Control Algorithm for 6-Primary Displays Minimizing Effects of Observer Metamerism

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Abstract

The paper deals with a stochastic algorithm applied to optimize the control of a 6-channel multiprimary display. The aim is to display multispectral input data at least possible error for any human observer. The colors reproduced by the display are calculated from the additive mixture of 6 narrow band primaries. The primaries are described by their ex-perimentally measured spectral power distributions used in a laboratory model. The algorithm requires the definition of a measure of quality of color reproduction. This is defined by the maximum color difference between an input and output color for 24 different human observers characterized by their respective color matching functions. The maximum color difference of the observers calculated in CIE ΔE94 units is minimized as a function of the 6 control vectors of the primaries.

For each specific input spectrum, a series of interlocked stochastic search procedures is applied by which the range of variation of the control vector is stepwise reduced while the starting vector is suitably varied. Side minima at the end of a chain of steps require repetitive procedures. The paper demonstrates the importance of the estimation of a good starting vector to reduce the time of calculations. The estimation uses a choice of different vectors derived from specific solutions for the average observer. The starting vectors are stored in a two dimensional look-up table addressed by chromaticity coordinates referenced to the average observer.

The paper demonstrates the effectiveness of the algorithm and shows that all the maximum errors $\Delta E94_{max}$ for the set of 355 representative color stimuli are below 1.5 even if the nonuniform spectral characteristics of an experimental 6-channel display are assumed. Quantization errors of the practical device are not yet taken into account in this paper.

Introduction

Multiprimary displays have been proposed in a number of papers.[1,2] Their aim is to achieve a wide color gamut on the one hand and to reduce the metamerism index of different observers on the other. Experimental developments are typically focused on 6 channels to compose colors from the additive mixture of 6 primaries. The laboratory model of a 6-primary display using two LCD-projectors is shown in Fig. 1. The optical channels of the projectors are equipped with 50 nm bandpass transmission filters to produce narrow band spectral primaries.[1,7,9]

Figure 1. Laboratory model of a 6-channel display using two LCD-projectors with channels providing 50 nm narrow band spectral power distributions.

The resulting color gamut of the display is indicated in the chromaticity diagram of figure 2 together with the sRGB triangle for comparison.

Since there are more than three primaries to be controlled, metameric sets of different control values will result in the same XYZ-values of an observer. So, additional features of color reproduction can be taken into account. Nevertheless, some of the published proposals are aiming at the reproduction of wide gamut XYZ-values for the CIE1931 standard observer (2^{o}) only.[3-5] Another proposal uses 6 equations to exactly match both the CIE 1931 standard observer and the CIE 1964 supplementary standard observer (10^{o}).[6] Others try to minimize the color reproduction error for a larger number of different observers by using optimization procedures on the basis of stochastic or linear programming.[7,8]

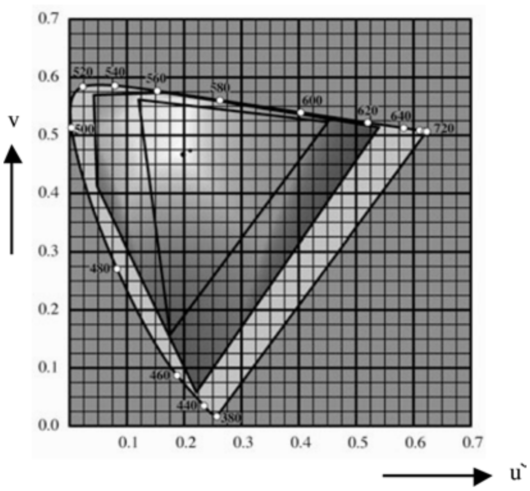

Figure 2. The 6-primary color gamut given in the CIE 1976 u’v’-diagram. The inner triangle represents the sRGB space for comparison.

Quality of a Multi-Primary Projection Display

An essential application of a multispectral display in the future will be its use as output device in a multispectral reproduction line.[2] Of course, a complete spectral match cannot be achieved by the low number of 6 channels available at present. Moreover, today’s light sources for pro-jectors and active displays are developed to achieve high efficiency and long life time and do not deliver uniform spectral radiating power but many spikes (see figure 3). Anyhow, a good spectral match is not really necessary in the case of a luminescent display. The elementary goal is to display original colors at minimum errors for any human observer. This situation is quite different from that in printing technology where external illuminants have to be considered in addition to the physical reproduction.

The color reproduction quality of the display is therefore only defined by the color differences of arbitrary displayed colors compared to their respective original colors represented by their spectral stimuli input data. These color differences should consider any human observer. In this paper, color differences are described by CIE $\Delta E94$ applied to 24 different color matching functions based on various observers (Fig. 4). The color reproduction errors are cal-culated for a set of 355 representative spectral stimuli.[12] So, there are finally 384 x 24 color reproduction errors defining the display’s quality. The maximum color difference of all combinations of observers and spectral input stimuli is taken as a single measure $\Delta E94_{max}$. Effects of color appearance are not considered. Hence, the reproduction assumes the same illuminant, maximum lightness, background and surrounding conditions for the comparison of the original and displayed colors.

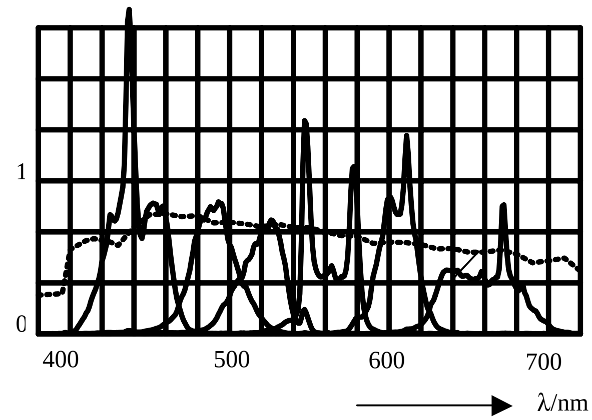

Figure 3. Spectral radiating power of the 6 primaries of the lab-ratory model of figure 1 and spectral illuminant D65 (dotted)

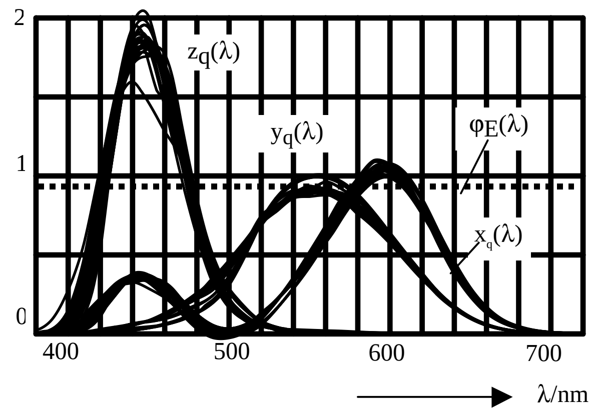

Figure 4. Spectral matching functions of 24 human observers including the CIE 1931 standard- and the CIE 1964 supplementary standard observers,[10] the standard deviator[11] and curves measured by Stiles and Burch.[10] The dotted line represents an equal energy stimulus

The Stochastic Algorithm

The goal to find the “best” amplitudes of the 6 primaries to display each input color stimulus is solved by the stochastic variation of the 6 amplitudes and checking the respective result of reproduction quality. The structure of this algorithm is shown in figure 5. The control values of the 6 amplitudes of the primaries (called channel values) are derived from the spectral stimulus input. The channel values are components of the channel vector $\mathbf{c} = \{c_1, c_2, c_3, c_4, c_5, c_6\}$. The procedure starts by determining an estimation vector $\mathbf{c_0}$ from the spectral input stimulus. For each observer, the tristimulus values are calculated from the sum of precalculated observer primaries weighted by respective components of $\mathbf{c_0}$ in the next step. The results are stored in the output table. Similarly, the tristimulus values are calculated from the spectral input stimulus for any observer, providing a table of original tristimulus values. Then, the measure of color error ΔE94max is calculated from both tables. The subsequent decison network decides whether the error is below a chosen threshold or not. If not, another estimation vector is chosen from a number of different estimations and the error is calculated again (dotted line in figure 5).

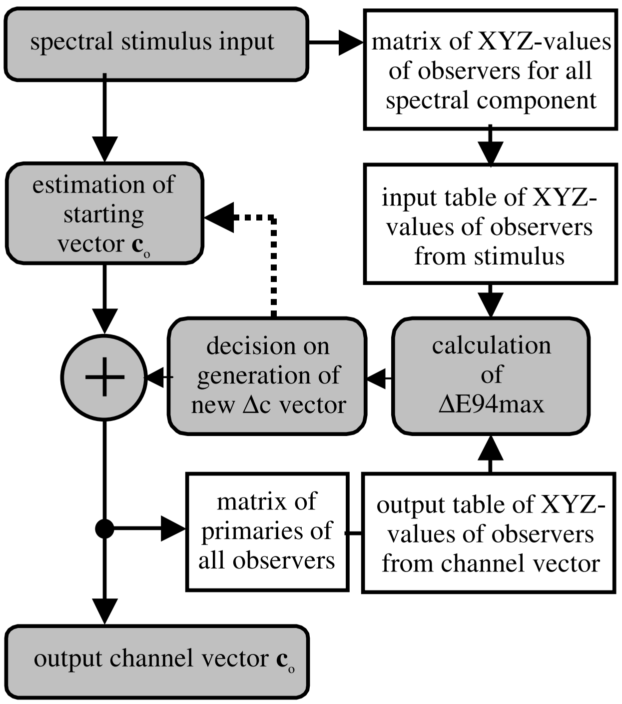

Figure 5. Structure of the algorithm to calculate channel vectors aiming at a least color error ΔE94max of 24 observers by stochastic variation

As discussed later, the use of a number of different estimation values turned out to be very appropriate to start with. After choosing the best estimation, the 6 components of the vector **c** are stochastically changed by adding small variations followed again by the calculation of the error measure. This is done several times until improvements in the color error ΔE94max are the result.

In order to stop the process after a reasonable time, a realistic threshold value is defined for ΔE94max. If the error is still above the threshold after a number of cycles, the amplitude range of the stochastic components is reduced to find out if further improvements in the range of a local minimum can be found. If this is not the case, the procedure is repeated once more by adding again a large amount of variation to find a different local minimum and so on, until an error below the chosen threshold is reached. If this is not possible after a specified number of cycles, the threshold is not realistic and has to be increased.

Generation of Estimation Vectors

Estimation vectors as input of the stochastic process are derived best for the tristimulus values XYZ of the average observer of the set of 24 (Fig. 4). The aim must be to find an estimation value which leads to the shortest time of stochastic optimization afterwards. Yet, there is no general rule to find the "best" one. Therefore, a number of different estimation values are applied and selected by "try and error". Another important point to be considered in practical applications is the speed which characterizes the generation of different estimation values. For the purpose of speed enhancement, all combinations of XYZ values are reduced to chromaticity coordinates addressing a look up table (LUT). At each address of chromaticity coordinates of a LUT, a 6 component channel vector is stored, calculated for a certain reference lightness Y. The CIE 1976 UCS chromaticity diagram has been applied therefore. Of course, linearity between channel control and tristimulus color output must be assured to use this method because the actual lightness information Y is no longer part of the database and has to be accounted for again afterwards. Correction of channel non-linearities is therefore assumed to be performed seperately within the display device.

The derivation of estimation values for the average observer in a first step faces the same problem as the control of a 6-channel display for one particular observer as discussed in Ref. [2]. In addition, care has to be taken of the observer metamerism. Of course, a spectral stimulus such as the stimulus of an equal energy distribution (Fig.4) will not cause any observer metamerism problem. So, smoothness of the distribution of channel values could be one aim. Considering the primaries for the average observer $\mathbf{P}_n=\{X_n,Y_n,Z_n\}$, the tristimulus value $\mathbf{A}$ = {X,Y,Z} to be displayed can determined from the general equation

$$\mathbf{A} = \left\{X, Y, Z\right\} = \sum_{n=1}^{N} c_n \mathbf{P}_n, \tag{1}$$

where c_n are components of channel vector **c** and N = 6. If c_n = 1, the white reference color **W** is displayed:

$$\mathbf{W} = \left\{X_w, Y_w, Z_w\right\} = \sum_{n=1}^{N} \mathbf{P}_n; \mathbf{c}_w = \left\{1, 1, 1, 1, 1, 1\right\}. \tag{2}$$

A simple solution for equation 1 can be found if only two adjacent primaries surrounding **A** are mixed with the sum of all primaries weighted by the same factor c_w:

$$\mathbf{A} = \left\{X, Y, Z\right\} = \left(c_i - c_w\right)\mathbf{P}_i + \left(c_k - c_w\right)\mathbf{P}_k + c_w \sum_{n=1}^{N} c_n \mathbf{P}_n. \tag{3}$$

The result provides smooth distribution of channel values for unsaturated colors and good results of observer metamerism (figure 6).

The spectral stimuli distributions for colors of higher saturation are more complicated. An example for a color of higher saturation and lightness resulting in a channel vector of less uniformity is shown in Fig. 7, step 1.

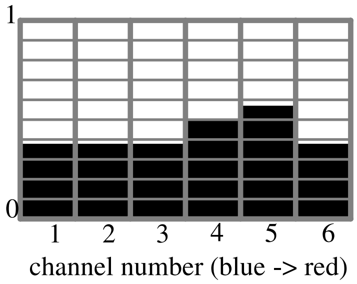

Figure 6. Example of channel vector resulting from Eq. 3 for the average observer and A ={0.5, 0.5, 0.45}

Moreover, it is not guaranteed that the highest displayable lightness is produced by this kind of solution for a given chromaticity (notice $c_n <= 1$!). So, it might happen that there is no solution for the required lightness Y of the input stimulus. This is the case for the example of figure 7 with **A** = {0.46, 0.8, 0.31}. The tristimulus value **A** is located near the primaries 3 and 4, but the highest lightness is limited by $c_3 = 1$ to Y = 0.6. Yet, additional solutions improving the result can be found using the free parts of components not yet filled up to 1 as is the case for n = 1, 2, 4, 5 and 6. In general, when using the structure of Eq. 3, there are up to N(N-1)/2 different possible solutions (15 for N = 6), though not all of them provide physically realizable values of $\mathbf{c}_n$. For the derivation of estimation values in this paper, a process of stepwise filling up the components adjacent to the maximum of step 1 has been developed by applying Eq. 3 to the c_n-values not yet filled up to 1. This leads to the stepwise concentration of components around a maximum resembling the spectral distribution of optimal colors (figure 7 steps 2 - 3). The achievable lightness increases from step to step. For the example considered here, the maximum lightness limited by the upper border of the color space of the display is automatically reached after the third step. Between one and four steps are required in general to realize the maximum lightness which is possible (only one step, if the color is a mixture of only two primaries). The result of any step provides a suitable estimation value if its lightnesses Y are large enough. If the lightness is smaller than the maximum of the calculated solution, a simple reduction of all components can be applied as shown in figure 7, step 4.

The computation of estimation values as described so far is time comsuming. To reduce this time in the actual system, the estimation values of all possible chormaticities are precalculated together with their maximum lightness values and stored in look-up tables. At each address, the channel vector for maximum lightness is stored. The reduction to the actual lightness is done in a second step. If the maximum lightness is not high enough, a gamut mapping process has to be applied. A bank of up to 4 LUT`s are used in the investigated system providing different estimation values resulting from the process described above.

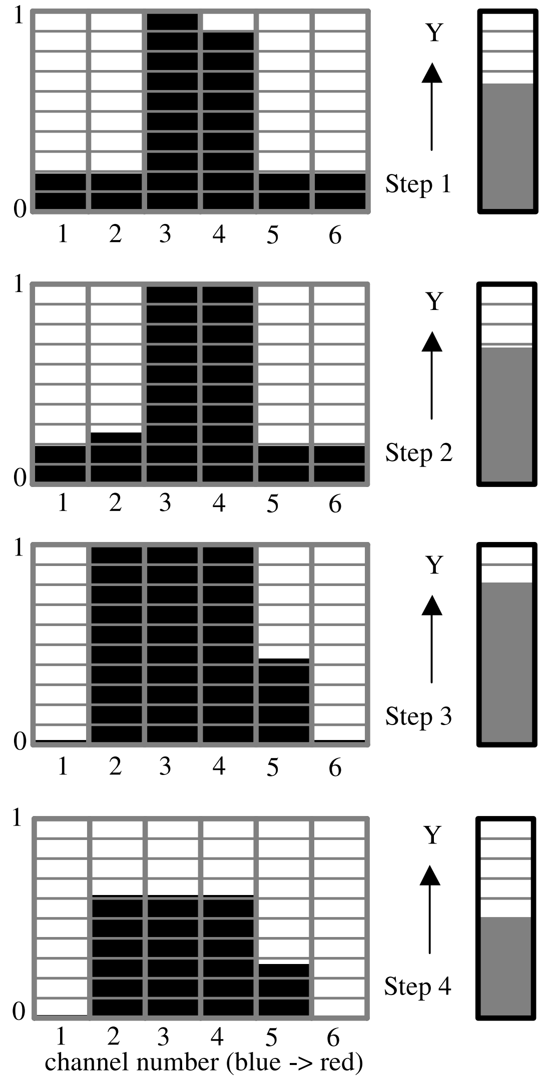

Figure 7. Steps to determine the chromaticity coordinates of A = {0.46, 0.8, 0.3} up to the maximum lightness (steps 1 to 3) and reduced amplitudes to match the lightness of Y = 0.5 (step 4)

Results

On the basis of the experimental radiating power distributions of six primaries measured in the center of the screen of a laboratory model (figure 3), simulations of the control algorithms and the resulting color errors have been performed using the color test data set of Vrhel.[12] The resulting errors $\Delta E94_{max}$ for the application of two different vectors after step 1 and the last step of the estimation process are shown in figures 8a and b, respectively. The errors of 355 colors for the first step of the estimation (no stochastic optimization applied!) is still resulting in values of more than $\Delta E94_{max}$ = 8. If its lightness is too small, it is replaced by the next estimation step in the diagram shown here. The results for the final estimation step providing the highest lightness is given in

Fig.8b. Obviously, most errors have become smaller, but not all. So, it is appropriate to select the estimation value providing the smallest error (figure 8c). Only a few errors are now larger than a threshold of $\Delta E94_{max} = 1.5$ assumed in the algorithm here. The colors with errors below this threshold do not need additional stochastic optimization. Only the colors with errors above the threshold are undergoing the stochastic optimization process until the error drops to or below the threshold value. In the example shown here, all the color errors are finally below the threshold (figure 8d). A small percentage requires a larger time of computation to meet this goal (figure 8e). All attempts to reduce the threshold further were no longer successful in this case.

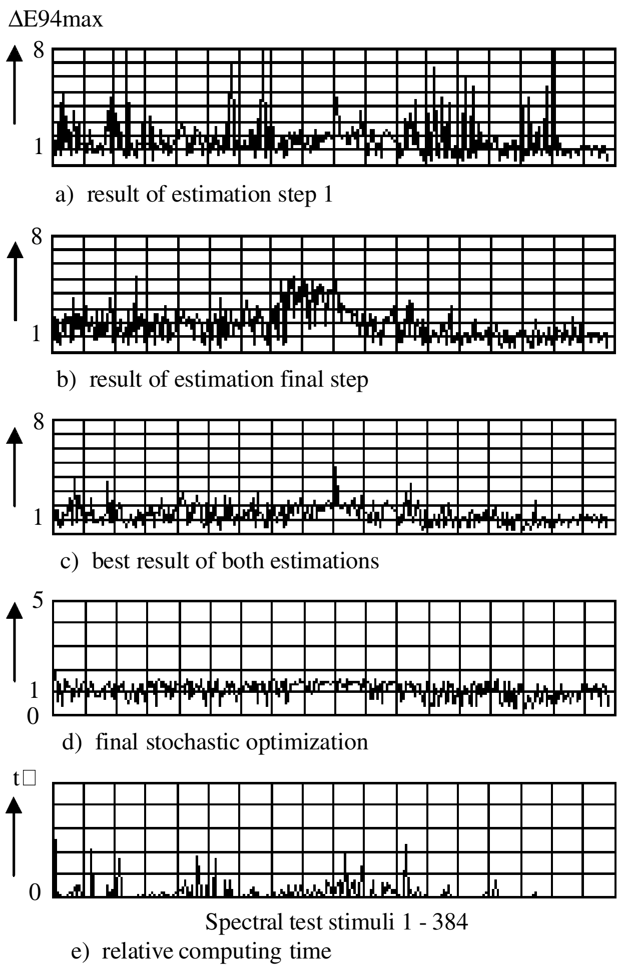

Figure 8. Error distribution of 384 spectral test stimuli for a) the first estimation values after step 1, b) the second estimation values (maximum lightness reduced to 1.0), c) the minimum error of both and the result d) with final stochastic optimi-zation and e) the required relative computing time tr

Conclusions and Outlook

The algorithm described in this paper provides the basis to optimize the control of the 6 channel display with respect to a threshold value for all the test colors. The color stimuli are undergoing different processing steps that lead to variable times of computation depending on their structure. It is shown that a set of different estimation vectors to start the algorithm is very advantageous to reduce the time of computation. Only a small number of critical colors obvisously requires the stochastic optimization, a fact which can be used to reduce the computing time remarkably.

In experimental systems, additional errors will be introduced by the quantization, linearization of display components and uniformity errors across the image screen. Strong improvements of those characteristics are still required to realize theoretical results in experimental devices.

For real time control of a display, the stochastic process is still too time consuming. Yet, it will be used to optimize control LUTs for various classes of colors. The concept considers a bank of two dimensional look-up tables addressed by chromaticity coordinates. The tables contain control vectors $\mathbf{c}_0$ for the respective maximum lightness as described below for the case of the generation of estimation values. This method of addressing via chromaticity diagrams works very fast. The estimation and stochastic optimization described in this paper supports the optimization of control values for classes of colors in the tables using a knowledge based concept. The selection of tables is planned to be controlled and trained by parameters derived from the spectral input stimuli in combination with characteristics of the type of image or class of colors to be presented (figure 9).

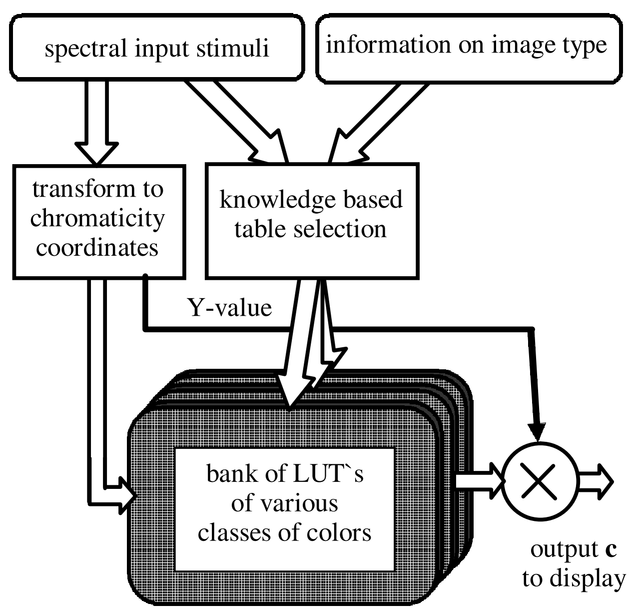

Figure 9. Future concept of knowledge based display control via LUT`s addressed by chromaticity coordinates

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Biography

Bernhard Hill received his diploma and Dr.-degree in Electrical Engineering from the Aachen University of Technology. In 1969, he joined the Philips Research Laboratory Hamburg, Germany and started research in the field of laser beam deflection, laser recording and holography. He became head of the optics group in 1974 and developed erasable magnetooptic memory technology and optical printing devices. In 1984, he changed to the Aachen University of Technology. He is now focused on color management, gamut mapping and multispectral imaging. From 1990 to 1994, he was manager and dean of the faculty. He is member of IS&T, SID, VDE and vice president of the german society for color science and applications DfwG, and he is the german representative in CIE - Division 8.

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