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An optimized Radial Basis Function model for color characterization of a mobile device display

Ante Poljicak *, Jurica Dolic, Jesenka Pibernik

University of Zagreb, Faculty of Graphic Arts, Getaldiceva 2, Zagreb, Croatia

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A B S T R A C T

This paper presents an optimized color characterization model based on Radial Basis Functions (RBFs). The performance of the proposed model was tested on a number of different mobile devices and compared with the performance of other state of the art color characterization models. We compared the accuracy of models using the CIELAB color difference. Four different models were discussed in detail: Piecewise Linear Model Assuming Variation in Chromaticity, Polynomial regression, Artificial Neural Network, and proposed Radial Basis Function model. For training and evaluation of the models we measured a large number of color samples on various mobile device displays. Results have shown that our optimized RBF model has superior accuracy over other models with median color difference of 0.39. In addition, it has particularly good accuracy for colors on the boundary of device's gamut with maximum color difference of 0.87, where other models shown unacceptably high (>10) color difference.

1. Introduction

Mobile devices today are ubiquitous and used in wide range of different applications from personal communication to image reproduction. Equipped with powerful imaging and processing hardware, mobile devices enable users to capture and view high resolution static images and interactive content. The expanding functionality of mobile devices is followed by rapid development of transmissive and emissive mobile display technologies.

Most mobile devices on the market feature an Active Matrix Liquid Crystal Display (AMLCD) or an Active Matrix Organic Light-Emitting diode (AMOLED) display. AMLCD is a transmissive display technology based on controlled orientation of molecules in the liquid crystal (LC) layer through which light passes and forms the rendered image on the display. The LC layer is situated between two electrodes, one being controlled by active-matrix backplane and the other situated beneath the color filter. By controlling the voltage difference between the electrodes, molecular array of liquid crystals can be adjusted, thus controlling the intensity of the transmitted light [1]. Several different configurations of molecules in the LC layer, or Liquid Crystal Display Modes, exist: Twisted-Nematic (TN), In-Plane Switching (IPS), Vertical Alignment (VA) and Patterned Vertical Alignment (PVA). AMOLED represents an emissive display technology. AMOLED panels consist of series of organic thin films situated between two electrodes, a metal-based cathode and transparent anode. Instead of usual RGB subpixel array, AMOLED displays found in mobile devices often feature a RG-BG subpixel array, also known as PenTile array [2]. Compared to AMLCDs, AMOLEDs usually offer wider-viewing angles, better contrast ratio, significantly wider gamut and thinner construction, which make this technology attractive for mobile displays.

The progress and widespread use of mobile technology is not adequately followed by research on colorimetric characterization of mobile devices. The display characterization in general is extensively researched. Authors in [3–5] give an extended overview of methods for characterizing CRT displays. While methods for characterization of LCD displays is given in [6–8]. On the other hand, research on characterization focused just on mobile displays is very limited. Only Piecewise Linear Model Assuming Constant

* Corresponding author.
E-mail addresses: ante.poljicak@grf.hr (A. Poljicak), jurica.dolic@grf.hr (J. Dolic), jesenka.pibernik@grf.hr (J. Pibernik).

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Chromaticity (PLCC), Piecewise Linear Model Assuming Variation in Chromaticity (PLVC), and masking models where applied on mobile device displays [9].

The goal of our paper is to broaden the available research on the subject of color characterization of mobile device displays, and to develop flexible and accurate model for color characterization of mobile device display. We propose a model for color characterization of mobile device display based on Radial Basis Functions (RBFs) and compare its performance against other popular approaches for color characterization: Piecewise Linear Model Assuming Variation in Chromaticity (PLVC), Polynomial regression model, Artificial Neural Network (ANN) model. We compare performance of the models in respect to number of training samples needed and color difference between estimated and measured data. For training and evaluation we use data obtained from twenty different mobile devices with different AMLCD and AMOLED display technologies.

2. Theoretical

The main goal of the colorimetric characterization of a device is to obtain a model that will accurately transform color information from device dependent color space to device independent color space and vice versa. With the obtained model it is possible to estimate exact driving signals of the device for a needed color. A device dependent color space such are RGB and CMYK color spaces are not absolute color spaces, i.e. they differ from device to device. A device independent color space such are CIEXYZ and CIELAB are absolute and describe color as it is seen by a CIE standard observer [10]. In literature X, Y and Z values of CIEXYZ color space are also known as CIE tristimulus values.

According to [11], all methods or models can be classified in three different groups: the methods that try to physically model the behavior of a color device, the methods based on numerical models, and the methods that are using 3D Look Up Tables (3D LUT).

Physical modeling is usually carried out in three steps. Firstly, the linearization of the tone reproduction curves (TRCs) of the devices' channels is done by modeling curves with a gamma law (CRT) or S-shaped curves (LCD) [12–17]. When the signals are linearized, transformation from device dependent color space (RGB) to the device independent color space (CIEXYZ) is done. Finally, an offset is added to the output (1).

$$\mathbf{i} = \mathbf{M} \cdot f(\mathbf{d}) + \mathbf{o} \quad (1)$$

where $\mathbf{i}$ denotes output vector in independent color space; d denotes vector with driving signals in dependent color space, $f(\cdot)$ is linearization function; $\mathbf{M}$ represent transformation matrix, while $\mathbf{o}$ denotes offset vector.

Generally, physical models assume a number of simplifying conditions such are channel independence, chromaticity constancy, spatial uniformity, and angle view independence. Channel independence assumes that the primaries of the device operate independently from one another. Chromaticity constancy assumes that each primary has constant chromaticity values regardless of the intensity of a driver signal. Spatial uniformity ensures that the output values will be the same, irrespective of the position on the device. Angle view independence assumes constant output values indifferent to the viewing angle. Color characterization of CRT displays was extensively studied in the past [18–20,12,4,21] and these assumptions where tested and validated in experiments [18,22].

Numerical characterization estimate transformation from a device dependent space to a device independent space using a numerical model. This model can be based on a number of different methods such as polynomial regression of n-th degree [23], neural networks [24,25], sequential linear interpolation [26], or Radial Basis Functions (RBFs) [27,28]. In comparison with the physical models, this approach is able to successfully model devices without assumption of channel independence. However, for this to be possible, large number of measurements are needed. It should be noted that numerical methods are extensively used for characterization of printers as well [6,29].

3D LUT models are based on tables with the information how to translate color information from a device dependent space to a device independent space. The accuracy of the model depends on the number of measurements taken to create the table [30], and the interpolation method to transform the color information for data that is between measurement points [31]. The main disadvantage of this approach is the need for large number of measurements. On the other hand, its advantage is that this approach does not imply any assumptions regarding the display technology.

2.1. Piecewise Linear Model Assuming Variation in chromaticity

PLVC model was first proposed in 1980 by Farley and Gutmann in [32]. Later it was extensively used and evaluated for CRT displays [12,33,5] and for LCD displays [7,6,34]. It is extension of Piecewise Linear Model Assuming Constant Chromaticity (PLCC), which it supersedes in accuracy, especially for displays where the chromaticity shift for different illuminance levels is high [11].

According to PLVC model, tristimulus values for any driving signal of the device can be expressed as a sum of tristimulus values for each primary for that driving signal. PLVC model can be generalized for any number of primaries, as well as for any number of possible levels of a driving signal. For a device with N primaries with L possible driving signal levels PLVC model is defined in (2).

$$\begin{aligned}
X(p_1(s_1), p_2(s_2), \ldots, p_N(s_N)) &= \sum_{i=1}^{i=N} [X(p_i(s_i)) - X_k] + X_k \\
Y(p_1(s_1), p_2(s_2), \ldots, p_N(s_N)) &= \sum_{i=1}^{i=N} [Y(p_i(s_i)) - Y_k] + Y_k \\
Z(p_1(s_1), p_2(s_2), \ldots, p_N(s_N)) &= \sum_{i=1}^{i=N} [Z(p_i(s_i)) - Z_k] + Z_k
\end{aligned} \quad (2)$$

where X, Y, Z denote CIE tristimulus values; p_i is ith primary ($i \in [0, N]$) and s_i is a driving signal level for ith primary ($s_i \in [0, L]$). X_k, Y_k, Z_k denote tristimulus values for black level, (i.e. $s_i = 0 \ \forall \ p_i$).

Since the values of the black level are included in every measured sample it is important to subtract it first from all samples, and then add it only once to ensure correct standard observer color space [35].

Main advantage of PLVC model is that it needs only a small number of measured samples. In addition, it is very simple to implement. On the other hand, this model does not take into account channel interdependence.

Implementation of PLVC was done using (2) for $N = 3$ primaries (i.e. R, G and B). Nine different driving signals of each primary were used for the model ($Sr, Sg, Sb \in [0, 32, 64, 96, 128, 160, 192, 224, 255]$). To calculate response of the model for other driving signals, linear interpolation was used as this approach was used in previously published research [7,6,34]. Note that the interpolation method can influence the performance of PLVC, however, this is not within the scope of this paper.

2.2. Polynomial Regression models

Regression models are statistical models used for estimation of relationships among variables. These well-known methods are used in wide range of applications from data fitting to data predic-