UDC 535.24 DOI:

Method for the numerical evaluation of the color rendering quality of matrix photodetectors

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Abstract

To objectively evaluate the color image of an architectural object when changing its spectral quality and luminance in lighting, it is necessary to ensure its accurate fixation. The measurement of the color coordinates of an object provides the fully capture of its appearance, but this does not allow to get an adequate evaluation of the visual impression without visualizing the lighting scene. This requires a thorough procedure of reproducing the same color coordinates for each point of the image and the object with the same angular coordinates. In this work, an attempt is made to develop a numerical criterion for evaluating the quality of color rendering of the camera as a fixer of color visual impression of the selected scene. The development of a numerical detailed method for evaluation of the quality of color rendering of cameras will allow capturing more reliably such a subjective concept as the correspondence of the visual impression of the real scene and the image file of this scene. The digital format, which contains information about the object, avoids the problems associated with aging of the image. The proposed method of developing ways to numerically evaluate color distortion in photography is considered on the example of digital cameras Nikon D300s, Sony DSC-H5. The described approach for the case of known spectral characteristics allows to unambiguously link the calculated reaction of the camera with the chromaticity coordinates of spectrally pure colors. Modern methods of evaluating the quality of light sources (IES TM-30-15) allow evaluation of the direction of the shift. The proposed indicator – graph $E(\lambda_i)$ numerically characterizes the difference between the reaction of the camera and the reaction of the human eye and does not give an idea in which direction there is a difference, conditionally red or blue image compared to the natural scene, but is the simplest and most understandable to the untrained user. It is shown that with an accuracy of measuring spectral characteristics of 1% for the considered example with Nikon D300s, this indicator at different wavelengths is calculated with an uncertainty of not more than 0.002.

Keywords: matrix receivers; color coordinates; numerical evaluation.

Received: 29.10.2021 Edited: 10.12.2021 Approved for publication: 15.12.2021

1. Introduction

Changing the spectral quality and luminance in lighting of an architectural object is a natural process and one of its characteristics. It is necessary to standardize light sources or take into account the influence of their characteristics, for example, in [1] it is stated that the measurement of chromaticity X, Y luminance is carried out by light source C. Color distortion when reproducing a photo of the object on different screens and methods of its minimization are considered in [2]. The aim of this work is to propose a numerical approach for step-by-step full-color fixation of the appearance of the selected scene. Today a standardized approach to evaluating the quality of any device is an urgent need and the relevant documents are being developed and constantly improved. For example, the evaluation of the quality of photometers is currently numerically regulated by methods that are not limited to the uncertainty evaluation [3]. In the field of the color of light sources, the transition from a numerical evaluation of the color rendering index R_a according to CIE 13.3-1995 to an evaluation according to IES TM-30-15 [4, 5] is discussed that allows more detailed characterization by distortions in perception.

2. Method

A camera whose spectral sensitivities of the channels are in the visible range is considered. If the spectral sensitivities for the red, green, and blue elements of the matrix $X_f(\lambda_i)$, $Y_f(\lambda_i)$, and $Z_f(\lambda_i)$ are known, then the camera's response $R_{f,i}$, $G_{f,i}$, $B_{f,i}$ to monochromatic radiation can be calculated [6, 7].

Table 1

Formulas for calculating color coordinates for the average human eye and the selected camera

Characteristic	The average human eye	The selected camera
Color coordinates	$X(\lambda_i) = \int \delta(\lambda - \lambda_i)\overline{x_0}(\lambda)\partial\lambda = \overline{x_0}(\lambda_i)$	$X_i^f = R_f(\lambda_i)$
	$Y(\lambda_i) = \int \delta(\lambda - \lambda_i)\overline{y_0}(\lambda)\partial\lambda = \overline{y_0}(\lambda_i)$	$Y_i^f = G_f(\lambda_i)$
	$Z(\lambda_i) = \int \delta(\lambda - \lambda_i)\overline{z_0}(\lambda)\partial\lambda = \overline{z_0}(\lambda_i)$	$Z_i^f = B_f(\lambda_i)$
Chromaticity coordinates	$x_i = X_i / (X_i + Y_i + Z_i)$	$x_i^f = X_i^f / (X_i^f + Y_i^f + Z_i^f)$
	$y_i = Y_i / (X_i + Y_i + Z_i)$	$y_i^f = Y_i^f / (X_i^f + Y_i^f + Z_i^f)$
Coordinates of chromaticity in equal contrast graphics	$u_i = 4x_i / (-2x_i + 12y_i + 3)$	$u_i^f = 4x_i^f / (-2x_i^f + 12y_i^f + 3)$
	$v_i = 9y_i / (-2x_i + 12y_i + 3)$	$v_i^f = 9y_i^f / (-2x_i^f + 12y_i^f + 3)$

The ratio between the sensitivities of the channels (white balance) is assumed to be constant. Then, according to known formulas, the camera color coordinates and chromaticity coordinates corresponding to monochromatic radiation can be calculated at wavelengths λ_i and then in equal contrast space $u'_f(\lambda_i)$, $v'_f(\lambda_i)$. It is proposed to compare each of these points with the known chromaticity coordinates of CIE 1931 $x(\lambda_i)$, $y(\lambda_i)$ and $u'(\lambda_i)$, $v'(\lambda_i)$. As a measure of the quality of color rendering of the device, it is proposed to use a graph of the distance from $u'_f(\lambda_i)$, $v'_f(\lambda_i)$ to $u'(\lambda_i)$, $v'(\lambda_i)$ for each wavelength, that is for each color tone. This graph will allow selecting the appropriate camera to capture scenes in blue, green or red. As a result of applying [8, 9], we obtain two geometric locations of points, the first characterizes the average human eye and the second for the selected camera (Table 1).

The common graph $u'_f(\lambda_i)$, $v'_f(\lambda_i)$ and $u'(\lambda_i)$, $v'(\lambda_i)$ for each wavelength by the distance between the points allows seeing how different are the reactions of the human eye and the studied camera, and in the direction of the shift – in which direction the distortion occurs. For each wavelength of monochromatic radiation recorded by the camera, and hence the coordinates of the points ($u'_f(\lambda_i)$, $v'_f(\lambda_i)$ and $u'(\lambda_i)$, $v'(\lambda_i)$), we can calculate the distance between these points at each length waves as

$$E(\lambda_i) = \sqrt{(u_i^{'} - u_i^f)^2 + (v_i^{'} - v_i^f)^2}. \qquad (1)$$

In those wavelength ranges where this function is small, the camera adequately renders the visual impression of objects with dominant wavelengths in the appropriate range. In those wavelength ranges where the color comparison functions with the standard colors of the standard CIE observer or the relative spectral sensitivities of the camera pixels are absent, the graph of the function may be supplemented by the same values greater than 0.58. This addition allows evaluating the color perception of the camera in the case when the area of its spectral sensitivity does not coincide with the visible range of wavelengths.

If data on the spectral sensitivity of the camera are not available, it is proposed to photograph monochromatic radiation at known wavelengths. Using any program that allows to determine the ratio of red, green and blue ($R_f(\lambda_i)$, $G_f(\lambda_i)$, $B_f(\lambda_i)$) in the image file, one can determine X^i_f, Y^i_f, Z^i_f by the well-known formulas. Next, similar calculations are performed and similar graphs ($v'_f(\lambda_j)$ from $u'_f(\lambda_j)$, $v'(\lambda_i)$ from $u'(\lambda_i)$) are constructed. If the wavelengths are unknown, then the graph $E(\lambda_i)$ also cannot be constructed, but the general form of the graphs $u'_f(\lambda_j)$, $v'_f(\lambda_j)$ and $u'(\lambda_i)$, $v'(\lambda_i)$ will allow to qualitatively evaluate the suitability camera for the selected task.

3. Calculation and measurement

As known spectral characteristic of the camera matrix, the calculation for the camera Nikon D300s was performed in Excel using built-in functions. The step in all calculations was 10 nm. Integration was replaced by summation. Since the estimates were made, such an approximation is sufficient. Fig. 1 shows the spectral sensitivities of the camera pixels obtained from the Internet, calculated graphs $v'_f(\lambda_j)$ from $u'_f(\lambda_j)$, $v'(\lambda_i)$ from $u'(\lambda_i)$ and calculated the dependence of $E(\lambda_i)$ in camera sensitivity range. Fig. 1 shows that the spectral sensitivities of the elements of the camera matrix are significantly different from $\overline{x}(\lambda_i), \overline{y}(\lambda_i), \overline{z}(\lambda_i)$ (the function of comparing colors with the reference colors of a standard CIE observer), in the region with a wavelength of less than 400 nm and more than 700 nm sensitivity is virtually absent.

This means that regardless of the form, ($R_f(\lambda_i)$, $G_f(\lambda_i)$, $B_f(\lambda_i)$ distortions will be significant, which is manifested in the significant values of $E(\lambda_i)$. Sony DSC-H5 was used as a camera with an unknown spectral sensitivity. An image of a monochromatic spot from light passed through a monochromator on a white screen every 10 nm was photographed. The spectral range was selected from the conditions of

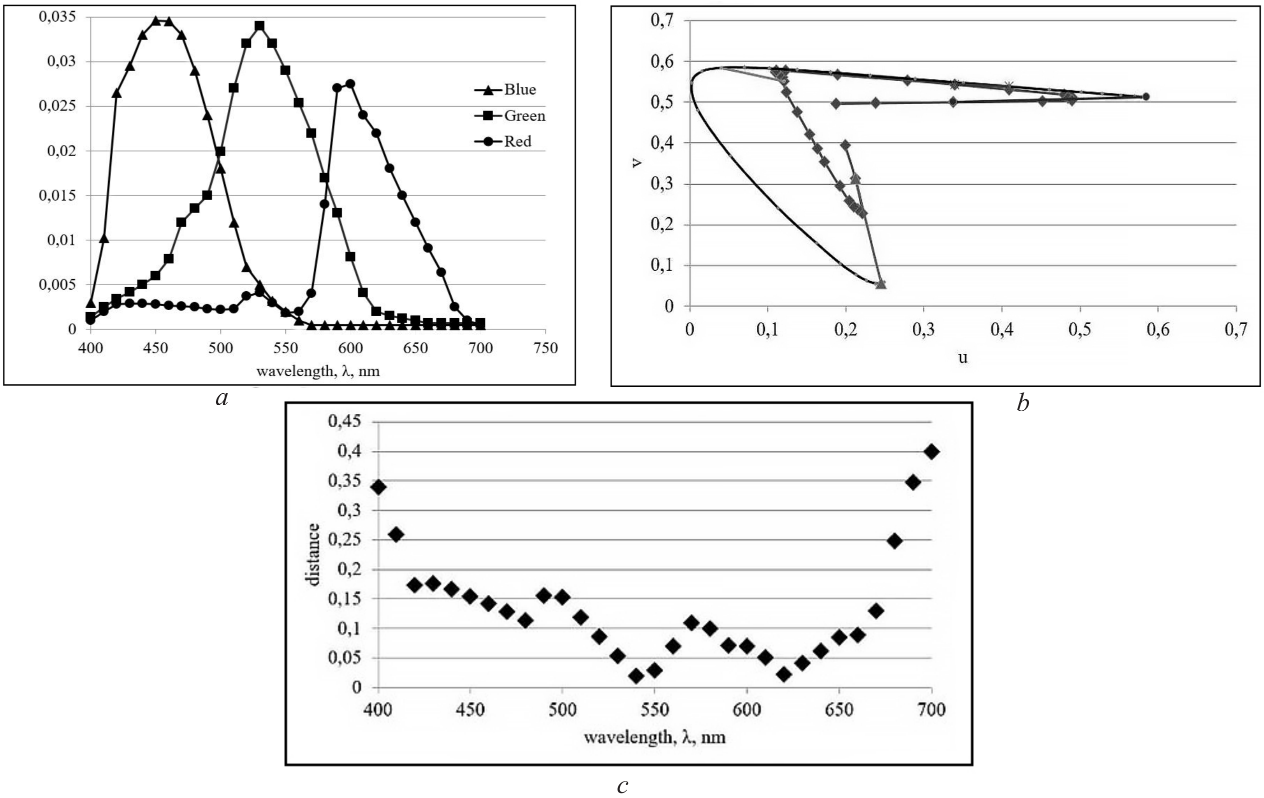

Fig. 1: *a* – spectral sensitivity of elements in the camera's matrix Nikon D300s and the results of the layout for the elements of the matrix of the camera; *b* – coordinate locus $v'_f(\lambda_j)$ from $u'_f(\lambda_j)$ and $v'(\lambda_i)$ from $u'(\lambda_i)$ for monochromatic wavelength λ_j with lines, where to set the coordinates with the same wavelengths of 410 nm, 520 nm, 600 nm and 680 m; *c* – the distance between the coordinates $v'_f(\lambda_j)$ from $u'_f(\lambda_j)$ and $v'(\lambda_i)$ from $u'(\lambda_i)$

visibility of the light spot. The main difficulty was to ensure linearity, in that the values of $R_f(\lambda_i)$, $G_f(\lambda_i)$, $B_f(\lambda_i)$ would be clearly less than 255 units. The illuminance of light spots at different wavelengths was different, no special measures were taken to align them. Chaotically located areas in the central part were processed, avoiding the edges of the image, which show a significant scatter of light. The values $R_f(\lambda_i)$, $G_f(\lambda_i)$, $B_f(\lambda_i)$) in each photograph depending on the place of processing usually varied by 10–30%. The approach described in [10] was used to determine the coordinates. The results of the calculation are presented in Fig. 2.

Fig. 2*a* shows that the spectral sensitivities of the camera matrix elements also differ from $\bar{x}(\lambda_i), \bar{y}(\lambda_i), \bar{z}(\lambda_i)$ which can be seen by the nonmonotonic change $u'_f(\lambda_j)$, $v'_f(\lambda_j)$ (Fig. 2*b*). It can be seen that in the green-red region visually the curves $u'_f(\lambda_j)$, $v'_f(\lambda_j)$ and $u'(\lambda_i)$, $v'(\lambda_i)$ are close, but only distortions in the region near 540 nm are minimal. If the wavelengths of the photographed images are unknown, it will be possible to obtain only the graph shown in Fig. 3, the wavelengths corresponding to the image points of the photographed wavelengths will need to be set visually, approximately. Fig. 3 shows lines between pairs of identical images that correspond to approximately the same wavelengths, the wavelength at the locus $u'(\lambda_i)$, $v'(\lambda_i)$ is determined approximately, by visual impression.

The graph shows that the red color becomes paler and acquires a purple hue, orange becomes paler and yellower, green pales with a slight change in color, and blue becomes purple.

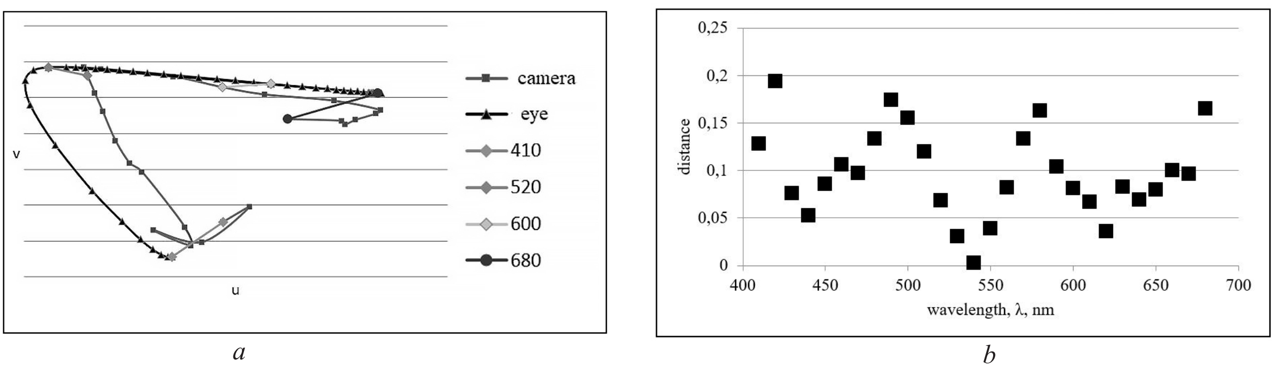

Fig. 2. Calculation results for camera matrix Sony: *a* – coordinate locus $v'_f(\lambda_j)$ from $u'_f(\lambda_j)$ and $v'(\lambda_i)$ from $u'(\lambda_i)$ for monochromatic radiation with a wavelength λ_j with lines connecting coordinates with the same wavelengths of 410 nm, 520 nm, 600 nm and 680 nm; *b* – the distance between the coordinates $v'_f(\lambda_j)$ from $u'_f(\lambda_j)$ and $v'(\lambda_i)$ from $u'(\lambda_i)$

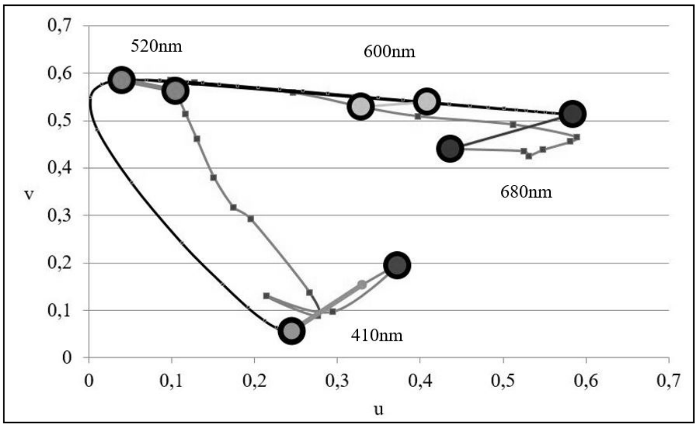

Fig. 3. Systematization 2020, sample

4. Accuracy of the method

Factors influencing the accuracy and reliability of the proposed approach are divided into separate groups. The first group is related to the fact that a color is characterized by three coordinates, the vast majority of regulations use only two – chromaticity coordinates. For this task, this simplification is quite acceptable, because in the future the image file is used to create an image on any screen, and, as a rule, the luminance as a third coordinate can be changed. In addition, the equal contrast of the space *u*′, *v*′ is conditional. It has been proved that it is impossible to achieve the transformation of ellipses into ideal circles of equal diameter by both linear and nonlinear transformations [11]. In [12], it was proposed to measure the distances between points in the color space by the number of Mac Adam ellipses, so the color gradations are the least noticeable, but currently experimental data are insufficient. The second group – methodological issues. The formula used to calculate X^i_f, Y^i_f, Z^i_f by $R_f(\lambda_i)$, $G_f(\lambda_i)$, $B_f(\lambda_i)$ is conditional, assumes the use of generally accepted but rather arbitrary primary colors. The difference between the sensitivity range of the human eye and the sensitivity range of the camera makes it necessary to take this difference into account for any reason. The text of the article intentionally simplifies these issues. The third group is the uncertainties obtained by statistical or one or another method. The specific feature of calculations in color measurements is that multistage formulas are used, so the calculation of impact factors according to [13] is complicated and it is more appropriate to use the Monte Carlo method according to [13–14].

To evaluate the uncertainties when using photographs in the image of the light spot at each wavelength, 10 measurements were performed, calculated and presented in Fig. 4*a*. Graphs and calculated dependences of the standard deviation of the

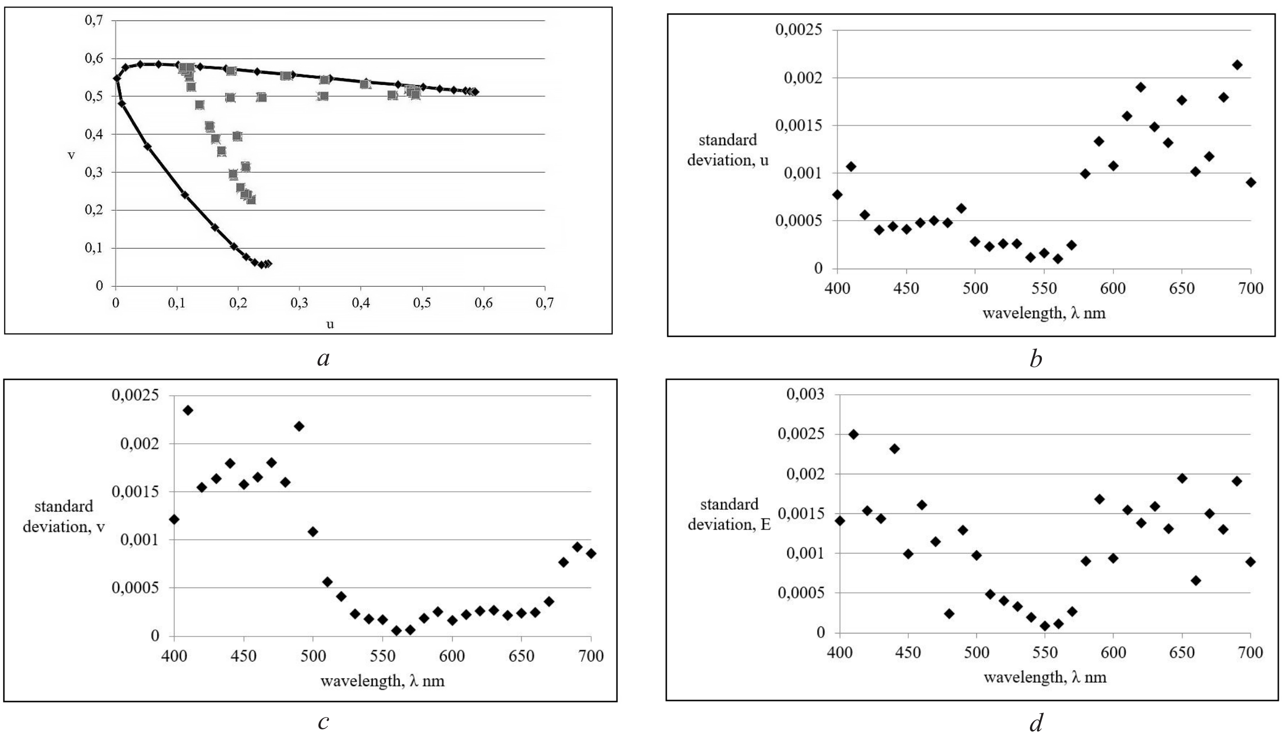

Fig. 4. The results of the calculation: *a* – the coordinates $v'_f(\lambda_j)$, $u'_f(\lambda_j)$ for 10 measurements compatible with the locus $v'(\lambda_i)$, $u'(\lambda_i)$; *b* – the standard deviation of the value $u'_f(\lambda_j)$; *c* – the standard deviation of the value $v'_f(\lambda_j)$; *d* – the standard deviation of the value $E(\lambda_i)$. The results of the standard deviation were obtained for spectral measurements with a relative standard uncertainty of 1%

values $v'_f(\lambda_j)$, $u'_f(\lambda_j)$ and $E(\lambda_i)$ are presented in Fig. 4. It is seen that a significant scatter of measurement results by photographing on a high-contrast graph is not noticeable. Uncertainty due to the finite spectral interval (spectral width of the slit) was previously considered in [2].

The calculation results of $v'(\lambda_i)$, $u'(\lambda_i)$ and the calculated dependence of the standard deviation of the values $E(\lambda_i)$, $v'_f(\lambda_j)$ and $u'_f(\lambda_j)$ are presented in Fig. 4*b*–4*d*. Graphs 4*b* and 4*c* show that the standard deviation of the measurement results starting from 500 nm for $v'_f(\lambda_j)$ and starting from 460 nm for $u'_f(\lambda_j)$ and further towards larger wavelengths does not exceed 0.01, which can be considered an acceptable result. The graph of the calculated values of $v'_f(\lambda_j)$ from $u'_f(\lambda_j)$ due to the small scatter of the calculated points has no practical difference from that shown in Fig. 4*c*. The obtained standard deviations were considered as uncertainty evaluation caused by 1% uncertainty when measuring the spectral sensitivity of the camera. The relationship between the uncertainties of $u'_f(\lambda_i)$, $v'_f(\lambda_i)$, $E(\lambda_i)$ and the uncertainties of sensitivity measurements is assumed to be linear. It is seen that the results of calculations for all quantities do not exceed 0.002, i.e. an order of magnitude more accurate than for measurements by photography.

5. Conclusions

The method has been proposed for step-by-step full-color fixation of the object's appearance. The described approach for the case of known spectral characteristics (Nikon D300s) allows to unambiguously link the calculated response of the camera and the chromaticity coordinates of spectrally pure colors. With an accuracy of measuring the spectral characteristics of 1% for this example with Nikon D300s, this figure at different wavelengths is calculated with an uncertainty of not more than 0.002. The case of using monochrome images of Sony DSC-H5 also showed that the use of different parts of the photo, which leads to a significant (tens of percent, sometimes twice) difference in RGB distinction, does not lead to a significant difference in the coordinates $u'_f(\lambda_i)$, $v'_f(\lambda_i)$. This means that the accuracy of determining these values is of the order of 1%.

The proposed indicator, graph $E(\lambda_i)$, numerically characterizes the difference between the reaction of the camera and the reaction of the human eye, but does not give an idea in which direction there is a difference. The diagram u', v' is much more visual and informative than the graphs $E(\lambda_i)$ and at the same time less convenient for numerical evaluation of distortions.

Метод чисельної оцінки якості передання кольорів матричних фотоприймачів

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Анотація

Для об'єктивної оцінки колірного зображення архітектурного об'єкта при зміні його спектрального складу і яскравості в процесі освітлення потрібно забезпечити його точну фіксацію. Для повної фіксації зовнішнього вигляду об'єкта необхідно виміряти його координати кольору, але це не забезпечить адекватну оцінку зорового враження без візуалізації сцени освітлення. Для цього потрібна наскрізна методика відтворення однакових координат кольору для кожної точки зображення і об'єкта з однаковими кутовими координатами.

Зроблено спробу розробити чисельний критерій оцінки якості передання кольору фотоапарата як фіксатора колірного зорового враження від обраної сцени. Розробка чисельного детального методу оцінки якості передання кольору фотоапаратів дозволить надійніше фіксувати таке суб'єктивне поняття, як відповідність зорового враження від реальної сцени і файлу зображення цієї сцени. Цифровий формат, що містить інформацію про об'єкт, дозволяє уникнути проблем, пов'язаних зі старінням зображення.

Запропонований метод розробки шляхів чисельної оцінки спотворення кольору при фотографуванні розглянуто на прикладі цифрових фотокамер Nikon D300s, Sony DSC-H5. Показано, що описаний підхід для випадку відомих спектральних характеристик дозволяє однозначно пов'язати розрахункову реакцію фотоапарата з координатами кольоровості спектрально чистих кольорів. Сучасні методики оцінки якості джерел світла (IES TM-30-15) дозволяють оцінити напрямок зсуву. Запропонований показник – графік $E(\lambda_i)$ чисельно характеризує відмінність реакції фотоапарата від реакції людського ока, але не надає уявлення, в який бік спостерігається відмінність (умовно, червоніє або синіє зображення в порівнянні з натуральною сценою), однак найбільш простий і зрозумілий для непідготовленого користувача. Показано, що при точності вимірювання спектральних характеристик в 1% для розглянутого прикладу – цифрової камери Nikon D300s – цей показник на різних довжинах хвиль розраховується з невизначеністю не більше 0,002.

Ключові слова: матричні приймачі; колірні координати; чисельна оцінка.

Метод численной оценки качества передачи цвета матричных фотоприемников

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Аннотация

Для полной фиксации внешнего вида объекта необходимо измерить его координаты цвета, но это не обеспечит адекватную оценку зрительного впечатления без визуализации сцены освещения. В этой работе сделана попытка разработать численный критерий оценки качества цветопередачи фотоаппарата как фиксатора цветового зрительного впечатления от выбранной сцены.

Предложенный метод разработки путей численной оценки искажения цвета при фотографировании рассмотрен на примере цифровых фотокамер Nikon D300s, Sony DSC-H5. Показано, что описанный подход в случае известных спектральных характеристик однозначно связывает расчетную реакцию фотоаппарата с координатами цветности спектрально чистых цветов, а использование методики оценки качества источников света (IES TM-30-15) позволяет оценить направление смещения. Предложенный график $E(\lambda_i)$ численно характеризует отличие реакции фотоаппарата от реакции человеческого глаза и пригоден для неподготовленного пользователя, но не дает представления о направлении смещения. Показано, что при точности измерения спектральных характеристик в 1% для Nikon D300s этот показатель на разных длинах волн рассчитывается с неопределенностью не более 0,002.

Ключевые слова: матричные приемники; цветовые координаты; численная оценка.

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