EXTENSION OF SCIELAB FOR A VIRTUAL IMAGE CHAIN

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Abstract

This paper describes an extension of the S-CIELAB image comparison model and its use in the Virtual Image Chain for inkjet and medical display (project VICTOR: granted by European commission). The extension starts from the representation of the perceived image in Fourier space with CSF-filters in AC_1C_2. For the achromatic channel bandpass-characteristics (edge enhancement) and anisotropy (Daly's work) are introduced, presenting an alternative normalization of the bandpass filters (DC component = 1). To obtain the best representation of the perceived image, the edge enhancement should be measured and modeled. After filtering with the extended model (VICTOR S-CIELAB) similarities between images are quantified by higher order image quality metrics. Please include a brief abstract of this paper. Avoid using figures or equations in the abstract.

Introduction

Since several years, much research work is focused on modeling of the various aspects of human perception in order to integrate the performance of the Human Visual System (HVS) in the context of visible image difference metrics. *Johnson* [1] gave a comprehensive overview of the existing models. There are mainly two groups of models for both grayscale and color images. The group of linear models is based on the implementation of the eye's Contrast Sensitivity Functions (CSF) as overall linear filter, whereas on the other hand, more complex models are based on a more complete description of non-linear phenomena in the human eye [2, 3]. In the first case, the modeling of HVS is a linear approximation of a non-linear system. Approximately fifty years ago, the first experiments were conducted on sinusoidal grating patterns in order to psychophysically determine the Contrast Threshold Function (CTF). For practical use, the CSF was simply defined as the inverse of the CTF. For the achromatic channel, in terms of opponent color space representation, the shape of the CSF is typically bandpass (resembling optical blurring and lateral inhibition effects, a.k.a. "edge enhancement"), whereas a low pass shape is found for chromatic channels [4]. For the achromatic channel, the most complete description of CTF corresponds to the work of *Barten* [5], which is based on many psychometric measurements and investigations. It allows detailed control of many relevant ambient parameters, like field size, luminance level, viewing distance, etc. Moreover, the CSF model given by *Barten* is used for the Medical Display DICOM Standard and is regarded standard in medical imaging. Furthermore, *Daly* proposed a model to take the anisotropy of the HVS into account, described by *Sullivan* [6].

From a simplified point of view CSF is compared to a Modulation Transfer Function (MTF) [1]. In order to apply the CSF as spatial filter to an image a 2 dimensional filter needs to be constructed from the CTF data. In case of color (channels C_1, C_2) the normalization of the corresponding inverse CTF data is straightforward and does not modify the shape of the CSF, since they are low pass in nature. For the achromatic CSF (channel A) normalization is often done such that the maximum value of the inverse CTF data (i.e. the bandpass peak) was set to 1. In addition, filter response at frequencies below was arbitrarily set to 1 to finally end up with a low pass filter, which preserves the DC signals (level of flat field). Obviously this procedure changes the frequency response of the achromatic CSF filter considerably. Alternative approaches, which maintain the bandpass character of the so normalized CTF data result in a DC component smaller than 1. In this case, the level of a constant signal (spatial frequency 0, "flat field") is not conserved when applying the spatial filter. Obviously, treatment of the DC component is closely linked to normalization when applying CSF as spatial filter.

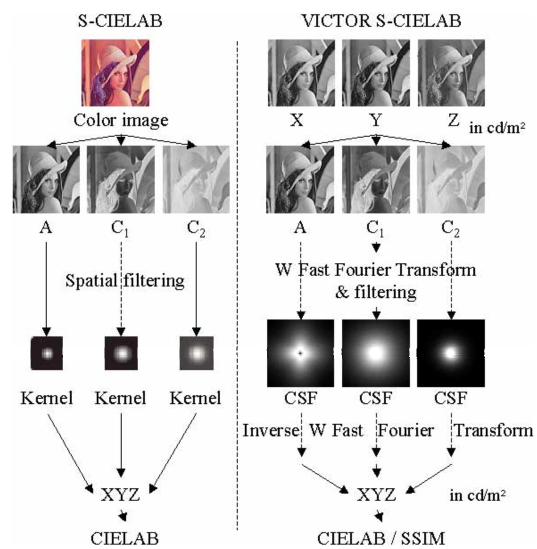

***Figure 1**. Flow chart of Victor S-CIELAB.*

Zhang [7] proposed an extension of CIELAB by adding the spatial blurring of the eye in the opponent color space representation. The problem of the conservation of the DC is circumvented by the application of kernels in spatial domain, which actually represents a low pass filter and does not take edge enhancement into consideration. In this article, we propose an extension to the existing S-CIELAB model, starting from XYZ values in *cd/m^2* and applying the CSF in *Fourier* domain [1]. A specifically normalized achromatic CSF is proposed and psychophysically validated. The parameterization (least-squares fitting) of the psychophysical CSF data obtained from a contrast matching experiment uses elements of *Barten*'s model. The orientation-anisotropy of the CSF at 45° is re-investigated and anisotropy weights at different frequencies are fitted with the weight function defined by *Daly*. The normalization of the chromatic CSF is not discussed here, since their shape is low-pass. Color anisotropic effects reported for isoluminant color gratings of rather saturated colors (as opposed to chromatic gratings crossing neutral) are not considered [8]. Chromatic CSF's used in the proposed extension of S-CIELAB are taken from *Johnson* [1]. The purpose of this work is to come up with a still "simple" but more complete linear HVS model that can be used as perceived filter in the context of a virtual image chain [9, 10] simulation for imaging systems (project VICTOR).

Methods

Input data for the model are radiometric images in terms of intensities (cd/m^2) represented in the *XYZ* color space.

Opponent color space representation

XYZ intensity is converted into the opponent color space representation [11] (one achromatic channel *A* and two chromatic channels C_1 and C_2) (cf. equation 1).

$$\begin{vmatrix} A \\ C_1 \\ C_2 \end{vmatrix} = \begin{vmatrix} 0.279 & 0.720 & -0.107 \\ -0.449 & 0.290 & -0.077 \\ 0.086 & -0.590 & 0.501 \end{vmatrix} \cdot \begin{vmatrix} X \\ Y \\ Z \end{vmatrix} \tag{1}$$

Contrast Sensitivity Functions

Achromatic channel

The goal of this study is to estimate a normalized achromatic CSF. One of the standard methods is determination of CTF (at threshold level) from a single stimulus test and then to use the inverse data for the CSF with the problem of subsequent normalization as explained before. On the other hand, normalization of CSF can be more directly addressed in a contrast matching experiment.

Protocol of the study by matching

The first study by matching was described by *Georgeson* [12], who describes the protocol of such a two-stimuli test, in which two patches associated to different frequencies of sinusoidal gratings are presented to an observer as illustrated in figure 2. One of the patches, the reference patch, is kept constant (wrt. contrast and frequency) throughout each test session. The second one represents the test patch with the same or a higher spatial frequency of the grating as compared to the reference patch. Starting from low contrast levels, the contrast of the test patch is increased continuously during a session until the observer judges the contrast of the two patches identical. Once the tested patch matches the reference patch, the session for the given frequency is over. Number of (repetitive) sessions covering a range of frequencies of the test pattern are run for several observers. The result of this experiment provides two contrast values, the contrast level of the reference frequency pattern and the psychophysically measured contrast of the test frequency pattern. The reference frequency is the lowest frequency used in the experiment and serves as approximation of the DC component. Then, the ratio between the two contrasts corresponds to the contrast sensitivity for the tested frequency. If the contrast matched for the test frequency is lower than that of the reference frequency, an "amplification" of contrast perception is observed, which corresponds to "edge enhancement". In the other case, a signal degradation is observed which corresponds to blurring (filtering). Contrast is measured according to *Michelson* (*contrast* = $(L_{max}-L_{min})/(L_{max}+L_{min})$).

For the contrast matching experiment a psychophysical test room is set-up according to the corresponding international standards (ISO 3664−2000, ITU *BT*.500−11), validated by a reference center (Poitiers University, France, [13]). One innovate feature of this implementation is a modular "box-in-a-room" design (3x2x2 meters). The panels have a neutral grey color with 20 % refletance.

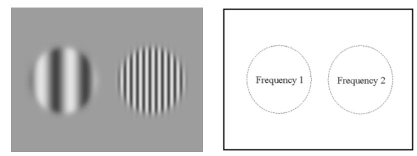

***Figure 2**. Left: principle of contrast matching: the patch with frequency remains at fixed contrast, whereas the contrast of the patch with frequency 2 continuously increased until contrast match is observed; right: example.*

The room is indirectly illuminated by fluorescent tubes with a correlated color temperature of 5000 K. The monitor is a LaCIE CRT-22 inches with a resolution of 1600x1200. The monitor's white color temperature is set to D50 with a maximum intensity of 77 cd/m^2. With the monitor switched off the amount of light diffusely entering the eye due to the indirect illumination is 3 cd/m^2. Stimuli have been constructed according to the following constraints: stimuli are gamma corrected according to the monitor; the total angular size of one patch equals to 6.5 degree; a safe viewing distance of 1.5 meters was chosen to work with high frequencies; the highest frequency of the stimuli is given by the required minimum of 10 pixels per sinusoidal cycle; the lowest frequency is determined by the requirement of at least two cycles in the field of view (6.5 degree) since the CSF does depend of the number of cycles [5]. To avoid artifact as results of any edges in the stimuli, the sinusoidal gratings were modulated by a 2 dimensional filter (*Butterworth*). The test frequencies were selected in a pre-study [13], which has shown that high frequencies (above 9 cpd) were already difficult to judge in this matching experiment. Therefore, a range of ten frequencies was chosen (0.42 to 8.7 cpd), allowing fast tests (ca. 10 min for all frequencies) for the comfort of the observer. The number of observers involved is 8 (4 experts and 4 non-experts). The general course of each experiment is to increase the contrast of the test patch for a given frequency in steps of 0.01 per second, until the observer judged them to match. At this low speed of contrast change, temporal effects on the CSF are negligible.

Vertical study: The two-stimuli-contrast-matching-method is used to measure the "vertical" CSF, which means that both of the two gratings in reference and test patch, respectively, are oriented vertically. The experiments were repeated for three different levels of contrast of the reference patch, namely 1, 0.7, 0.5, in order to obtain a supra-threshold CSF.

Horizontal study: The CSF is known to be the same when measured on either vertical or horizontal gratings. This study is performed in order to double-check the reported lack of orientation dependency for vertical and horizontal gratings. The grating at reference frequency is kept in vertical orientation, whereas the grating of the test frequency is presented "horizontally", i.e. rotated by 90 °.

Study at 45°: As for the horizontal study, the goal of this study is to determine the anisotropy of the CSF. Indeed, the sensitivity to contrast is known to decrease when looking at gratings with a diagonal orientation. Thus, the reference grating stays vertical, and the tested frequency is rotated to 45°.

Image difference metrics: DCIE2000 and SSIM

Two metrics for image comparison are explored. The first one is ΔCIE2000 recommended by CIE [11], which is a pixel by pixel comparison of colors expressed in L*a*b*. In addition, the structure similarity metric SSIM[14, 15] is used, which determines similarity between two images in terms of achromatic luminance, contrast and structure.

Results

Achromatic channel

Results of the studies on the achromatic channel are summarized in figure 3.

Vertical study: Figure 3*a* shows measured CSF from the two stimuli matching experiment with a reference contrast of 0.7, which is based on pooled data of 8 observers in up to 3 repetitive sessions. CSF results at different supra-threshold contrast levels of the reference patch (1.0, 0.7, 0.5) based on 2 observers are presented in figure 3*b*. In addition, a normalized plot of the *Barten* model for the viewing conditions of the test protocol (Luminance, stimulus size, viewing distance. . .) is given, which marks the CSF at threshold level. Normalization is based on lowest frequency in the experiment ($f0$=0.4 *cy/deg*), which was arbitrarily chosen to represent the DC component. Frequencies below are omitted.

Horizontal and 45° study: Figure 3*c* represents the result from both orientation studies, namely the ratio of matched contrast of horizontal and 45° oriented gratings vs. contrast of vertical reference. Two observers performed the horizontal study, the study on diagonal gratings with 8 observers. Detailed results of the 8 observers in the ”diagonal study” are presented in figure 3-*d*). For the vertical-horizontal study, a practically constant ratio of 1 is found, which confirms the same contrast sensitivity of the HVS in vertical and horizontal direction. For the vertical-diagonal study, a decrease of the ratio is observed at higher frequencies, which corresponds to a loss in contrast sensitivity. These data correspond to the anisotropy of the CSF at 45° as described by *Daly*. Figure 3*e* represents a crosscheck study for 1 observer. One curve represents the result of a two stimuli contrast matching experiment with both patches under diagonal orientation (45°/45°). The other curve is derived from the ratio of the vertical-diagonal study, which for each frequency is applied as factor to the results of the vertical-vertical study. The two results are consistent (Mean Squared Error (MSE) of 0.7 %).

Model of normalized achromatic CSF

CSF model inspired from Barten

The experimental CSF at reference contrast of 0.7 is fitted with a function inspired by the model of *Barten*. By omitting noise contributions, two terms are conserved: the optical MTF (filtering of the high frequencies) and the lateral inhibition (edge enhancement) (cf equations 2 and 3. Figure 3-*a* shows the result of the fit with the following parameters: A=0.0131, B=0.376 and C=0.768). MSE is 0.02 %.

$$CSF_{Achromatic}(u) = MTF_{optical}(u).M_{LateralInhibition}(u) \tag{2}$$

$$CSF_{Achromatic}(u) = e^{-\pi^2.A^2.u^2}.(B.(1-e^{-(\frac{u}{C})^2})+1) \tag{3}$$

Daly's model for the anisotropy

A fitting of the experimental ratio (8 pooled observers) with the formula from *Sullivan/Daly* [6] (cf. equation 4) results in a ratio value (w) of 0.72, reproducing the value 0.70 found by *Daly*.

$$\overline{u}_{xy} = \frac{u_{xy}}{\frac{1-w}{2}\cos(4\theta_{xy}) + \frac{1+w}{2}}; \quad \theta_{xy} = \arctan\left(\frac{u_y}{u_x}\right) \tag{4}$$

Chromatic channels

The CSF's used for chromatic channels in this extension of the S-CIELAB model are taken from *Johnson* [1] as given in equation 5, and with the following parameters for the red/green channel (a_1 = 109.1413, b_1 = 0.00038, c_1 = 3.42436, a_2 = 93.59711, b_2 = 0.00367, c_2 = 2.16771) and the yellow/blue channel (a_1 = 7.032845, b_1 = 0.000004, c_1 = 4.258205, a_2 = 40.69095, b_2 = 0.103909, $c2$ = 1.648658). CSF of equation 5 presents noticeable differences of the curves between the two channels as shown in figure 4. Other color CSF data reported in literature show less pronounced differences between C_1 and C_2.

$$CSF_{C_1,C_2}(u) = a_1.e^{-b_1.u^{c_1}} + a_2.e^{-b_2.u^{c_2}} \tag{5}$$

Specifications to the user

A specific optimized discrete fast *Fourier* transform [16] is used without limitation of image resolution to the power of two or to square resolution. For the filtering in *Fourier* domain, equations 5 and 3 of chromatic and achromatic CSF (reference contrast=0.7) are used to implement a 2 dimensional filters based on a simple rotation, taking into account the *Euclidian* distance of frequencies. The maximum available frequency is limited to $f_{max} = 1/2.ElementSize$ according to the *Nyquist-Shannon* theorem. For the anisotropy of the achromatic channel, equation 4 is used with w=0.72. In the VICTOR platform [17], a specific image data format with float values is used to avoiding clipping issues when applying the achromatic CSF with edge enhancement (values upper than the maximum=$2^{NumberOfBit} - 1$).

Example

A test image with synthetic disks from a virtual X-ray system simulation (VICTOR) [10] is taken as example illustrating the effects of edge enhancement and anisotropy. The input image (figure 5*a*) represents the virtual display of a simulated radiograph in terms of XYZ intensity. This image is then filtered by the original S-CIELAB model and with the extended version proposed here, either having edge enhancement or anisotropy activated. Figures 5*c* and 5*d* represent maps of absolute differences between original S-CIELAB filtered and extended S-CIELAB (VICTOR) filtered images, with only edge enhancement activated. Differences are translated into gray values, with white referring to ”no differences” and black ”large differences”. In the magnified view of figure 5*d*, the edge enhancement effect is clearly seen. Figure 5*b* shows the analogous comparison of anisotropy switched on/off in the extended SCIELAB model.

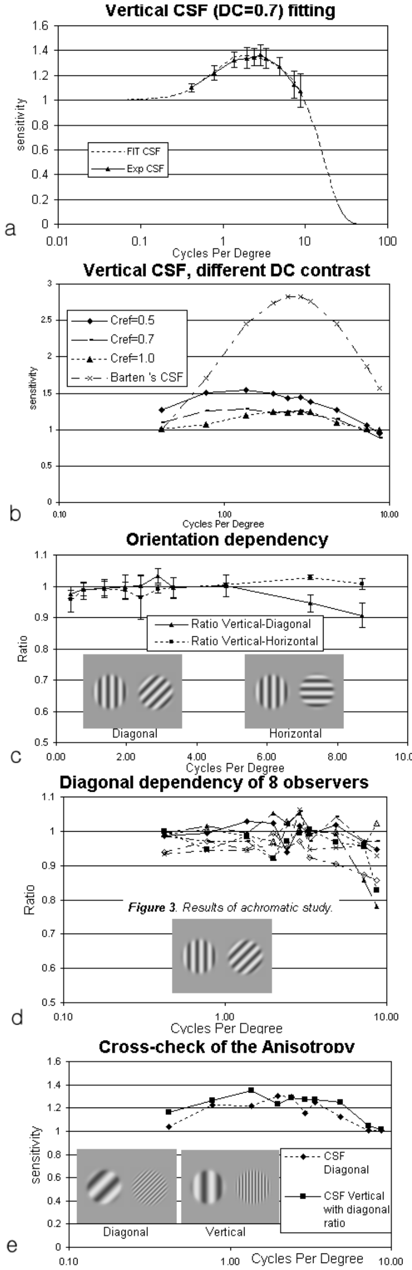

Figure 3. Results of achromatic study.

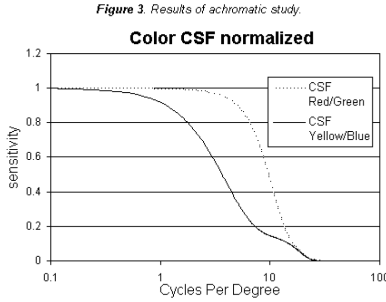

Figure 4.Color CSF from Johnson-Fairchild

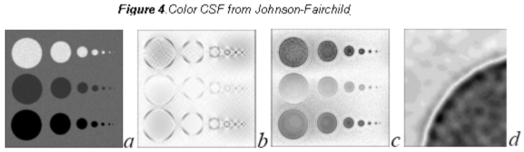

***Figure 5**. a: test pattern, b: map of absolute differences between image filtered by VICTOR S-CIELAB with and without anisotropy, c: map of absolute differences between image filtered by S-CIELAB and by VICTOR S-CIELAB with edge enhancement, d: zoom of c.*

Conclusion and acknowledgments

This paper described an extension of S-CIELAB, which provides a normalized CSF that introduces edge enhancement and anisotropy in the achromatic channel. Still this model is limited by the fact it is an overall linear approximation of the HVS. For more realistic modeling, a better approach is to work with more complex models like the Multi-scale Observer Model [3]. Special thanks to P. Ganapathy, R. Geelen, F. Mindru, for their help in preparing this paper. The European Commission in the 5th framework program of Marie Curie industry fellowships (IST-2002-83045, VICTOR) granted this work.

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