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FEATURES OF DIGITAL COLOURIMETRY APPLICATION IN MODERN SCIENTIFIC RESEARCH

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ABSTRACT

The paper is devoted to digital colorimetry, has a character of review, and deals with the main issues of colorimetric calculations and transformations during digital colour registration. The presented materials are intended to help researchers already at the stage of registration to exclude colour losses and, accordingly, errors of measurements, taking into account the following features:

– The connection of colorimetric measurements with digital circuit design is shown, which results in digital colorimetry as a tool for acquiring and processing accurate colour information about the object of study;

– Important issues such as: selection criteria for parameters of photodetector arrays, colour separation systems, working colour spaces, formats of colour images, and post-processing methods for colour information of images;

– Colour separation systems of photodetector arrays, their advantages and disadvantages, influence on the registration result and prospects of new developments in this field are described;

– Working colour spaces of digital recording systems, and also colour systems are considered allowing maximum saving colour parameters of digital impression;

– To understand human colour perception, the problem of hardware-independent reproduction of colour and images after image registration is considered;

– It is proposed to use such colorimetric systems in the analysis of colour parameters in scientific studies, which give understanding of human image perception in the analysis of image quality.

The paper gives a broad overview of the digital colorimetry main aspects and researches on this topic for specialists who use digital colour recorders as a tool in their experimental research. This material can also be useful for specialists with deep knowledge in colorimetry who use digital colour recorders as part of their main tasks in the definite field of science and technology.

Keywords: digital device, colorimetry, photodetector array, colorimetric system, colour space, colour system, image processing

1. INTRODUCTION

At the present time the development of methods for measuring characteristics and parameters of research objects using digital photo and video cameras for providing metrological traceability and implementing the principle of comparison with reference values is continuing [1, 2]. Digital recorders are used in modern science and technology everywhere [3–7]. Modern digital colorimeters calculate colour and chromaticity parameters in different colorimetric systems. At once we note that, in principle, any device for colour definition is a colorimeter. Therefore, modern digital photo and video cameras, scanners, digital minilabs can also be classified as colorimeters. In order to understand all the issues of colorimetric calculations and transformations in digital colour registration and to conduct successful scientific work, this paper gives specific advice to researchers on preparing and conducting experiments using digital devices.

Being a part of computer optics, digital colorimetry is more and more often used in such spheres as light engineering [3], medicine [4], chemistry [5], biology [6], agricultural production [7], etc. The last example is particularly illustrative. An approach to detecting a set of features and forming a classifier model to improve the ability to distinguish the classification of different seeds by colour is being sought [8]. Other researches show that the colour trait can be used as a reference in breeding programs to make it possible in the future to prevent grain drops in the fields [9]. Also illustrative is the example of using digital colorimetry to study agricultural fields by means of a digital photo camera (DPC) on unmanned aerial vehicles [10]. The main task of this research was to light-correct RGB-images of different parts of the field to create a whole picture of the farmland terrain. The above examples show the advantages of using digital colorimetric diagnostics in the agro-industrial complex to improve crop yields and survival rates.

Professionals applying digital recording devices as a tool in their research face the problems of selecting a digital device and obtaining a quality colour impression as close to the real scene as possible. There is a tendency to analyse digital images from a smartphone camera [11, 12].

Accurate colour calculations are required in those fields of knowledge, where the goal is to describe the colour itself: polygraphy, colorimetry, graphics, etc. In industry, the main task of colorimetric systems application is product quality control. Determination of colour change is one of the tools to meet the requirements of standards and rules and regulations.

Researchers face the challenge of using digital recording devices to work successfully with minimal loss of colour quality. Trying to work with an already prepared image, researchers often encounter problems on facing with the limitations of digitally represented images; in particular, the limited colour coverage of the recording system. The colour component of an image undergoes great changes at different stages of information input: from registration to digital conversion [13]. As a result, the chromaticity of an original image does not correspond to the real scene, which introduces errors into the research results. The proposed modern digital recording devices are mainly oriented on adequate transfer of brightness information, while the colour component of an image is mainly corrected only by special processing algorithms. For successful scientific research it is necessary to know the basics of digital colorimetry.

The purpose of this work is to reveal the important issues of colorimetry in digital colour registration, necessary for conducting relevant experimental studies and works. In accordance with that, the following tasks were set:

– To recognize the selection criteria of photodetector arrays (PDA);
– To describe PDA colour management systems;
– To characterize working colour spaces of digital systems;
– To analyse colour image formats;
– To highlight the basic methods of colour information processing of images.

This topic refers to the issues of implementing the systems and methods of information transfer, signal reception and processing, machine vision, as well as technologies of image and signal processing, analysis and recognition – strategic directions of science and technology development.

2. DIGITAL PHOTODETECTOR ARRAYS

Digital colourimetry begins with the conversion of colour parameters into digital form. The latter takes place in the PDA, which consists of an array of photo-sensitive cells. The clarity and colour rendering of the recorded image depend on the parameters of the light sensing elements of the array, and therefore more attention should be paid to the PDA selection when carrying out scientific research.

The dynamic range of a device directly depends on the capacity of the photo-sensitive cell [1, 13]. The greater its charge capacity, the more correct will be the division of light into gradations during further processing in an ADC. The charge level in a photo-sensitive cell depends not only on the number of photons falling on it, but also on other factors, first of all, on changes in array temperature. Therefore, even in a photodetector completely shut off from light a certain parasitic "image" appears after some time. It is generally accepted that the dark charge doubles for every (6–8) °C increase in temperature [14]. At long exposures used to increase the sensitivity, the photodetector must be cooled.

Different types of matrix photo-sells (MPS) are known. Two of them are mainly used in DPCs: photo-responsive sensors based on complementary metal oxide semiconductor (CMOS) structures and charge-coupled devices (CCD) [13–16]. The fundamental difference between CMOS and CCD arrays is in the method of implementation of the readout and sensor devices. The type of array itself, CMOS or CCD, in research today, is not so critical. Whereas earlier it was believed that CCD arrays had a greater dynamic range and therefore better colour reproduction, modern CMOS arrays are much more advanced in this direction. At the moment, CMOS sensor manufacturers enable the creation of cameras with a wide dynamic range, capable of producing high-quality images in high-contrast lighting conditions. First of all, this is due to the low power consumption of such systems and their popularity in smartphones and other battery-type systems. However, when using older models of DPCs, it is still recommended to choose CCD-arrays.

Due to the partial scattering of light by the electrode surface in CCD element circuits where polycrystalline silicon electrodes are used, their light sensitivity is limited, so an array with backlighting was used. This type of array is highly sensitive in the blue and UV regions of the spectrum, which allows its application in astronomical photography [17].

In scientific research, it is necessary to determine the type of photography. If one needs to record fast-flowing processes, such as physical or chemical reactions, with subsequent frame-by-frame processing, one should use a video camera with electronic shutter and obtain very short exposure times (up to 1/10000 s) [10, 18, 19]. If there is no time limit for the experiment, it is better to choose a camera without video recording functions, which will allow obtaining shots with the maximum possible dynamic range and colour rendering due to less connecting volume of the sensor. A considerable part of a sensor with video recording function is occupied by shift buffer registers – up to 2/3 of the light-sensitive area, whereas a full-frame sensor uses only 1/3 of the latter [13]. In addition, attention should be paid to the availability of micro-lenses. This is still a controversial indicator, since such systems not only direct the rays to the centre of the sensor, but also absorb a part of the light.

The next important parameter of a DPC is the light sensitivity of its sensors, which is denoted in the same way as the ISO sensitivity of film. The lowest of its ISO numbers is the most accurate way to characterize the true sensitivity of the sensor, because the other values can be achieved by simply amplifying the signal at the sensor's output. The way to increase the sensitivity by changing the signal processing algorithm of the sensor leads to the appearance of noise. When shooting an object having the same brightness and chromaticity over its whole surface, pixels of other colours and brightness will be observed in its image [20, 21]. The latter is critical in scientific research with analysis of groups of image pixels.

In PDA, there is quite a lot of noise affecting the colour of a digital image such as dark current, as well as due to thermal, fixed distribution, colour, brightness and yellow noises. Noise reduction systems operate quite coherently in modern arrays [22, 23]. Today iterative (multi-pass) algorithms and algorithms based on neural networks are the best, but require a lot of computing power. Besides, they are realized only in software *RAW*-converters. The disadvantages of these processing systems are that the DPC software performs digital brightness filtering of pixels using significantly different technique for neighbouring pixels; this can lead to loss of fine contrast details of an image, on which the sharpness of the image depends first of all. The researcher should take several images with different noise reduction modes in order to decide whether this algorithm is necessary for this study or whether it is better to refuse from digital adjustments.

3. COLOUR SEPARATION SYSTEMS

The colour separation system of the DPC directly affects the colour reproduction and must be known when choosing a DPC. This is a fundamental point, because when we work with a digital device we may not be aware of auxiliary colours such as RGBT, RGBE, CMYK or CMYG, in addition to the primary (red, green and blue) colours.

The most interesting from a colour separation point of view are the single-frame DPCs with one or three arrays and the three-frame ones [13]. Dispersing elements are used in single-frame DPCs with three arrays, which split the transmitted light into the main colours recorded by each array separately. Using all three high-resolution CCDs is expensive, but effective. Such kind of DPCs is suitable for colorimetric studies, but it should be taken into account that dispersing elements may absorb up to 1/3 of the luminous flux.

Three-frame DSCs use a single two-dimensional array. It is necessary to take three separate images through three light filters of primary colours to obtain a colour image [18, 24]. Such technology allows refusing colour interpolation used in single-frame DPCs with one array, but is mainly intended for registration of still objects.

Single-frame DPCs with a single sensor are the most common today. They provide high speed image digitization, which is demanded in smartphones [5, 11], but have weaker resolution and colour reproduction than the above mentioned DPCs. These DPCs are called cameras with colour calculation. This type of cameras is used in smartphones and semi-professional DPCs. Despite fundamental shortcomings in colour reproduction, these cameras are widely used in scientific research due to their fast performance [25, 26].

As the three-frame cameras, the single-frame single-array DPCs use a flat array, but the colour data registration is made through a template of film light filters applied to the CCD surface, consisting of primary and, sometimes, additional colours. Each pixel of the image stores data on only one of the primary colours. To define a multicolour image, the processing program interpolates the colour data of neighbouring pixels. Reconstruction errors at the stages of noise reduction and interpolation are critical for the resulting image [27, 28], but single-frame DPCs provide high-quality imaging of moving objects in one exposure.

Single-array DPCs with spatial colour separation have a specific colour pattern that covers the entire array [13]. The most common type is the Bayer pattern. Each cell is "covered" with red, blue, or green light filters arranged in groups of four cells, with two green ones having one red and one blue, Fig. 1. This mosaic filter scheme is designated *RGBG* (Red – Green – Blue – Green). Additive filters are two-layer, which lowers the transmittance. Human vision is most sensitive to green shades, so 1/2 of the original frame is the green component and only 1/4 is blue and red. To combat the regular structure, modified schemes for the placement of light filters were proposed with dense vertical or horizontal lines. These modifications regularly repeat a pattern of 12 or 24 elements.

In Bayer schemes, there are "extraneous" colours; this leads to significant colour distortions due to low spectral sensitivity in the short-wavelength part of the spectrum. This also entails the need to carefully adjust the white balance and image brightening [29].

For colour correction in the blue-green part of the spectrum, additional light filters *E* (blue-green) and *T* (emerald) were proposed, differing in a darker shade. *RGBT* and *RGBE* arrays, Fig. 1, eliminate distortions in the blue-green area only partially [13].

A set of RGBP light filters with a "panchromatic" pixel (without light filters) has been developed. Manufacturers assumed that if film filters absorb 2/3 of the luminous flux incident on CCD array, then abandoning them will improve the dynamic range of the image in the brightness component of the image.

Colour separation systems based on subtractive scheme, or CMY image synthesis, have been developed. A number of DPC models use CMYG or CMYB schemes, Fig. 1, with an additional green or blue filter, respectively. CMY application allows the use of single-layer filters, which leads to an increase of transmittance and sensitivity of the whole array. An additional advantage of such templates is the possibility of direct printing. CMYG or CMYB is supposed to coordinate registration and printing devices without loss of image quality, but in the transition from CMY to *RGB* system (for visualization of the received image by monitors and video projectors) the colour gamut is narrowed and the colour image quality is lost.

A relatively new and promising development is multilayer type arrays [30–32]. The essence of this technology is the application of the physical phenomenon in the semiconductor itself: as a wavelength increases, the depth of photon penetration

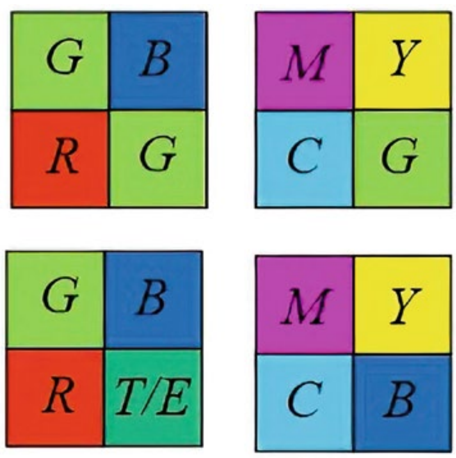


Fig. 1. Templates of light filters of photodetector arrays

into the semiconductor increases. Thus, it became possible to register information of all three primary colours in a single pixel. The technology includes the possibility of changing the pixel size. Such "super-pixel" aggregation reduces the frame acquisition time, can increase the signal-to-noise ratio, providing high-quality shooting in low-light conditions, and accelerates the autofocusing process [13, 30].

Thin film on ASIC (TFA) technology, in which the entire receiving surface is photosensitive, has been proposed. The TFA technology works using the multispectral photodiode principle with a fast voltage change; this allows reading three colour components sequentially [13, 32]. Thus, TFA-sensors should increase the dynamic range and colour resolution, but due to the high cost of production this development is not widespread.

When choosing a digital recorder for the experiment, we should pay attention to the PDA and its spectral characteristics, by which the colour model of the system and the possible "purity" of the main colours become immediately clear. Virtually every DPC instruction manual has information about its PDA model that gives us the spectral characteristics of the main channels. Modern manufacturers try to select new materials and new ways of creating film filters. In order not to complicate PDA production, most manufacturers create complex algorithms to process colour information in spectral and polarization regions [33]. The result is bright, saturated colours, which have a mediocre relationship to the actual colour information. In scientific research with the use of arrays based on a spatial colour separation system, it is recommended to work in *RAW* format [3, 24]. The latter allows storing the primary colour information in each pixel without processing, which later allows colour conversion to different colorimetric systems without information loss. And for the information to be as "clean" as possible, it is necessary to choose PDAs with the smoothest, symmetric, dome-shaped spectral curves working in a certain area, without inclusion in other areas.

There are also studies of the spectral characteristics (curves) of PDAs from different manufacturers [34, Fig. 1]. PDA-1 had fairly smooth curves without secondary peaks, although the curves for green and blue channels slightly overlapped each other. When examining the spectral characteristics of PDA-2, we could see the minor equal-sized peaks of the curves in the red and blue channels overlapping each other, and the curve in the blue channel, the widest one, had a lower transmittance. Spectral characteristics of PDA-3 were similar to those of PDA-2: curve maxima, being broad and uneven, had "tails" in nonworking areas, which worsened array performance and transmission of "pure" colours.

In the study [34], 14 reference colours from the Mancell atlas were also calculated for each PDA. As a result, PDA-1 turned out to be the best. The study showed: the flatter and sharper the characteristic maxima, the "cleaner" the colours will be.

4. WORKING COLOUR SPACES OF DIGITAL SYSTEMS

The CIE *RGB* colour model with a wide colour body was developed for a standard colorimetric observer, which did not fit the colour description on the monitor. That is why several colour spaces were proposed for working with digital images on different monitors. These include the common working colour spaces of digital systems *standard-RGB* and *Adobe-RGB* [34, 35]. The *sRGB* system has been developed as a standard for web and multimedia applications. In fact, this colour space and the following one are the basic for all digital image registration devices. The *AdobeRGB* space has an increased colour gamut compared to the previous system and is used in typography and in digital printing.

Modern variants of the *RGB* colour space are *Apple RGB*, *ProPhoto RGB* (*ROMM RGB*), *Ekta RGB*, *PAL/SECAM*, *Wide Gamut RGB*, *DCI-P3*, Fig. 2; they differ in different coordinates of primary colours, different reference white light and different gamma correction value [36]. The latter is a relatively new colour space that imitates the colour palette of film. *DCI-P3* was developed by the Society of Motion Picture and Television Engineers as a standard for digital theatres and surpasses *sRGB* in colour gamut, while compared to *AdobeRGB* it is narrower in the green-yellow area and wider in the yellow-red area. Now *DCI-P3* is being implemented in smartphones and tablets. *PAL/SECAM* is based on the colours of the colour-forming stimuli recommended by the European broadcasting video standard, and serves as a standard for TV and video transmitting systems. The *Wide Gamut RGB* space is formed by pure spectral emitters with the highest possible colour gamut, while *ProPhoto RGB* practically covers the range of colours perceivable by humans and is designed to enable storage of photographic images and pictures without losing information if the colour gamut of the PDA working colour space is insufficient.

Colour spaces like *EktaRGB*, *ProPhotoRGB (ROMM RGB)*, and *Wide Gamut RGB* are used in the post-processing stage of *RAW* image registration, which can be very difficult for users, but for researchers is simply necessary to preserve the primary information of the image as much as possible. At the same time, as already mentioned, attention should be paid to spectral characteristics of PDA.

The main difference of the spaces is in the body of colour coverage. And the bigger it is, the better, but not always. When studying seven colour spaces for three different PDAs of well-known firms a correlation between spectral characteristics of PDAs and the body of colour coverage of the chosen space was noted [34]. Thus, for PDAs with smooth spectral characteristics, the best colour spaces in this study were *Wide Gamut RGB* and *ProPhoto RGB*, which have the largest colour gamut. For an array with irregular spectral characteristics and second-step peaks, ProPhoto RGB was the worst, and the best results were obtained for sRGB and PAL/SECAM with a small colour space. Thus, it was found that the more uneven spectral characteristics of PDAs, the smaller the colour coverage body of the working colour space should be. Probably, the presence of negative branches in small colour spaces compensates the secondary maxima of PDA spectral characteristics.

5. COLOUR IMAGE FORMATS

There are many graphical formats used for storing and re-editing images in digital form. However, only some of them are most commonly used in DPCs: *JPEG*, *TIFF* and *RAW*; for example, *GIF* format is used very rarely. The graphic file format *BMP* is also widely used for storing images [4, 5].

Files saved in *JPEG* format have the extension. *jpg*. The developers have put several features into the standard. The compression algorithm allows us to adjust the compression degree: the higher the degree used, the smaller the file will be, but the lower the quality of the image will be. The full-colour image in the file is obtained by interpolation of primary colours, after reading the photocurrents for each pixel. The methods of interpolation are various: linear, cubic, bicubic, plus various author's techniques

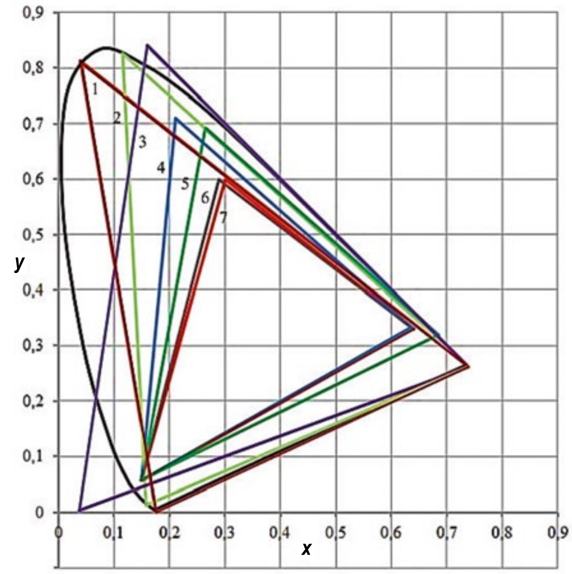


Fig. 2. Colour systems on the *x, y* locus:
1 – *M1N1P1*; 2 – *Wide Gamut RGB*; 3 – *ProPhotoRGB*; 4 – *AdobeRGB*; 5 – *DCI-P3 RGB*; 6 – *PAL / SECAM*; 7 – *sRGB*

[28, 37, 38]. It's rather difficult to understand which method was chosen for a specific digital device: the manufacturers don't provide such information, although the influence of interpolation method on a colour picture is colossal. Colour interpolation averages all primary colours in a certain pixel area, which results in blurring the fine details and colour values of the real scene.

It is recommended to choose the *RAW* image format [35, 39] for those scientific studies that require the information to be taken into account in a pixel-by-pixel manner. The development of this format is done independently by all DPC manufacturers. As a rule, digital image files undergo minimal processing in a DPC and represent a sequence of data bits received from the A/D converter of a photographic sensor. The *RAW* format has a number of advantages, including minimum image registration processing and extensive image processing capabilities, such as white balance adjustment after taking a picture, and the enhanced image quality that comes with high bit resolution when one change the brightness, contrast, and saturation of the image.

Pictures which are saved in the *TIFF* format have high image quality, but excessive volume: as a result, the image recording time is increased. This format exists in different modifications, the last of which supports different compression algorithms and different colour spaces. The *TIFF* format used in DPCs does not support these features. Files are saved with the extension*.tif,* have the colour space *RGB* and are not compressed. This means that an image saved in this format will have high image quality and a sufficiently large file size.

EPS and *PSD* formats [40] allow us to store a large amount of information with maximum quality. *EPS* format is used to store images intended for printing. It allows us to store additional information (calibration curves, clipping paths, etc.). The *PSD* format, being the internal format of Adobe Photoshop, supports all types of images from two-colour to full CMYK colour, thus saving all the necessary information, including layers, clipping paths, and so on.

6. THE BASICS OF COLOUR INFORMATION PROCESSING METHODS

6.1. Software

As noted above, each DPC manufacturer has developed its own *RAW* format and, accordingly, its own *RAW* image processing software. When choosing a format, one should adjust to the software requirements, in which the image will be analysed. Current popular programs like *Adobe Photoshop* and *MathCAD* do not support 16-bit images (*TIFF, RAW*) [35, 41]. Even if such an image is loaded into such programs, it is converted into an 8-bit image. Then there is no point in working with *RAW* and *TIFF* formats, which can increase the image file and the processing time. One can work with 16-bit images in such programs as ImageJ and *MATLAB* [24, 25, 42]. (The latter also allows us to make the necessary calculations with the appropriate programming.) *C++* and *Python* programs may also be useful for this purpose. The program *ImageJ* stands out against the general background; it is widely used in scientific research due to its accessibility and user-friendly interface in terms of capabilities in processing colour digital images.

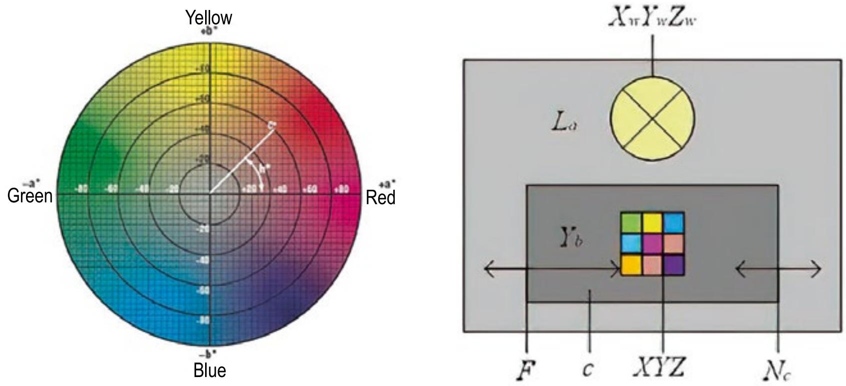
6.2. Reference White

Researchers often underestimate the influence of the reference white colour, and digital images taken at the colour temperature of source type A are translated into spaces with the reference white colour D_{65} or D_{50}, which leads to a distortion of the primary information. In general, D_{65} serves as the reference white for the colour spaces. Exceptions are Wide Gamut *RGB* and *ProPhoto RGB* with D_{50} colour, which have no analogues in terms of wide body colour coverage [36]. It is worth knowing about different chromatic adaptation methods such as *CAT02*, *CMCCAT2000*, von Chris, Bradford and others, which are array transformations and can transform colour coordinates for different emission sources. But no matter how accurate the transformations are, there will be losses in colour coordinates [43]. And if these losses can be unnoticeable for amateurs, in scientific research such manipulations lead to distortion of colorimetric experiment. It is recommended to carry out researches with that source of radiation, which is a reference for the colour space chosen as a working one in the digital system.

6.3. Colour Difference

Methods of colour information evaluation include finding the colour difference between experimental and reference colour values. Despite the variety of colour spaces, all colour parameters are commonly represented in the international colorimetric CIE *XYZ* 1931 system [44, 45]. The *XYZ* system is universally recognized, but it is not equally contrast, therefore it is necessary to translate coordinates into the equally contrast colorimetric system for adequate comparison of the received values with theoretical (reference) values where the colour difference threshold of two colours should be identical throughout the whole colour space.

According to the CIE recommendation, the *CIEUVW*, *CIELUV*, *CIELAB* and *CIECAM* systems are suitable for finding the colour difference [46–48]. All of them are focused on determining the colour change. In the case of matching the colour space to the spectral characteristics of PDA, it is necessary to focus more on the adequacy of chromaticity transfer. Many factors influence the colour values in a real digital system: dynamic range, size of the sensitive surface, noise, etc. Colour depends on luminosity, while chromaticity is constant. In mathematical modelling of the experiment, it is rather difficult to take into account the factors influencing on the luminosity registration [49]. Therefore, in order to be able to compare the results of mathematical study with experimental ones in future, the author recommends to analyse the colour difference by chromaticity in equal-contrast graphs $u\ v$ 1960 or $u'\ v'$ 1974 (in the latter, the yellow, or-



a) ***b)***

Fig. 3. Necessary parameters in equal contrast systems *CIELAB* (*a*) and *CIECAM* (*b*)

ange and red chromaticity are more balanced) [24, 42]. At the same time, the difference in colour is acceptable if it does not exceed 0.005 units. To find the difference between the two colour coordinates, use the *CIELAB* equal-contrast system [48], Fig. 3, *a*. Let's consider different equations for determination of colour differences for this system. In 1976 CIE recommended a formula for finding the colour difference as a Euclidean distance. This expression is simple for calculations, but it limits the possibilities of the system itself. The *CIELAB* system is a curvilinear transformation of the *XYZ* system and, therefore, this approach to finding the colour change is fundamentally wrong.

Taking into account the disadvantages of the proposed method, CIE proposed a modification of the *CIELAB* system itself: *CIELCH* [36]. The polar coordinates for *H* colour tone and *C* chromaticity were suggested. The coordinate *H* is denoted as $h°_{ab}$ and is defined by an angle, and the coordinate *C* is denoted as C^*_{ab}, and it is also denoted by a radius relative to the centre of coordinates *(L*-axis*). Such a modification made it possible to describe colour in this system as a process of colour representation by the human visual system. Therefore to improve accuracy, in 1994, CIE approved a new formula, taking into account the colour tone, chromaticity and weighting coefficients K_H, assuming values appropriate for graphic arts, printing, textile industry, etc.

The formula was later refined and in 2000, CIE adopted expressions that involve more complex calculations and include measures of saturation, colour tone, and luminosity. But the analysis of the resulting Euclidean distance is done as in the previous formulas. Differences in colour are considered in connection with definition of tolerances, within which colour equality is observed. So, in the colour space *CIELAB*, specially constructed for alignment of tolerances at definition of colour equality, the identical for visual perception are considered the colours, which are distant from each other not more than by 1 unit of colour difference.

For more complete analysis of various expressions of *CIELAB* system, researches were conducted [50], which showed that the most accurate method of colour change estimation is CIE2000, as it takes into account more nuances of colour description. But it is rather complicated for people who are not familiar with colorimetry. That is why, for example, CIE1994 method is more suitable for production quality control, which is similar to CIE2000 method by its results, having a calculation expression including all necessary variables for exact calculation and not burdened with additional parameters and intermediate calculations. The CIE1976 formula is applicable when evaluating poorly saturated and little visible colours. But the change of angle and radius relative to the centre of coordinates should still be taken into account here as well, especially say, in such an area as the evaluation of diamonds and jewels. For small colour differences, the methodology developed for more precise calculations must be chosen carefully [51]. It is also worth considering in scientific studies the peculiarities of the *CIELAB* system, which is somewhat stretched in the violet area and compressed in the red-orange area [46].

An equal-contrast system (model) *CIECAM02*, Fig. 3, *b* has been developed; it is simpler and more practical than its predecessor *CIECAM97s*. The two main parts of the model are the chromatic adaptation, transformation, *CIECAT02*, and its equation for calculating the mathematical correlates for the six technically defined dimensions of colour appearance: brightness, lightness, colouring, colour saturation, saturation and hue [52].

After selecting the relative brightness of the surround, the degree of nonlinearity and the values of the surround induction coefficients N_c and F are chosen. Intermediate values N_c and F are also allowed in *CIECAM02*. The colorimetric information needed for colour calculations in this system is: the tricolour *XYZ* values for the modelled colour area; the tricolour $X_wY_wZ_w$ values for the white standard or source; the adaptation brightness Y_b for the surrounding background colour. There are also context parameters (contrast factors, exponent *c*) and factors (luminance adaptation factor, power function, chromatic contrast factors, and *z* and *n* exponents).

Since *CIECAM02* uses the array transform *CIECAT02*, which is a chromatic adaptation, it should not be confused with *CIECAM02* itself.

It is clear from what was said that *CIECAM02* takes into account all the subtleties and nuances of human perception of colour and can neutralize such difficulties in assessing colour as metamerism and the Purkinje, Hunt, and Bartleson – Breneman effects. This makes the *CIECAM02* system indispensable in areas such as biology, medicine, psychology, and lighting technology. However, for most researchers, calculations in this system can be complicated, and the parameters and factors are redundant (for example, for technological control of colour change). In such cases, the *CIELAB* system is the best solution. In addition, it is worth paying attention to the new unified colour space *CAM16-UCS* [53]. The new *CAM16* is simpler than the original *CIECAM02*. In addition, considering chromatic adaptation only, a new *CAT16* transform is proposed to replace the previous *CAT02* transform. A new end-to-end solution for colour prediction and colour difference estimation can now be proposed.

Despite the CIE recommendations, the listed systems can be considered quasi-equal contrast. So, if we translate all the coordinates of the *McAdam* ellipse axes into the *CIELAB* system, and then find their lengths and their elliptical surface, then the ellipticity will be 15, while in CIE *XYZ* – 26, and in CIE1960 (*u, v*) – 2.5. Currently, there are developments to create a strictly equal-contrast colour space based on tensor calculations, where the ellipticity of the colour surface is 1, that is, *McAdam* ellipses are transformed into equal-area circles [54]. Such a system can be useful for ultra-precise colorimetric measurements.

6.4. Colour Management Systems

The widespread use of colour management systems (CMS) is known. These systems are required for colour matching input/output devices. Despite the fact that they are used mainly by designers and photographers, researchers also use them in the study of digital images [55]. The use of such systems is due to the inconsistency of the colour spaces of digital input and output devices. So, the modern *sRGB* system is adjusted to the capabilities of monitors, and images in other colour spaces are not displayed adequately. In principle, any monitor can be calibrated so that it would display images in a different standard relatively correctly, but some of the colours will still be lost. And here the question arises about the problem of device-independent reproduction of colour and images. Modern displays are limited to a set of phosphors and LEDs. Nowadays, displays based on quantum dots with reproduction of almost the entire visible range have appeared [56]. This forward-looking development creates opportunities to revise the CIE colour standards for digital image input and output devices. Now it becomes possible to use new colour spaces with a wide gamut body not only at the stage of post-processing of the image, but also at the stage of its registration. An example of such developments is the proposed systems covering more than 80 % of the visible range [34, 35]. The spectral curves of these systems have either minimum negative sections or minimum secondary maxima, which makes it possible to realize them as spectral characteristics for PDAs. This alignment of characteristics at both software and hardware levels can advance the solution to the problem of matching input and output devices. On the basis of the proposed systems, experimental and mathematical studies were carried out with promising results on the implementation of these developments in digital devices. [24, 42].

6.5. Colour Calibration

Before conducting scientific research, profiling and calibration of a digital device by colour standards is necessary. For this, test objects are used: colour targets and colour scales, such as *Gretag-Macbeth ColourChecker*, which allows us to visually establish the correctness of the colour rendering concerning photographic material using a set of reference colours. To evaluate image input devices, one usually resorts to the use of tabular profiles based on the use of *Colour Look Up Table* (*CLUT)* [13, 55]. Matrix-type profiles or profiles that store both data structures, that is, an array of colour coefficients (*MatTRC tag*) and a *CLUT* table (*AToB tags*) can also be used. In this case, the software that will use the colour profile can convert images from the colour space of an input device to the internal *CMS* colour space both by recalculating colour coordinates using a colour coordinate conversion array and using the *CLUT* table. However, all these methods are aimed at adjusting a digital device to certain shooting conditions. It should also be borne in mind that colour sets are not intended for assessing the adequacy of digital images to the original, but for correcting images and building a colour profile based on captured colour targets. Thus, the colour distortions arising at the stage of image input are corrected. It is not the technical capabilities of the camera that are evaluated, but the capabilities of the device software. Researchers can use colour atlases*: RAL*, *PANTONE*, *DIN*, or *Munsell atlas* to analyse the colour capabilities of a digital device before conducting research. Samples of these atlases are needed to measure the colours of objects by visual and instrumental comparison. Also when carrying out an experiment, standardized coloured optical glasses (light filters) from the corresponding catalogue and according to standzard GOST 9411–91, which have stability of parameters and ease of use, can be useful. An example of using these samples as reference is well described in the sources [24, 42] where light filters served as reference samples and the basis for the implementation of a three-frame DPC colour separation system.

6.6. Colour Models

After processing and analysis of colour digital images, it can be convenient for researchers to use such colour model as *HSI* [36] for classification of colour parameters of objects. This model is based on a human-readable division of colours by saturation, luminosity and colour tone. There are other models that describe these concepts: *HSB* and *HSV*, but the *HSI* in the form of an inverted cone is the most accurate description of the human perception of colour. The top of the cone is a point of black, which begins to expand with the transition to the base (more luminance). A person distinguishes colours worse and distinguishes shades less when the luminance is low. This model will fit well in studies that require classification of the resulting colour parameters of an object to implement further temporal traceability of these parameters at the visual level [8].

7. CONCLUSION

The presented material shows the connection of colorimetric measurements with digital circuit design, as a result of which digital colorimetry appears as a tool for obtaining and processing accurate colour information about the research object.

The work was done in order to create the most complete overview of the main aspects of digital colourimetry for specialists who use colour digital recorders as a tool in their experimental research. The material presented is intended to help researchers eliminate colour loss, and, accordingly, measurement errors, already at the registration stage.

The main criteria for the choice of PDA are given: dynamic range, light sensitivity, type of shooting. Practical advice on working with digital recorders is recommended. The colour separation systems of three-frame and one-frame DPCs with one and three PDAs are considered. Particular attention is paid to a single-frame PDA with a spatial colour separation system, the most common in digital cameras and smartphones. The formats of the picture are given for the accurate acquisition of a digital print of colour images. The relationship between the choice of the DPC working colour space and the PDA spectral characteristics is described. The main colour image processing methods are noted; they may not be noticed by researchers without knowledge of the colourimetry basics: reference white light, various equal contrast systems for determining colour differences and colour standards. It is noted that there are already modern technologies that allow revising the colour standards for digital input and output devices.

For all the problems noted, links are given to sources of modern knowledge with examples of methods for registering and processing a colour digital image, which will help readers study individual issues in more detail.

The paper can be useful not only for researchers who use digital recorders to fulfil the main tasks of their area of activity but also for specialists with deep knowledge in the field of colourimetry.

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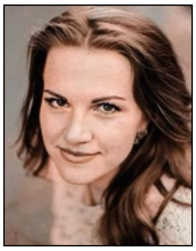

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