Color Correction in the Framework of Color Logarithmic Image Processing

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***Abstract*—The Logarithmic Image Processing (LIP) approach is a mathematical framework developed for the representation and processing of images valued in a bounded intensity range. The LIP theory is physically and psychophysically well justified since it is consistent with several laws of human brightness perception and with the multiplicative image formation model. In this paper, the so-called Color Logarithmic Image Processing (CoLIP) framework is introduced. This novel framework expands the LIP theory to color images in the context of the human color visual perception. Color images are represented by their color tone functions that can be combined by means of basic operations, addition, scalar multiplication and subtraction, opening new pathways for color image processing. In order to highlight the CoLIP relevance with color constancy, a color correction method based on the subtraction is proposed and tested on CoLIP approach and Logarithmic hUe eXtension (LUX) approach, also based on the LIP theory, on differently illuminated images: underwater images with a blue illuminant, and indoor images with yellow illuminant.**

I. Introduction

The authors' initial goal when addressing the color logarithmic image processing is to set up an algebraic mathematical framework that considers color images as vectors. The idea is to apply the Logarithmic (LIP) theory [1], [2] in the context of human visual perception of color. The aim is to develop a model for color image representation and processing using a logarithmic framework, in accordance with the human color visual perception. Such a model has been investigated by Luthon et al. (Logarithmic hUe eXtension or LUX model) [3], [4] but is more restricted that the proposed one as it does not match exactly each step of human color vision and is not algebraic.

The paper is organized as follows: section II briefly expresses the trichromacy and opponent process visual theories and outlines the main stages of the human perception of color. Section III is an introduction to the LIP framework. Section IV introduces the color logarithmic image processing (CoLIP) model, based on the LIP approach and the different stages of human color perception, and compares it to the LUX framework. Section V compares an application of color correction method in the CoLIP framework, and LUX framework.

II. Trichromacy and opponent process theories for human color perception

Two complementary theories of color vision model the representation and processing of color in different stages within the whole visual pathway [5]. Trichromacy theory (Young-Helmoltz) states that the retina's three types of cones are preferentially sensitive to red, green, and blue. The opponent process theory (Hering) states that the human visual system interprets information about color in an antagonistic way.

Trichromacy models the retina, where color vision begins with light absorption by so-called cones photoreceptors denoted L, M and S according to the ordering of the wavelengths of the peaks of their spectral sensitivities (for Long, Medium, and Short wavelength, respectively). When illuminated by an incident light (called a stimulus) with power distribution $P(\lambda)$, the total power absorbed by the cones is:

$$L = \int l(\lambda)P(\lambda)d\lambda \quad (1)$$

$$M = \int m(\lambda)P(\lambda)d\lambda \quad (2)$$

$$S = \int s(\lambda)P(\lambda)d\lambda \quad (3)$$

where $l(\lambda)$, $m(\lambda)$, and $s(\lambda)$ are the cone response curves and λ stands for the optical wavelength.

The opponent process theory is physiologically justified. The neural signals produced by the photoreceptors pass up through several layers of cells in the retina which send the signal to the lateral geniculate nucleus (LGN) via the optic nerve. When converted to a neural signal, these signals are compressed. Psychological studies have shown that the neural response from a stimulus is close to a logarithmic curve. These results are highly related to psychophysical measurements, and in particular to the logarithmic Fechner's law [5]. Finally, the LGN produces three opposing pairs of processes, one achromatic and two chromatic channels, which are linear combinations of the cones' neural responses [5], [6]. The three antagonist signals are then interpreted in the visual cortex.

III. The Logarithmic Image Processing approach

The LIP has been introduced In the mid 1980's as an ordered algebraic and functional framework, which provides a set of special operations for the processing of bounded range intensity images [1], [7]. The LIP theory was proved to be not only mathematically well defined, but also physically and psychophysically well justified. Indeed, it is consistent with the transmittance image formation laws, the multiplicative reflectance and transmittance image formation model, and with several laws and characteristics of human brightness perception [1], [2]. The LIP approach is still an active research area.

In the LIP framework, images are represented by mappings, called *gray tone functions* valued in the positive real number range $[0, M_0)$. A gray tone function f corresponds to an incident spatial light distribution represented by the intensity function F through the following relationship:

$$f = M_0\left(1 - \frac{F}{F_{max}}\right) \tag{4}$$

where F_{max} is the saturating light intensity level, called the *upper threshold* or the *glare limit* [2] of the human visual system. Thus, a gray tone function f corresponds to an intensity function F valued in the positive bounded real number range $(0, F_{max}]$.
The addition of two gray tone functions f and g and the multiplication of a gray tone function f by a real number μ are defined as follows:

$$f \mathbin{\triangle\!\!\!\!\!+} g = f + g - \frac{fg}{M_0} \tag{5}$$

$$\mu \mathbin{\triangle\!\!\!\!\!\times} f = M_0 - M_0\left(1 - \frac{f}{M_0}\right)^{\mu} \tag{6}$$

In order to introduce the opposite of a gray tone function f denoted $\triangle\!\!\!\!\!-\, f$, the gray tone range is extended to $(-\infty, M_0)$. $\triangle\!\!\!\!\!-\, f$ is then defined as follows:

$$\triangle\!\!\!\!\!-\, f = -M_0\frac{f}{M_0 - f} \tag{7}$$

This definition allows the subtraction between two gray tone functions f and g to be defined as:

$$f \mathbin{\triangle\!\!\!\!\!-} g = M_0\frac{f - g}{M_0 - g} \tag{8}$$

The set of gray tone functions valued in the range $(-\infty, M_0)$, structured with operation $\triangle\!\!\!\!\!+$ and $\triangle\!\!\!\!\!\times$ extended to any real number, defines a real vector space isomorphically related to the classical vector space of functions through the isomorphism denoted φ and defined by:

$$\varphi(f) = -M_0 \ln\left(1 - \frac{f}{M_0}\right) \tag{9}$$

IV. The Color Logarithmic Image Processing approach

A. Initial goal

In this paper, the idea is to apply the LIP theory in the context of human visual perception of color. The first step consists in defining the notion of *color tone function* for color image representation following the different human color vision stages, and the second step consists in developing a mathematical framework for color image processing using the LIP framework .

B. From cone intensities to achromatic and chromatic antagonist tones

The first stage models light absorption in the retina. Following the LIP representation, the *chromatic tones* (l, m, s) are related to the cone intensities (L, M, S) as follows:

$$f_c : C \longrightarrow c = M_0\left(1 - \frac{C}{C_0}\right) \tag{10}$$

where $C \in \{L, M, S\}$ and $c \in \{l, m, s\}$, C_0 is a reference intensity value and M_0 is a context dependent scaling factor (in the digital case and for 8-bits images $M_0 = 256$ for L, M and S). The chromatic tones (l, m, s) belong to $[0, M_0)^3$. The nonlinear (logarithmic) response of the retinal stage is modeled by applying the LIP isomorphism φ on each neural cone response. More precisely, each chromatic tone c is transformed through the corresponding isomorphism denoted φ_c defined by:

$$\tilde{c} = \varphi_c(c) = -M_0 \ln\left(1 - \frac{c}{M_0}\right) \tag{11}$$

The outputs of this nonlinear stage are called *logarithmic chromatic tones* and are denoted $(\tilde{l}, \tilde{m}, \tilde{s})$ for the inputs (l, m, s). The last stage models the opponent process. It consists in applying a linear colorimetric transformation P_{CoLIP} to $(\tilde{l}, \tilde{m}, \tilde{s})$ in order to produce a *logarithmic achromatic tone* denoted $\tilde{a}$ and two *logarithmic chromatic antagonist tones* denoted $\tilde{rg}$ and $\tilde{yb}$ (for red-green and yellow-blue opponent channel respectively):

$$P_{CoLIP} = \begin{pmatrix} \alpha & \beta & \gamma \\ \alpha^{'} & \beta^{'} & \gamma^{'} \\ \alpha^{''} & \beta^{''} & \gamma^{''} \end{pmatrix} \tag{12}$$

$$\begin{pmatrix} \tilde{a} \\ \tilde{rg} \\ \tilde{yb} \end{pmatrix} = P_{CoLIP}\begin{pmatrix} \tilde{l} \\ \tilde{m} \\ \tilde{s} \end{pmatrix} \tag{13}$$

where α, $\beta, \gamma \geq 0$ define the achromatic channel, $\alpha^{'}, \gamma^{'} \geq 0$, $\beta^{'} \leq 0$ define the red-green channel, $\alpha^{''}$, $\beta^{''} \geq 0$, $\gamma^{''} \leq 0$ define the yellow-blue channel.
If $L = M = S$, the image is achromatic (i.e. a gray level image). Therefore $\tilde{rg} = 0$, $\tilde{yb} = 0$ and $\tilde{a} = \tilde{l} = \tilde{m} = \tilde{s}$. The parameters matrix P_{CoLIP} (12) satisfy the following relations:

$$\begin{cases} \alpha + \beta + \gamma = 1 \\ \alpha^{'} + \beta^{'} + \gamma^{'} = 0 \\ \alpha^{''} + \beta^{''} + \gamma^{''} = 0 \end{cases} \tag{14}$$

In writing $(\tilde{a}, \tilde{rg}, \tilde{yb})$, as logarithmic achromatic and chromatic antagonist tones derived from the corresponding *achromatic and chromatic antagonist tones* denoted (a, rg, yb) through the isomorphism φ_c defined in (11) with $c \in \{a, rg, yb\}$, achromatic and chromatic antagonist tones can be derived from chromatic tones (l, m, s) by the function $\varphi_c^{-1} \circ P \circ \varphi_c$ as follows:

$$\begin{cases} a = M_0 - (M_0 - l)^{\alpha}(M_0 - m)^{\beta}(M_0 - s)^{\gamma} \\ rg = M_0\left(1 - (M_0 - l)^{\alpha'}(M_0 - m)^{\beta'}(M_0 - s)^{\gamma'}\right) \\ yb = M_0\left(1 - (M_0 - l)^{\alpha"}(M_0 - m)^{\beta"}(M_0 - s)^{\gamma"}\right) \end{cases} \tag{15}$$

C. The vectorial structure

In the CoLIP framework, a color image associated to the cone intensities function F is represented by its *color tone function* denoted f, which is a three component valued function. Its first component is the *achromatic tone function* a, and the last components are the two *chromatic antagonist tone functions* rg and yb. They are related to the cone intensities (L, M, S) by (10) and (15). A color tone function is defined on a compact set D (called the spatial support) in $\mathbf{R}^2$ and is valued within $(-\infty, M_0)^3$:

$$f(x,y): \begin{pmatrix} L(x,y) \\ M(x,y) \\ S(x,y) \end{pmatrix} \mapsto \begin{pmatrix} a_f(x,y) \\ rg_f(x,y) \\ yb_f(x,y) \end{pmatrix} \tag{16}$$

It can be shown that the CoLIP addition of two antagonist tone functions f and g, denoted $f \,\triangle\!\!\!\!\!+\, g$, is defined as follows:

$$f \,\triangle\!\!\!\!\!+\, g = \begin{pmatrix} a_f \,\triangle\!\!\!\!\!+\, a_g \\ rg_f \,\triangle\!\!\!\!\!+\, rg_g \\ yb_f \,\triangle\!\!\!\!\!+\, yb_g \end{pmatrix} \tag{17}$$

The CoLIP scalar multiplication of an color tone function f by a real scalar μ denoted $\mu \,\triangle\!\!\!\!\!\times\, f$ is defined as follows:

$$\mu \,\triangle\!\!\!\!\!\times\, f = \begin{pmatrix} \mu \,\triangle\!\!\!\!\!\times\, a_f \\ \mu \,\triangle\!\!\!\!\!\times\, rg_f \\ \mu \,\triangle\!\!\!\!\!\times\, yb_f \end{pmatrix} \tag{18}$$

The CoLIP opposite of an color tone function f denoted $\triangle\!\!\!\!\!-\, f$ is defined as follows:

$$\triangle\!\!\!\!\!-\, f = \begin{pmatrix} \triangle\!\!\!\!\!-\, a_f \\ \triangle\!\!\!\!\!-\, rg_f \\ \triangle\!\!\!\!\!-\, yb_f \end{pmatrix} \tag{19}$$

This definition allows the subtraction between two color tone functions f and g, denoted $f \,\triangle\!\!\!\!\!-\, g$, as follows:

$$f \,\triangle\!\!\!\!\!-\, g = \begin{pmatrix} a_f \,\triangle\!\!\!\!\!-\, a_g \\ rg_f \,\triangle\!\!\!\!\!-\, rg_g \\ yb_f \,\triangle\!\!\!\!\!-\, yb_g \end{pmatrix} \tag{20}$$

The set of antagonist tone functions defined on the spatial support D with values in $(-\infty, M_0)^3$, denoted I, and structured with operations $\triangle\!\!\!\!\!+$ and $\triangle\!\!\!\!\!\times$ is a real vector space.

D. The LUX approach

Based on the LIP theory, the LUX approach has also been built by following steps of human color visual perception [4]. Cone intensities are represented by (R, G, B) channels and transformed into chromatic tones (r, g, b) (see (10) with $C \in \{R, G, B\}$ and $c \in \{r, g, b\}$), then the non-linear response of the retinal stage is modeled by the LIP isomorphism φ_c applied on each chromatic tone channel (see (11)). The opponent process is modeled by the (Y, C_r, C_b) colorspace transformation matrix called P_{LUX} in the present article:

$$P_{LUX} = \begin{pmatrix} 0.3 & 0.6 & 0.1 \\ 0.5 & -0.4 & -0.1 \\ -0.2 & -0.3 & 0.5 \end{pmatrix} \tag{21}$$

Finally, as in the CoLIP framework, in applying the inverse isomorphism φ_c^{-1} on logarithmic achromatic and chromatic antagonist tones, achromatic and chromatic antagonist tones (l, u, x) can be derived from chromatic tones (r, g, b) as follows:

$$\begin{cases} l = M_0 - (M_0 - r)^{0.3}(M_0 - g)^{0.6}(M_0 - b)^{0.1} \\ u = M_0\left(1 - (M_0 - r)^{0.5}(M_0 - g)^{-0.4}(M_0 - b)^{-0.1}\right) \\ x = M_0\left(1 - (M_0 - r)^{-0.2}(M_0 - g)^{-0.3}(M_0 - b)^{0.5}\right) \end{cases} \tag{22}$$

Nevertheless, the LUX approach is not an algebraic framework as Luthon et al. do not introduce vectorial operations to combine LUX channels. CoLIP operations defined in the present article (see (17), (18), (19) and (20)) can be applied to LUX achromatic and chromatic antagonist tones as done on CoLIP achromatic and chromatic antagonist tones.

V. Color correction in the framework of Color Logarithmic Image Processing

A. White balance problem

The human visual perception can adapt to changes of illuminant color. A white object illuminated with a low temperature light source becomes reddish. The same object illuminated with high temperature light source becomes bluish. But the human observer will still recognize it as white. This human visual perception's property is called color constancy [5]. Nevertheless, artificial imaging systems do not have the ability to adapt to illuminant changes. In order to mimic the human color vision, such systems need to apply a transform so that the output image matches the scene visually observed. This is called the white balance, and the transform used to perform the white balance is called a chromatic adaptation transform.

B. Color correction method

The color correction method presented in this paper consists in modelling the human visual system's ability to discount the illuminant, in subtracting with CoLIP operation $\triangle\!\!\!\!\!-$ the color tone values from a white point (a set of tristimulus values that represent white under the picture's illuminant) from color tone values of each original image's pixel:

$$f_{I_{corrected}} = f_I \,\triangle\!\!\!\!\!-\, f_{WF} \tag{23}$$

As explained in the LIP framework [2], the CoLIP operation $\triangle\!\!\!\!\!-$ of a color tone vector from a color tone function can be intepreted as the subtraction of the color filter representing the illuminant from the all image.
In the framework of CoLIP, (a, rg, yb) and $(a_{cor}, rg_{cor}, yb_{cor})$ are original and corrected color tone functions and

Fig. 1: From left to right, color correction on indoor reflected light images (1 and 2) and underwater images (3 and 4). From top to bottom: original images, CoLIP corrected images, and LUX corrected images.

$(a_{wp}, rg_{wp}, yb_{wp})$, the white point color tone values, respectively.

$$\begin{cases} a_{cor} = a \triangle a_{wp} \\ rg_{cor} = rg \triangle rg_{wp} \\ yb_{cor} = yb \triangle yb_{wp} \end{cases} \quad (24)$$

In the framework of LUX processing, (l, u, x) and $(l_{cor}, u_{cor}, x_{cor})$ are original and corrected color tone functions and (l_{wp}, u_{wp}, x_{wp}), the white point color tone values, respectively.

$$\begin{cases} l_{cor} = l \triangle l_{wp} \\ u_{cor} = u \triangle u_{wp} \\ x_{cor} = x \triangle x_{wp} \end{cases} \quad (25)$$

The difficulty is to define the value to give to the illuminant white point. If the illuminant is not known, it can be a pixel of the image that is recognized as white under standard illumination. Here, in order to eliminate local saturation phenomenons, the white point is calculated in taking pixels that have greatest values of images on all channels until a certain percentage p of image pixels is reached, and then taking the mean of these pixels on each channel.

C. Experimental results

The white point has been calculated on each image with a percentage $p = 1\%$.

In the CoLIP framework, the image has first to be transformed from its original representation space to the cone pigment absorption space (L, M, S). In the case of the (R, G, B) space, a linear transformation matrix U is given by Faugeras [8]:

$$U = \begin{pmatrix} 0.3634 & 0.6102 & 0.0264 \\ 0.1246 & 0.8138 & 0.0616 \\ 0.000 & 0.0602 & 0.9389 \end{pmatrix} \quad (26)$$

Then in CoLIP and LUX frameworks, intensities are mapped into tones. In the digital case, image intensities are expressed on 256 gray levels with a floor quantization so the scaling factor M_0 is set to 256 and the tone function f_c is as follows:

$$c = f_c(C) = M_0 - C - 1 \quad (27)$$

$C \in \{L, M, S\}$ and $c \in \{l, m, s\}$ in CoLIP framework, $C \in \{R, G, B\}$ and $c \in \{r, g, b\}$ in LUX framework.

In the CoLIP framework, the antagonist transformation matrix P_{CoLIP} is given by Vos and Walraven [9]:

$$P_{CoLIP} = \begin{pmatrix} 40/61 & 20/61 & 1/61 \\ 1 & -12/11 & 1/11 \\ 1/9 & 1/9 & -2/9 \end{pmatrix} \quad (28)$$

In the LUX framework, the antagonist transformation matrix P_{LUX} is (Y, C_r, C_b) colorspace transformation matrix (21) [4]. The two color correction methods have been applied on both indoor reflected light images (yellow illuminant) and underwater images (reflected light images captured through a water filter, blue illuminant) (fig. 1). The CIELAB distance

TABLE I: CIELAB distance Δ_{ab} between D_{65} white and three expected white points in original images and resulting images with CoLIP and LUX color corrections.

Image	Original	CoLIP	LUX
Indoor 1	64,742	10,660	12,748
	65,950	15,204	18,185
	61,317	2,5682	3,5128
Indoor 2	64,143	9,8982	11,579
	66,177	6,7957	10,883
	65,418	3,2010	6,7542
Underwater 3	48,263	3,0475	16,219
	48,757	4,7135	14,756
	48,964	6,5451	12,531
Underwater 4	51,399	4,860	21,404
	51,445	5,5322	25,545
	54,336	13,884	28,931

Δ_{ab} between three points on each picture that should be white or approaching white under daylight illumination, and CIE D_{65} white that represent the human eye white, whith CoLIP and LUX correction is indicated in table I. Distances from top to left are representing points in top images (fig. 1) from left to right. The experimental results shows that the color correction method applied whithin the CoLIP framework give better results than whithin the LUX framework. This can be explained by the fact that the LUX approach does not match exactly each step of human color vision: the cone intensities are represented by (R, G, B) intensities, whereas the CoLIP model integrates a transform matrix to the (L, M, S) space. Furthermore the opponent stage is modeled by the (Y, C_r, C_b) television colorspace transformation matrix (22) which has no physical signification whereas CoLIP model maps logarithmic chromatic tones to antagonist logarithmic tones with the Vos and Walraven matrix (28) which comes from psychological results [9] and is also used by the lasts CIE color appearance models (CAMs) [5].

VI. Conclusion and future work

Based on the Logarithmic Image Processing (LIP) mathematical theory a new algebraic framework called the Color Logarithmic Image Processing (CoLIP) has been introduced. Owing to its algebraic structure it allows the computation of addition, subtraction and scalar multiplication of color images while being consistent with two main theories of visual perception (trichromacy and opponent process), with the cones compression non-linearity, and with the visual color constancy. A CoLIP color correction method has been defined. It models the human visual system's ability to discount illuminant in performing a CoLIP subtraction of the color in the image that should be white to the eye under daylight illumination. This method has been successfully evaluated on both underwater images (blue illuminant) and indoor reflected light images (yellow illuminant), and experimental results verify that the color correction method performs better when applied whithin the CoLIP framework than whithin the Logarithmic hUe eXtension (LUX) framework, also based on the LIP approach, that does not match exactly each step of human color vision. Strong new pathways are opened since the CoLIP framework provides a vector space structure. Current researches are in various fields, such as contrast enhancement where the LIP model is known to give excellent results, and chromatic edge detection as opponent processing is known to decorrelate photoreceptors signals.

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