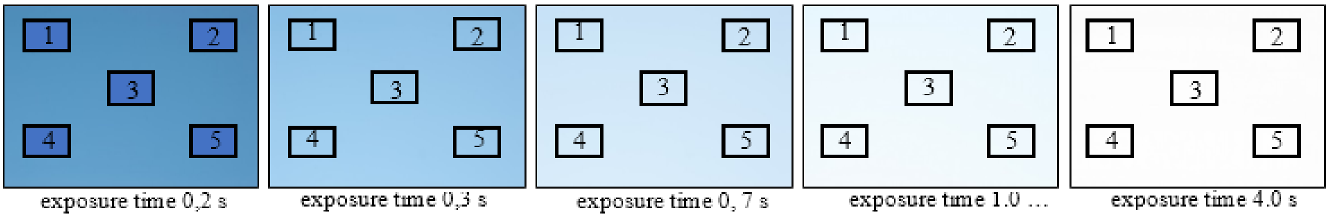
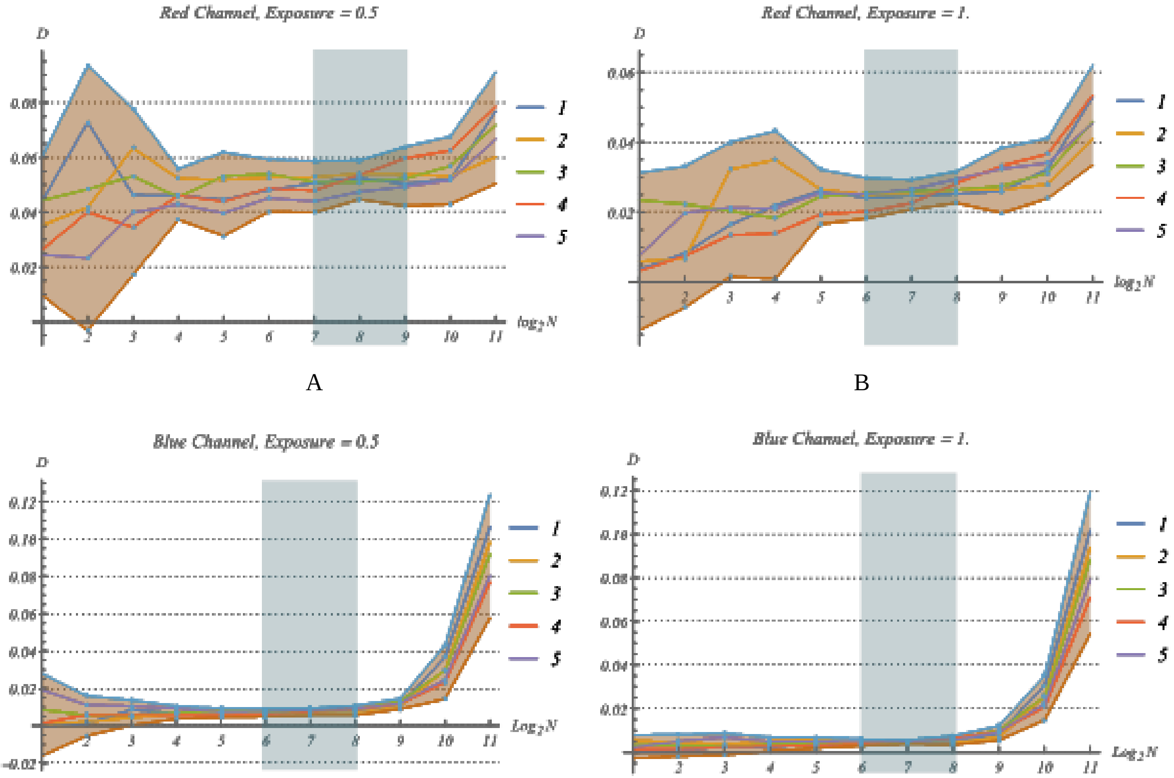


Fig 2: Localization of the sectors on test images

The variable factors are the sizes N×M of the image area belonging to the sector and the exposure time T. Mathematical expectations M[X] of the intensities over three color channels (R,G, B) and their variances D[X]- D(R), D(G), D(B) have been calculated for each area. The obtained dependences of intensity variances on the study area size for different image parts are shown in figure 3.



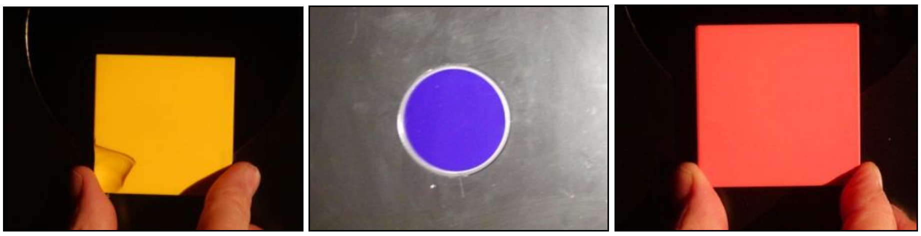
A B

Fig 3: Variance dependences on the size of the digital image area at different exposure times: a – 0,3 s; b – 0.7 s; c – 1.0 s; d – 1.3 s

The abscissa axis is a logarithmic scale of the region side size along the base 2 ($\log_2 N$). The y is an axis values of the variance. Lines 1-5 display the variance values for the corresponding of the same name regions. Probability densities of variance distributions in different regions at the level of three standard deviations ($M[X] \pm 3\sqrt{D[X]}$) are shown in the graphs by filling. Vertical dashed areas on the charts show the neighborhood of the desired optimal working area size of digital images corresponding to the measurement problem. Regression analysis revealed a traceable dependence and determined the optimal area of 128x128 or 0.068% of the total number of pixels. However, the size of the area may vary.

Conducting experiment

For the experiment we have chosen monochromatic reference samples "yellow matte", "blue" and "red matte" shown in figure 4. A standard light source of type "A" illuminated the samples at a certain angle of observation. The chromaticity coordinates of the samples were determined using a spectrophotometer "SPECORD-M40" (CARL ZEISS JENA), which is part of the National standard of the Republic of Belarus. Standard samples have the following chromaticity: "yellow matte" - x=0.5314, y = 0.4512; "blue" - x=0.2238, y = 0.1052; and "red matte" - x=0.6324, y = 0.2415, with extended uncertainty values 0.25 and color units 0.0007 chromaticity units. Simultaneously, series of each sample images with different exposure times were obtained using three digital cameras of semi-professional class. Then we processed the digital images by transforming the color spaces RGB $\rightarrow$ XYZ.



A B C

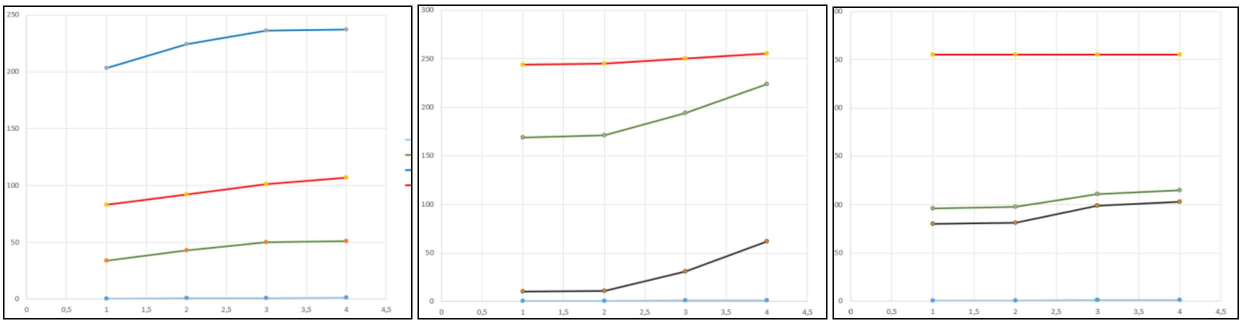
Fig 4: Appearance of monochromatic reference materials: a – «yellow matte», b - «blue», c - «red matte»

Averaged values of color coordinates R, G, B (mathematical expectations of intensities in red, green and blue channels of digital images) and their characteristics (medians and standard deviations) obtained as example from one camera are given in table 1.

Table 1: Experimental data of digital image processing in color space RGB

«yellow matte»			
0,3 s	R=243,59 m = 245 σ= 3,52	G= 169 m = 171 σ=3,24	B= 9,98 m = 8 σ= 9,43
0,7 s	R=245,43 m = 246 σ= 3,57	G= 171,16 m = 171 σ= 3,17	B= 11,01 m = 10 σ= 9,40
1,0 s	R=250 m = 255 σ= 0,04	G= 194 m = 193,34 σ= 3,06	B= 30,57 m = 31σ=11,32
1,3 s	R=255 m = 254,18 σ=1,48	G= 224 m = 224,72 σ=2,92	B= 63,81 m = 63 (σ=10,30)
«blue »			
0,3 s	R=83,58 m = 83 σ= 8,99	G= 33,97 m = 34 σ= 5,48	B= 203,44 m = 203 σ= 4,68
0,7 s	R=91,80 m = 92 σ= 11,56	G= 43,09 m = 43 σ=7,45	B= 224,27 m = 225 σ= 6,21
1,0 s	R=101,01 m = 100 σ= 10,97	G= 50,25 m = 51 σ= 8,43	B= 236,06 m = 236 σ= 6,72
1,3 s	R=106,84 m = 107 σ= 11,83	G= 48,87 m = 49 σ=8,22	B= 234,09 m = 234 σ= 6,26
«red matte»			
0,3 s	R=250 m = 255 σ= 0	G= 95,58 m = 96 σ= 4,26	B= 79,09 m = 79 σ= 7,38
0,7 s	R=252 m = 255 σ= 0	G= 98,63 m = 98 σ=3,94	B= 81,02 m = 82 σ= 7,45
1,0 s	R=253 m = 255 σ= 0	G= 111,02 m = 111 σ=3,64	B= 99,05 m = 99 σ= 7,36
1,3 s	R=255 m = 255 σ= 0	G= 115,39 m = 115 σ= 3,69	B= 103,49 m = 104 σ= 6,26

The obtained dependences of the intensities R, G, B on the exposure time T are shown in figure 5.



a) «yellow matte» b) «red matte» c) «blue »

Fig 5: Dependences of the intensities R, G, B on the exposure time T: a - «yellow matte», b - «red matte», c - «blue»

Further it is necessary to determine color coordinates X, Y, Z and coordinates of chromaticity x, y, z on the basis of the executed measurements and to compare them to reference values.

Processing and analysis of results. The applied methodology of precision calculation is based on the dispersive analysis at various levels of an experiment. The variances D_1 of the first level are caused by variation of intensity values in three color channels of the working image area (figure 1, area 1) and calculated by formulas [2]:

$$D_{1,m,n}[R] = \frac{1}{k-1}\sum_{i=1}^{k}\left(R_{m,n,i} - \bar{R}_{m,n}\right)^2 ; \tag{1}$$

$$D_{1,m,n}[G] = \frac{1}{k-1}\sum_{i=1}^{k}\left(G_{m,n,i} - \bar{G}_{m,n}\right)^2 ; \tag{2}$$

$$D_{1,m,n}[B] = \frac{1}{k-1}\sum_{i=1}^{k}\left(B_{m,n,i} - \bar{B}_{m,n}\right)^2 , \tag{3}$$

Where $D_{1,m,n}[R],\ D_{1,m,n}[G],\ D_{1,m,n}[B]$ – the first level variances in the relevant color channel for n-*th* image executed with m-*th* exposure time;
k – Number of pixels in the explored area;
$R_{m,n,i}, G_{m,n,i}, B_{m,n,i}$ – Intensity in the relevant color channels i-*th* pixel for n-*th* image executed with m-*th* exposure time;
$\bar{R}_{m,n}, \bar{G}_{m,n}, \bar{B}_{m,n}$ – Mathematical expectations of intensity in the relevant color channels of pixels of the explored area of the image for n-*th* image executed with m-*th* exposure time.
We use these mathematical expectations for determination of the second level of variance D_2 (figure 1, area 2) on formulas [2]:

$$D_{2,m}[R] = \frac{1}{n-1}\sum_{i=1}^{n}\left(R_{m,i} - \bar{R}_m\right)^2; \tag{4}$$

$$D_{2,m}[G] = \frac{1}{n-1}\sum_{i=1}^{n}\left(G_{m,i} - \bar{G}_m\right)^2; \tag{5}$$

$$D_{2,m}[B] = \frac{1}{n-1}\sum_{i=1}^{n}\left(B_{m,i} - \bar{B}_m\right)^2; \tag{6}$$

Where $D_{2,m}[R], D_{2,m}[G], D_{2,m}[B]$ – the second level of variance in the relevant color channel for n-*th* image executed with m-*th* exposure time;
n – Number of the images with m-*th* exposure time;
$R_{m,i}, G_{m,i}, B_{m,i}$ – Intensity in the relevant color channels for n-*th* image executed with m-*th* exposure time;
$\bar{R}_m, \bar{G}_m, \bar{B}_m$ – Mathematical expectations of intensity in the relevant color channels image for executed with m-*th* exposure time.
These mathematical expectations are used for transformation RGB→XYZ (figure 1, area 3) on formulas [3]:

$$X = 2.7689 \cdot R + 1.7517 \cdot G + 1.1302 \cdot B \tag{7}$$

$$Y = 1.0000 \cdot R + 4.5907 \cdot G + 0.0601 \cdot B \tag{8}$$

$$Z = 0.0565 \cdot G + 5.5943 \cdot B \tag{9}$$

The chromaticity coordinates were calculated according to the formulas [4]:

$$X = \frac{X}{X+Y+Z}; \tag{10}$$

$$y = \frac{Y}{X+Y+Z} \tag{11}$$

$$Z = \frac{Y}{X+Y+Z} \tag{12}$$

We use the received values x, y, z for determination of the third level of variances D_3 (figure 1, area 4) on formulas [2]:

$$D_3[x] = \frac{1}{m-1}\sum_{i=1}^{m}(x_i - \bar{x})^2 \tag{13}$$

$$D_3[y] = \frac{1}{m-1}\sum_{i=1}^{m}(y_i - \bar{y})^2 \tag{14}$$

$$D_3[z] = \frac{1}{m-1}\sum_{i=1}^{m}(z_i - \bar{z})^2 \tag{15}$$

Where $D_3[x], D_3[y], D_3[z]$ – variances of the third level of chromaticity coordinates for the images shot by one camera;
m – Number of values of an exposure time;
x_i, y_i, z_i – Chromaticity coordinates for i-*th* exposure time;

$\bar{x}, \bar{y}, \bar{z}$ – Mathematical expectations of the chromaticity coordinates for images with different exposure time of one camera.
To determine the variance D_4 of the fourth level (figure 1, area 5), we used the mathematical expectations M_4 obtained at the previous stage from the images taken by different cameras:

$$M_4[x] = \frac{1}{l}\sum_{i=1}^{l} x_i \tag{16}$$

$$M_4[y] = \frac{1}{l}\sum_{i=1}^{l} y_i \tag{17}$$

$$M_4[z] = \frac{1}{l}\sum_{i=1}^{l} z_i \tag{18}$$

$$D_4[x] = \frac{1}{l-1}\sum_{i=1}^{l}(x_i - M_4[x])^2 \tag{19}$$

$$D_4[y] = \frac{1}{l-1}\sum_{i=1}^{l}(y_i - M_4[y])^2 \tag{20}$$

$$D_4[z] = \frac{1}{l-1}\sum_{i=1}^{l}(z_i - M_4[z])^2 \tag{21}$$

Where $D_4[x], D_4[y], D_4[z]$ – fourth-level variances for images taken by different cameras;
l – number of cameras;
x_i, y_i, z_i – Chromaticity coordinates for i-*th* camera;
$M_4[x], M_4[y], M_4[z]$ – Mathematical expectations of chromaticity coordinates for it camera.
We compared the experimentally obtained average chromaticity value of the color standard in xyz space with its assigned value. Precision was evaluated empirically (by aggregating variances of different levels). Intralaboratory reproducibility was calculated by the formula ISO IEC 5725-2 [5]:

$$s_R^2 = s_r^2 + s_{(w)}^2, \tag{22}$$

Where s_r^2 - repeatability variance;
$s_{(w)}^2$ - Intermediate precision.
Repeatability variance s_r^2 was calculated according to [5] as an averaged variance over three color channels taking into account that the color is a vector quantity:

$$s_r^2 = \operatorname{var} \bar{e} = \overline{s_x^2} + \overline{s_y^2} + \overline{s_z^2}, \tag{23}$$

Where $\overline{s_x^2}$, $\overline{s_y^2}$, $\overline{s_z^2}$ – variance values averaged over the processing area from *n* pixels of m digital images on red, green and blue color channels.
The averaging was performed on theist section of the m-th image for the t-th exposure of the q-th sample according to the formulas:

$$\overline{s_x^2} = \frac{1}{nm}\sum_{i=1}^{n}\sum_{j=1}^{m} D_{i\,j}\,[X] \tag{24}$$

$$\overline{s_y^2} = \frac{1}{nm}\sum_{i=1}^{n}\sum_{j=1}^{m} D_{i\,j}\,[Y] \tag{25}$$

$$\overline{s_z^2} = \frac{1}{nm}\sum_{i=1}^{n}\sum_{j=1}^{m} D_{i\,j}\,[Z] \tag{26}$$

The intermediate precision was calculated according to ISO IEC 5725-3 [6] by combining the variances due to the spread of intensity values between T digital images with different exposure times t between the number of W digital cameras and Q standard samples:

$$s_{(w)}^2 = \frac{1}{TWQ}\left(\overline{s_X^2} + \overline{s_Y^2} + \overline{s_Z^2}\right) \tag{27}$$

The laboratory bias was calculated by the formula []:

$$\Delta = M_4 - \mu, \qquad (28)$$

Where M_4 – mathematical expectation of the measured value (chromaticity coordinates);
μ – reference value.
The experimental data are given in table 2.

Table 2: Experimental results and their precision

Camera	Exposure time, s							
	0,3		0,7		1,0		1,3	
	«yellow matte» x = 0.5314; y = 0.4512							
	x	y	x	y	x	y	x	y
1	0.5212	0,4501	0.5319	0,4516	0.5317	0,4498	0.5299	0,4510
2	0,5345	0,4557	0,5291	0,4486	0,5301	0,4515	0,5311	0,4517
3	0,5236	0,4434	0,5287	0,4517	0,5278	0,4513	0,5314	0,4507
$\bar{x}$, $\bar{y}$	0,5259	0,4492	0,5293	0,4501	0,5293	0,4504	0,5302	0,4507
$\bar{\bar{x}} \approx 0{,}5287$ $\bar{\bar{y}} \approx 0{,}4501$; $\Delta_{yellowX} = -0{,}0027$ $\Delta_{yellowY} = -0{,}0011$								
$s_{yellow}^2 = \bar{\bar{D}} \approx 0{,}00462$ $s_{yellow} \approx 0{,}068$								
	«blue» (x = 0.2238; y = 0.1052							
1	0.2316	0.1101	0.2236	0.1049	0.2240	0.1060	0.2233	0.1050
2	0.2229	0.1049	0.2239	0.1056	0.2235	0.1053	0.2239	0.1052
3	0.2246	0.1045	0.2232	0.1044	0.2236	0.1051	0.2242	0.1054
$\bar{x}$, $\bar{y}$	0,2264	0,1065	0,2236	0,1049	0,2237	0,1055	0,2238	0,1052
$\bar{\bar{x}} \approx 0{,}2244$ $\bar{\bar{y}} \approx 0{,}1055$; $\Delta_{blueX} = 0{,}0006$; $\Delta_{blueY} = 0{,}0003$								
$s_{blue}^2 = \bar{\bar{D}} \approx 0{,}00504$ $s_{blue} \approx 0{,}071$								
	«red matte» $(x = 0.6324;\ y = 0.2415)$							
1	0.6321	0.2473	0.6298	0.2302	0.6373	0.2413	0.6310	0.2313
2	0.6411	0.2410	0.6318	0.2407	0.6301	0.2398	0.6371	0.2387
3	0.6302	0.2301	0.6341	0.2316	0.6299	0.2317	0.6297	0.2301
$\bar{x}$, $\bar{y}$	0,6345	0,2395	0,6319	0,2342	0,6324	0,2356	0,6326	0,2334
$\bar{\bar{x}} \approx 0{,}6329$ $\bar{\bar{y}} \approx 0{,}2357$; $\Delta_{redX} = 0{,}0005$; $\Delta_{redY} = -0{,}0058$								
$s_{red}^2 = \bar{\bar{D}} \approx 0{,}00476$ $s_{red} \approx 0{,}069$								
$s_r^2 \approx 0{,}004807$; $s_r \approx 0{,}0693$; $s_R^2 \approx 0{,}001$ $s_R \approx 0{,}081$								

The standard deviation of the method repeatability was $s_r \approx 0.069$ chroma city units; standard deviation of the method Intralaboratory reproducibility was $s_R \approx 0.081$ chroma city units.

Summary and Conclusions

1. 1 Since color measurement in hardware and software environments is always based on averaging the intensity values over the working area of the digital image the developed methodology is applicable only to non-point (extended) measurement objects. The proposed method based on regression analysis of a series of test images allows to optimize the active area of the digital image at the preparatory stage in order to minimize the variance of the first level which characterizes the spread of intensity values in the color channels. It is established that the size of the optimal working area of the digital image on average is 128x128 pixels but they can vary depending on the task and registration conditions.
2. The experiment showed that the precision of colorimetric measurements in software and hardware environments depends equally on all factors of variability: the working area of digital image pixels, digital camera, exposure time, conditions, data processing algorithms. However, the measurement conditions namely the illumination angle of the samples and the positioning of the cameras in space make the most significant contribution to precision. Therefore, it is necessary to validate all elements of the measuring channel reducing the variance at all levels of the experiment to improve the accuracy and reliability of the measurement results.
3. Multiple registration of an object with different exposure time allows to solve the problem of its dynamic range limitation by additional processing of digital images based on intensity recalculation in color channels as shown in [7]. If we take the standard deviation of Intralaboratory reproducibility as the uncertainty of the method, the field of applicability assumes the requirements for the chromaticity characteristics of objects with an accuracy not worse than ≈0.2...0.3 Chroma city units.

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