Складність інтегрування систем управління кольором у робочий потік отримання цифрових півтонових зображень, через постійно змінні за потужністю та спектральним складом випромінювання умови експонування, призводить до появи на фото недоліків кольоровідтворення. Широкий спектр коректурних засобів графічних редакторів не дозволяють повною мірою усунути відхилення у кольоровідтворенні фотозображень через закладені у них недосконалі технічні підходи до реалізації самого коректурного ефекту.

Ускладнюється процес виправлення недоліків кольоровідтворення відсутністю методів об'єктивного кількісного оцінювання якісних характеристик цифрового кольорового півтонового зображення.

Розроблена методика кількісного оцінювання колірних характеристик цифрових зображень шляхом перерахунку актинічностей у значення ефективних густин забезпечує оптимальний та всебічний аналіз точності відтворення кольору. Методика полягає у представленні кольороподільних характеристик у вигляді залежності ефективних густин фотозображення від еквівалентно-сірих густин реєстрованого об'єкта. Стає можливим чисельно оцінити наявні на цифровому кольоровому фотозображенні недоліки відтворення кольорів.

Розроблена методика оцінювання стала основою для реалізації нового методу виправлення недоліків відтворення кольору при допомозі компенсативних коригуючих зображень, що забезпечують усунення недоліку по недостатній кількості кольору. Коректурний ефект забезпечується фізичним змістом компенсативних зображень, що містять ефективні густини по виділених кольорах, яких бракує на цифрових фотографічних зображеннях через неізоактинічність ізохромних кольорів.

Нова технологія виправлення кольоровідтворення реалізується у розробленому спеціалізованому програмному забезпеченні Image Redactor. Ефективність описаного методу доведено на підставі аналізу зображень, опрацьованих у створеному програмному продукті, за описаною у статті методикою графічного представлення кольороподільних характеристик. Матриці кольороподілу свідчать про суттєве підвищення корисних контрастів по виділених кольорах порівняно із аналогічними характеристиками кольоровідтворення на зображеннях до опрацювання. Це передбачає можливість застосування розробленого методу виправлення недоліків кольоровідтворення у цифровому робочому потоці опрацювання фотографічних зображень

Ключові слова: цифрова фотографія, світлочутливість, масив Баєра, оцінювання кольоровідтворення, питома ефективна густина

DEVELOPMENT OF A TECHNOLOGY FOR ELIMINATING COLOR RENDERING IMPERFECTIONS IN DIGITAL PHOTOGRAPHIC IMAGES

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1. Introduction

Digital photography today has confidently occupied position as an only means of obtaining half-tone images in the current working flow of recording optical information. However, the resulting photographs mostly require significant improvement of their quality characteristics in graphic editors and other software products. Photographic post-processing is additionally complicated by the absence of a standard procedure for objective assessment of digital photography quality and the list and maximum permissible values of quality indicators is not regulated by any normative document.

It is especially difficult to achieve satisfactory color rendering in digital photographic images because of technical limitations of application of color control systems in the digital photographic process. Color editing tools in known graphic

editors are based on the principles of tone correction without taking into consideration the origin of color separation imperfections. The mentioned reasons result in obtaining of halftone images with unsatisfactory qualitative characteristics.

Thus, there is a need for a technology for correction of color rendering imperfections which would provide corrective effect better than the technology solutions existing today.

2. Literature review and problem statement

To get a full-color image in the additive color space, it is necessary to record as accurately as possible its three single-color components: red, green, and cyan partial images. Accuracy of recording these information arrays is one of decisive factors influencing color characteristics of digital photographs (color rendering).

The chain of transformation of color information from the actual object (photographed object) to its digital image (digital halftone color image) is as follows. Radiation from a light source with energy distribution in the spectrum zones, $E_1(\lambda)$, which depends on the color temperature falls on an object with definite spectral characteristics (the ability to reflect visible spectral bands is described by function $\rho_0(\lambda)$). The light flux reflected and modulated by the photographed object enters the light energy receivers (elements of CMOS or CCD matrix) through the optical system of the lens with throughput $\tau_0(\lambda)$.

For separation of the polychromatic light flux into three monochromatic components, most of the modern digital phototechnical models (except for several models equipped with a Foveon multi-layer matrix which, however, has limited application) use arrays of light filters (Baer's arrays) with subsequent mathematical interpolation of color data in each pixel of the image (debaerization algorithms). The coefficient of throughput of the three light separating filters ($\tau_{f_1}(\lambda)$, $\tau_{f_2}(\lambda)$, $\tau_{f_3}(\lambda)$) installed in front of the photosensitive receivers determines the amount of light energy entering the receiver.

Thus, integral reaction of the receiver of light energy is defined as (1):

$$r = f(a) = f\left(\int_0^\infty \rho_0(\lambda) \cdot E_1(\lambda) \cdot \tau_0(\lambda) \cdot \tau_f(\lambda) d\lambda\right). \quad (1)$$

Technical features of recording optical signals with sensors of various types are considered in published sources [1]. Spectral characteristics of charge-coupled devices (CCD) and complementary metal-oxide semiconductors (CMOS) explain the need for separating devices in photosensitive matrices [2]. Both types of semiconductors do not have selective photosensitivity to individual bands of visible spectrum. Fig. 1 shows dependence of the quantum efficiency of photoreaction of photosensitive receivers (various types of CCD matrices) on the radiation wavelength. As dependence in Fig. 1 shows, the photoeffect magnitude is practically the same across the range of the visible spectrum (400 to 700 nm).

Status of spectral sensitivity of light energy receivers in digital photographic devices produced by three different manufacturers behind a standard set of light filters is given in Fig. 2 as a dependence of relative response of the receiver behind the light filter on the wavelength [4]. The cyan, green and red dash-and-dot lines demonstrate sensitivity of the receiver behind the cyan, green and red filter, respectively. It is clear from the graphic dependences that all filter sets are broad-band ones (transmission bands of the filters overlap

within the set) which will inevitably result in recording light fluxes of some individual radiation wavelengths behind two or even three light filters. This causes inaccuracy in recording color information and subsequent inaccuracy of color rendering of the photographed object in a digital image.
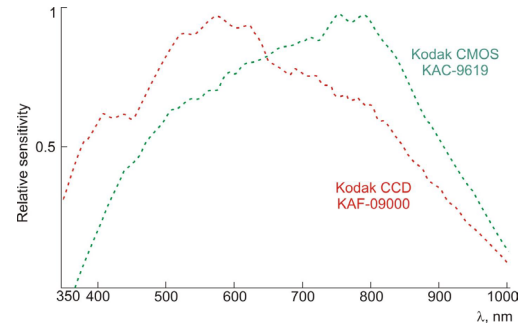

Fig. 1. Dependence of photosensitivity of semiconductor photocells on the wavelength of light radiation [3]
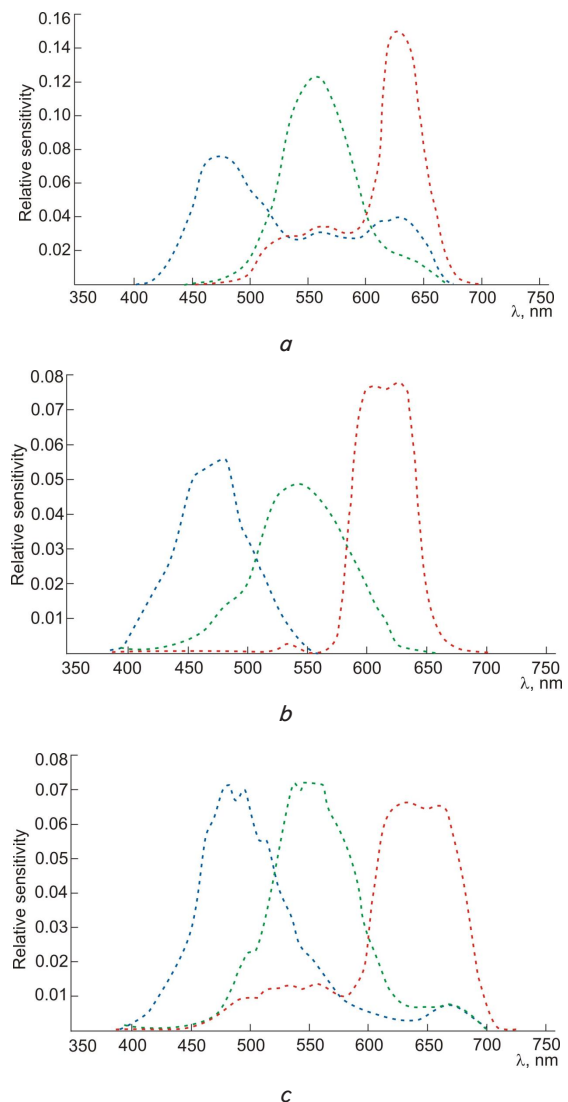

a

b

c

Fig. 2. Status of spectral sensitivity of CCD and CMOS matrix receivers of various configurations
(as the dependence of relative response of receivers on the wavelength of light radiation):
full-frame CCD Kodak matrix (*a*), CCD Sony matrix with column buffering (*b*); Agilent CMOS matrix (*c*)

Studies [6, 7] propose to correct color separation imperfections at the moment of digitization of an array of information from the matrix. However, it is technically feasible only in photographic devices equipped with CMOS matrices, and additionally complicates the work flow. Study [5] raises the issue of processing photographic images in a graphic editor to optimize rendition of one of the most important memorable colors (skin tints). However, this does not provide a complex solution of the color rendering problem.

Occurrence of color rendering imperfections caused by imperfection of separating media can be prevented by applying color control systems. Color control systems are intended to coordinate coverage of color for various colorimetric systems of devices for input and output (visualization) of information as well as transformation of color coordinates from one color system to another [4].

All color transformation operations are carried out using ICC profiles that describe abilities of rendering color coverage of a particular device (in particular, a digital camera) based on standardized colorimetric systems. For image input devices, a number of factors affect the end result of color rendition: optical system, characteristics of separating media and devices (filters, light sources), software.

As shown in [8], causes of limited use of color control systems in the workflow of digital photographic processes are explained by strong technological and technical constraints.

1. When photographing with digital photographic devices, exposure metering is performed each time when lighting conditions vary: both in light intensity and at its spectral composition which is especially critical for color rendering. The resulting profile will have a strictly narrow application for pictures taken only at specific lighting conditions. In each case, the profiling procedure should be repeated.

2. Profiling of the process of taking pictures with digital photographic devices is very labor-intensive and has a number of features:

– ensuring uniformity of lighting conditions of the photographed object (the use of identical light sources with strictly controlled color temperature, absence in the frame of outside illumination with different spectral composition, uniformity of the object illumination);

– test object must be positioned in the frame in such a way as to avoid reflexes from light sources and extraneous objects located in vicinity of the test object which will violate correspondence of colorimetric coordinates of fields of the test object proper;

– illumination of the test object must be strictly uniform in relation to intensity of the light flux and exposure itself must be precisely calculated to avoid under- or overexposure;

– when photographing, it is necessary to deactivate algorithms of improving qualitative and quantitative characteristics of the photographic image which are involved by default with software of the photographic equipment at the stage of processing data from the photosensitive matrix.

3. When constructing profile of input devices, test objects with a large number of control fields (from several hundred to several thousand) are used. Their absolute number directly affects the result accuracy. Each type of photographic material of which the test object is made for calibration is characterized by its unique features in color rendition which is explained by spectral characteristics of the dyes of photosensitive layers and masking layers in composition of the emulsion layers.

Thus, it is possible to apply color control systems only in a limited list of photographic genres: fashion photography, food shooting, portrait photography and other types of staged scenes that are static in time for which one can manage to carry out profiling before photographing. Instead, report, sports, street photography does not ensure preliminary shooting of the test object to construct the ICC profile because of dynamics of scenes and rapid change of events in the frame plane. If camera is not profiled, then it is impossible to avoid color rendering imperfections in the photographic image which should be further removed by post-processing in graphic editors. The studies carried out by authors suggest that it is impossible to completely eliminate imperfections of color rendering caused by non-isoactinity of isochromic colors and the use of broadband light filters with the help of corrective means used in the most popular graphic editors [9].

Analysis of studies in the chosen field shows that the issue of color rendering in digital photographic images is not fully resolved and requires continuation of studies.

3. The aim and objectives of the study

The study objective was to improve the technology of correction of color separation imperfections in photographic images taking into consideration physical content of causes of occurrence to reduce errors of rendering pure and binary colors. This will ensure high-quality processing of photographic images including color rendering as well as increase in productivity of digital post-photographic workflow.

To achieve this objective, the following tasks were formulated:

– develop a method for quantitative assessment of qualitative characteristics of color photographic images and detection of color rendering imperfections at the processing stage;

– work out technology of eliminating color rendering imperfections in digital photographic images and implement it using the means of specially created software possessing correctional means taking into consideration physical content of occurrence of color separation imperfections caused by non-isoactinity of isochromic colors.

4. A method of quantitative assessment of qualitative characteristics of color photographic images

None of ISO standards like (13655:2017, 12232:2006, 12233:2017, etc.) developed by the ISO/TC 42 Committee's Electronic Still Picture Imaging Working Group WG 18 proposes procedures for evaluating color characteristics of digital photographic images in the processing workflow. In view of the necessity of availability of such means, a method of effective densities developed and tested by the authors is proposed. In this method, to analyze qualitative characteristics of digital photographic images, analytical representation of color separation characteristics is proposed by conversion of actinicities into the values of corresponding effective densities [9]. Effective density of the colored area of the photographed object determines actinicity of coloring of the latter with respect to the receiver of light energy with an appropriate sensitivity status. As a result of separation of optical information by light filters of the photographic recording system, an image is formed in three channels. The color separation process is represented as three equations (2):

$$D_b^{ef} = \alpha_b^y D_b^y + \alpha_b^m D_g^m + \alpha_b^c D_r^c,$$

$$D_g^{ef} = \alpha_g^y D_b^y + \alpha_g^m D_g^m + \alpha_g^c D_r^c, \qquad (2)$$

$$D_r^{ef} = \alpha_r^y D_b^y + \alpha_r^m D_g^m + \alpha_r^c D_r^c,$$

where D_b^{ef}, D_g^{ef} are effective densities in relation to photosensitive receivers behind cyan, green and red light filters; D_b^y, D_g^m, D_r^c are monochromatic densities of one-color constituents (conditional amount of synthesis dyes); $\alpha_b^y, \alpha_b^m, ..., \alpha_r^c$ are angular coefficients characterizing growth of effective densities per unit of color quantity increment (specific effective densities).

Provided an ideal separation of colors exists, effective density of the colored portion of the image relative to one of the three light-sensitive receivers is determined just by the content of the color dye complementary to the color of the receiver's spectral sensitivity band. That is, two of the three angular coefficients must tend to zero in each equation (2). The degree of deviation from the formulated condition determines the size of color separation distortion. Bring the values of specific effective densities into the light separation matrices (3): (α) for pure colors (single layering), (β) for binary colors (pairwise layering).

$$(\alpha) = \begin{pmatrix} \alpha_b^y & \alpha_b^m & \alpha_b^c \\ \alpha_g^y & \alpha_g^m & \alpha_g^c \\ \alpha_r^y & \alpha_r^m & \alpha_r^c \end{pmatrix}, \quad (\beta) = \begin{pmatrix} \beta_b^r & \beta_b^g & \beta_b^b \\ \beta_g^r & \beta_g^g & \beta_g^b \\ \beta_r^r & \beta_r^g & \beta_r^b \end{pmatrix}. \qquad (3)$$

The matrix of pure colors characterizes color rendering of single-colored components (yellow, magenta, cyan) in three color separation channels. Rows of this matrix contain specific effective densities of three colors (Y, M, B) relative to one of the color separating channels. Columns of the matrix contain specific effective densities of each of the three colors (yellow, magenta, cyan) relative to each of the three-color separating channels: red, green and cyan. For a more accurate assessment of color separation, in addition to single colors, rendition of binary colors should also be taken into consideration in connection with the two-component composition since the task of precise rendering of already two-color components is solved. That is, for a thorough analysis of color separation quality, it is necessary to compose a matrix from specific effective densities of binary colors.

At ideal color separation, it should be ensured that the diagonal members of the matrix are equal to one while non-diagonal ones are equal to zero (4). That is, the closer the matrix of color separation characteristics to the single one the better is recording of single-color components by the light signal receivers.

$$(A) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (B) = \begin{pmatrix} 1 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \end{pmatrix}. \qquad (4)$$

The color image is described by gradation and color separation characteristics. Graphical representation of the latter requires a particularly careful approach since the choice of coordinates affects nature of color rendering curves. Color separation characteristics of the photographic image are objectively reflected by graphical dependences of the values of effective densities of grey-equivalent actinic densities [10].

The graphical method for determining color separation characteristics makes it possible to assess quality of color separation performed in particular by means of color separation in digital photographic devices. Lines of effective densities characterize functional dependence between magnitude of the effect obtained in each of the three color receivers expressed by effective density and the value of input parameter characterizing amount of yellow, magenta or cyan dye or paint of original.

To form matrices of color separation describing qualitative characteristics of color-separated images, it is necessary to construct three graphical dependences of the color separation characteristics. In this graphical representation, values that characterize quantitative characteristics of each of the single-color components are laid down on abscissa axes and effective densities of color scales on ordinate axes.

For qualitative and quantitative assessment of color separation, it is necessary to present color separation characteristics in a form of graphic dependences of effective densities of the D_{ef} fields of color scales of a photographic image on the magnitude of its grey equivalent densities D_{ged}.

According to the presented procedure, the color separation characteristics of photographic images obtained by two models of digital photographic devices equipped with different types of photosensitive matrices, that is CCD and CMOS matrices are presented in Fig. 3. For separation of single-color components of a full-color image, an array of Bayer filters is used in both camera models. The lines of effective densities in each coordinate plane reflect content of one of the dyes of subtractive synthesis (cyan, magenta, yellow). For objective analysis of color rendition, content of the listed dyes is determined for the following colors of the photographic image: yellow (Y), magenta (M), cyan (C), blue (B), green (G), red (R) and conditionally grey (CG.). The tangents of the angle of inclination of lines of effective densities to the abscissa axis (specific effective densities) are determined in the built graphs of color separation characteristics. The latter are quantitative characteristics of color separation since they reflect growth of effective densities depending on the increase in the amount of color. The values of specific effective densities are brought into matrices of separation of clear and binary colors (3).

Satisfactorily performed optical separation of light energy should result in the amount of color in non-isochromic colors approaching the minimum value (ideally, to zero) and the angular coefficient of approximated line approaching zero. Conversely, amount of color in isochromic colors should approach a direct proportional relationship and the angular coefficient should approach one.
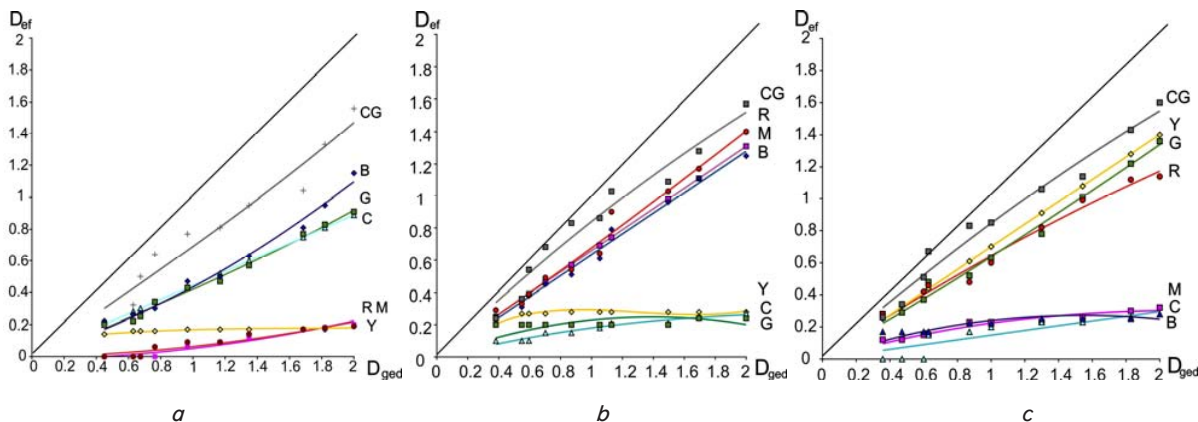
Bring angular coefficients in a matrix of separation of pure and binary colors (the photo obtained by a CCD matrix (5), the photo obtained by a CMOS matrix (6)).

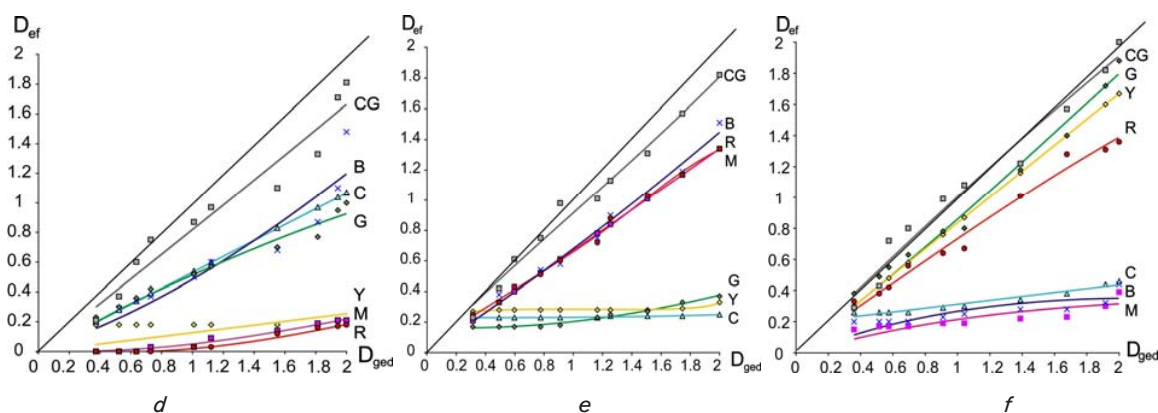$$(\alpha) = \begin{pmatrix} 0{,}81 & 0{,}21 & 0{,}12 \\ 0 & 0{,}68 & 0 \\ 0{,}14 & 0{,}16 & 0{,}64 \end{pmatrix},$$

$$(\beta) = \begin{pmatrix} 0{,}67 & 0{,}84 & 0{,}23 \\ 0{,}68 & 0{,}14 & 0{,}71 \\ 0{,}14 & 0{,}59 & 0{,}53 \end{pmatrix}. \qquad (5)$$

$$(\alpha) = \begin{pmatrix} 0.65 & 0.19 & 0.16 \\ 0.12 & 0.69 & 0.19 \\ 0 & 0.12 & 0.52 \end{pmatrix},$$

$$(\beta) = \begin{pmatrix} 0.63 & 0.58 & 0.21 \\ 0.75 & 0.18 & 0.62 \\ 0.12 & 0.48 & 0.47 \end{pmatrix}. \qquad (6)$$

1) color separation characteristics of the image obtained by Canon EOS 77D camera (CMOS matrix)

2) color separation characteristics of the photographic image obtained by the photocamera PowerShot SX430 IS (Canon) (CCD matrix)

Fig. 3. Color separation characteristics of digital photographic images: color separation of cyan paint (*a, d*); color separation image of magenta paint (*b, e*); color separation image of yellow paint (*c, f*)

One of the most important requirements to color illustrative originals is absence of color separation distortions or at least their minimum number. The color separation matrices for images taken both by CCD (5) and CMOS matrices (6) differ significantly from the single ones. This indicates nonideal recording of monochromatic components and presence of color rendering imperfections: insufficient amount of color in separated colors and excess color in non-separated colors, that is, non-isoactinity of isochromic colors takes place. The matrices of color separation in photographs indicate presence of color rendering imperfections in the first place: insufficient amount of separated color when useful contrasts are much lower than one (0.47, 0.48). Excess of dye in nonseparated colors in both images is very small (harmful contrasts do not exceed 0.21–0.23). Such color separation characteristics can be explained by the use of narrow-band filters in both models of photographic equipment.

5. Development of the method for correcting imperfections in color rendition of digital photographic images by separate compensatory corrective images

Presence of the above color separation imperfections necessitates processing of images in graphic editors. However, as the studies show, the use of correcting tools in the most popular graphic editors does not provide complete elimina-

tion of color separation imperfections [8]. Therefore, in order to eliminate insufficient actinicity in the separated colors, the authors propose a method for correcting imperfections of color rendering by superposition of each separate colored image with separate compensatory images. Physical content of compensatory images consists in the presence of density in separated colors which are missing in the images ((5), (6)). Each compensatory image is obtained by combining one positive color-separated image and one negative color-separated image. To achieve corrective effect, one needs to get three combinations of separate compensatory images. Their contents are as follows: the first compensator is a combination of a positive of a cyan-channel image with a negative of a green-channel image; the second compensator is a positive of a green-channel image with a negative of a red-channel image; the third compensator is a positive of a red-channel image with a negative of a green-channel image. At the next stage, compensators are brought together with corresponding color separated images.

The presented method can be analytically described by the following mathematical dependences (7):

$$D_c = a'_c D_r + a^m_c \left(D_r - D_g\right),$$

$$D_m = a'_m D_g + a^c_m \left(D_g - D_r\right),$$

$$D_y = a'_y D_b + a^m_y \left(D_d - D_g\right), \tag{7}$$

where $a_i'D_j$ is uncorrected actinicities of separated colors, and expressions $a_c^m(D_r - D_g)$, $a_m^c(D_g - D_r)$, $a_y^m(D_b - D_g)$ describe characteristics of the compensatory corrective image. Each individual compensatory image has an increased density in the separated colors, and all other color scales including conditionally grey scale are reproduced practically without contrast. As a result, a corrective effect of increasing specific effective density in the separated colors appears. The compensatory image contains mainly density of the separated colors that are absent in the images to be corrected and is not a positive or negative image because it is obtained by combining one of the positive color-separated images and one of the negative color-separated images. Schematically described method for correcting color rendering imperfections by separate compensatory corrective images is shown in Fig. 4.

This method of color correction consists of two stages:

1. Obtaining separate compensatory images:

a) a positive of a cyan-channel image combined with a negative of a green-channel image;

b) a positive of a green-channel image combined with a negative of a red-channel image;

c) a positive of a red-channel image combined with a negative of a green or cyan-channel image).

2. Combination of compensators with corresponding corrected color-separated images.

Let us consider the developed procedure of correction of color separation imperfections by separate compensatory corrective images in following steps:

1. Duplicate the uncorrected (original) image.

2. Divide the obtained copy into three separate single-channel (single-color) images and duplicate again the green-channel image (for magenta paint) as it is planned to use negative of the green-channel image twice: for compensators of cyan-channel and red-channel images (for yellow and cyan paints, respectively).

3. Create a compensatory image for the cyan-channel image:

3.1. Create a new (additional) layer for the cyan-channel positive image and copy into it one of the copies of the green-channel image via the buffer.

3.2. Convert the green-channel image in a new layer into a negative image, set normal overlay mode, 50 % transparency, and merge the layers in a single image. Thus, a compensator for the image of yellow paint is obtained in the cyan channel.

4. Create a compensatory image for the green-channel image:

4.1. Create a new (additional) layer for the green-channel positive image and copy via the buffer a copy of the red-channel image into this layer.

4.2. Convert the red-channel image in a new layer into a negative, set normal overlay mode, 50 % transparency and merge the layers in a single image. Thus, a compensator is formed in the green channel for the image of magenta paint.

5. Creation of a compensatory image for the red-channel image:

5.1. Create a new layer for the red-channel image (cyan paint) and copy via the buffer a copy of the green-channel image into this layer.

5.2. Transform the green-channel image in the new layer to a negative, set normal overlay mode, 30 % transparency (since the image of the cyan paint has minimal distortion) and merge the layers in a single image. Thus, a compensator is formed in the red channel for the image of cyan paint.

6. Delete the remained green-channel image duplicate to prevent discrepancy in further merging of channels.

7. Merge the channels with formed compensators into a single three-channel image (a color compensatory corrective image).

8. Create a new layer for the corrected image and copy via the buffer the newly created compensatory corrective image into the new layer.

9. Set normal overlay mode, 50 % transparency and merge layers in a single image.

10. Set the normal contrast of the corrected full-color image.

Methods for improving color rendering of photographic images are implemented using the developed ImageRedactor program. It was created in the C# programming language. Fig. 5 shows an example of the ImageRedactor's work window for implementing the described method for correction of color separation imperfections with separate compensatory correction images. According to the diagram presented in Fig. 6, the mentioned program product implements step by step (in a dialog mode) or fully automatically the described method of correcting photographic images as well as three more methods of correcting color separation imperfections in photographs:

1) with three separate color corrective images;

2) with separate compensatory corrective images;

3) with only single achromatic corrective image;

4) with only color compensatory corrective image.

Respectively, methods 1–4 in the program interface (methods 2–4 were not considered in this study).

The program interface is designed in such a way that in addition to the proposed methods of correction, the user can also apply basic tools for correcting imperfections of color and tone rendering in photographic images (exert influence on contrast, brightness of the image, etc.). Particular correction methods are chosen by the user on the basis of a preliminary analysis of the photographic image semantics (presence of memorable colors and neutral hues). In accordance with the assessment procedure developed in this study, qualitative characteristics of the image are determined and choice of the corrective method is done according to the size of color rendering imperfections respective insufficient or excessive color content.

Color separation characteristics of the image (obtained by the CMOS-matrix) corrected by the developed procedure are given in Fig. 6. The color separation matrices have the following form (8):

$$\alpha = \begin{pmatrix} 1.0 & 0.03 & 0 \\ 0.08 & 1.0 & 0.08 \\ 0 & 0 & 1.0 \end{pmatrix}, \quad \beta = \begin{pmatrix} 0.74 & 0.91 & 0.18 \\ 1.02 & 0.08 & 0.73 \\ 0 & 0.98 & 0.92 \end{pmatrix}. \quad (8)$$

Using specific densities of single-color images of pure colors, a conclusion can be drawn that due to this technology, a significant corrective effect is achieved. The diagonal members of the matrix of pure colors (7) (useful specific densities) are equal to one which corresponds to conditions for a perfect color separation. Non-diagonal members of the matrix are close to zero. Compared to the noncorrected image, characteristics of the image corrected by the described method have improved. Virtually, no harmful contrasts exist (from 0 to 0.08) and useful contrasts are at the level of one. The matrix of specific effective densities of binary overlays of colors shows that most of the useful contrasts approach one and harmful contrasts (the result of parasitic actinicity) can be significantly reduced. It should also be noted that the described correc-

tive method provides optimal grey balance: the content of cyan color slightly exceeds the content of the rest of colors of synthesis in achromatic tints. It is this color component ratio that is recommended by ISO12647-2:2013 standard.
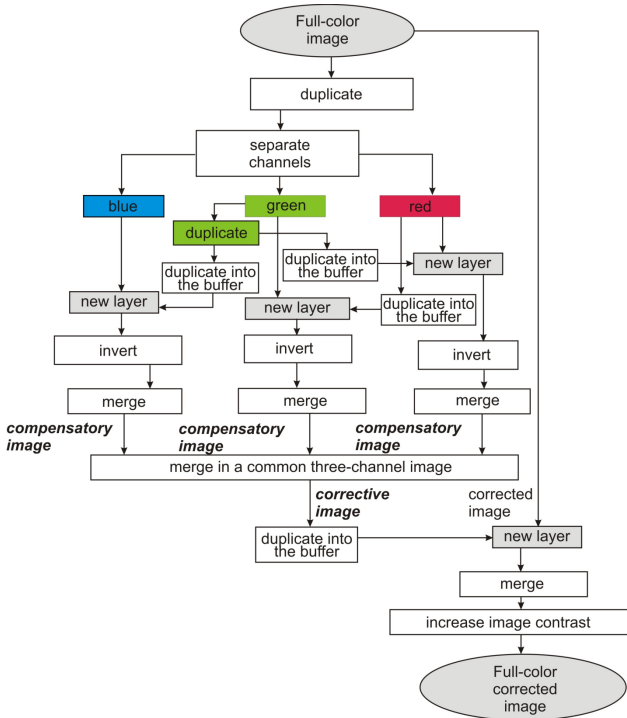

Fig. 4. Schematic presentation of the method of correction of color rendering imperfections by separate compensatory corrective images
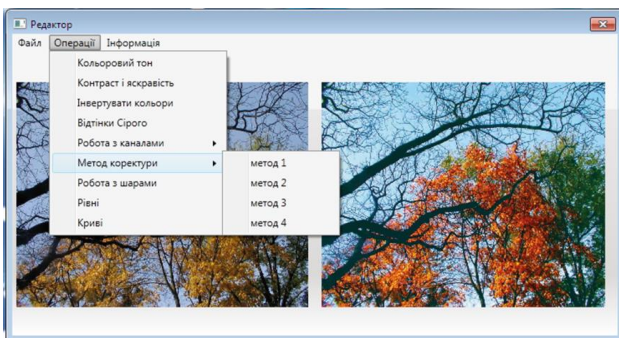

Fig. 5. Example of the working window of the ImageRedactor program

6. Discussion of results obtained in correcting color separation imperfections in digital photographic images with separate compensatory corrective images

As a result of correction of color characteristics by the developed method of correction with the use of separate corrective compensatory images, digital images have undergone a positive change. Color separation characteristics of the corrected images (Fig. 8) show that harmful contrasts were minimized for nonseparated colors and useful contrasts significantly improved compared with similar color images before correction (Fig. 3). The matrix of color separation for pure colors of the corrected image (8) shows color characteristics practically close to perfect (4). The resulting corrective effect is explained by the presence of increased effective density for separated colors in the compensatory corrective image.

Such positive corrective effect was achieved due to application of the developed method for assessing qualitative characteristics of photographic images in a digital form. Before moving the photographic image to a material carrier, it is possible to assess accuracy of separation and recording its one-color components and calculate the sought corrective effect (future characteristics of corrective images).

Advantage of the developed correction method consists in ability to apply it to every photographic image obtained digital photographic equipment of any class. Color control and camera profiling technologies have limited application in the digital photographic workflow because of technological complexity of implementation [4, 8]. It is impossible to achieve a satisfactory result of correction of color separation imperfections at the moment of recording optical information or in post-processing [5–7]. Thus, the developed method for correction of color separation imperfections with separate compensatory corrective images has been developed to provide a higher level of correction. It has the prospect of successful practical application in the digital workflow of processing digital halftone graphics.

At the same time, the proposed technological solution has certain features. Particularly, useful contrasts do not yet reach a sufficient level for partial images of magenta and yellow in binary overlays (Fig. 8). This feature imposes certain limitations on the use of the results that can be interpreted as a drawback of this study. Impossibility of removing these restrictions in the framework of this study leads to the search for new solutions to peculiarities of color rendering in digital photographic images, in particular, correction of the imperfections of rendering some separated colors.
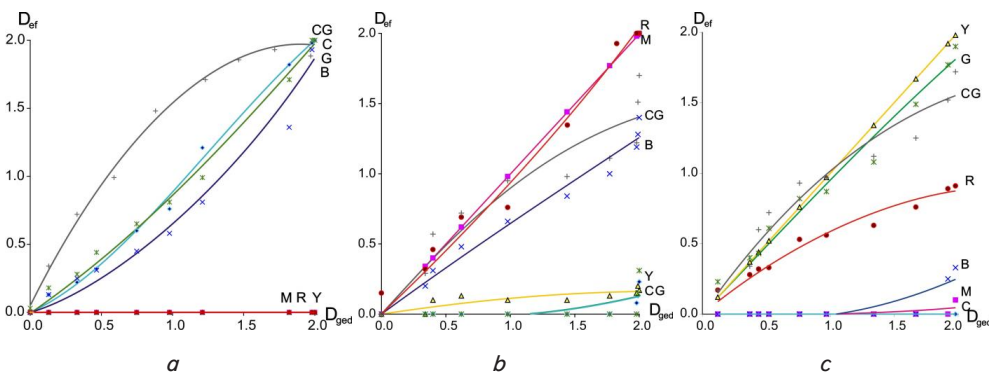

Fig. 6. Characteristics of color rendition in the image corrected by separate compensatory corrective images: color-separated image of cyan paint (*a*); color-separated image of magenta paint (*b*); color-separated image of yellow paint (*c*)

7. Conclusions

1. A method for assessing qualitative characteristics of photographic images in a digital form before their output to a material carrier by conversion of actinicity values in the values of effective densities.

2. Qualitative characteristics of digital photographic images obtained by various technical means were objectively analyzed with the use of the developed assessment method. Presence of color separation imperfections of two types (insufficient paint amounts in separated colors and excess amounts in nonseparated colors) was found in all images regardless of how they were obtained.

3. A method of correction of color separation imperfections with separate compensatory corrective images was developed. It makes it possible to obtain color images fully corresponding to the criteria of satisfactory color separation. In order to implement the corrective method, specialized ImageRedactor software was created. Its correction means take into consideration physical content of the origin of color separation imperfections which has enabled implementation of a new approach to correction.

4. It has been shown that the color separation characteristics of photographic digital images processed in accordance with the developed method in the created ImageRedactor software fully correspond to the formulated satisfactory color separation criteria. All useful and harmful contrasts are within the limits of the set tolerances in both pure and binary colors. At the same time, a proportional rendition of the entire tonal range of the image is ensured as opposed to the decisions on color correction in existing graphic editors.

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