https://doi.org/10.2352/CIC.2022.30.1.10

Color matching between regular display and LED lighting tiles in automotive

Jérémie Gerhardt, Greg Ward, Hyunjin Yoo, and Tara Akhavan; Faurecia IRYStec Inc. (Canada)

Abstract

For a few years, the automotive industry has produced new cars with continuous changing display models, this by combining display sizes, forms and technologies all together to bring new experiences to the users. In this paper we will present the color matching solution implemented for a new car display system where regular LCD display technology and LED lighting tiles are mixed together. The solution we proposed is based on accepted display model providing the transformation device RGB space to CIE XYZ independent color space and in reverse. The approach we followed choose the LCD display as reference, then transformation matrix is derived to modify the RGB LED control values. Once the color matching operation is applied, the color difference between the two display areas is greatly reduced.

Introduction

Innovation in automobile also comes from the technology available in the cockpit. From the heated seat, air conditioning, sound system, display to user customization. Increasing the display visual comfort in all viewing conditions to transforming all cockpit surfaces as potential space for displaying information or lighting.

What we present here is the color matching problem for a new type of display in automotive which combines more than one type of display technologies or technologies to produce colored light.

The problem is not new - matching colors of different displays [2] or just exploiting gamut shapes [4] - but the environment it takes place in is. Building a cockpit requires to put together hardware coming from various sources, produce software that will link all elements, often create a new pipeline with the requirement to function for years. Color matching is really important, data pipeline may function and convey information to the displays, but without color management the colors won't match and the whole car system can be disapproved.

In a general approach, we want to know the color profile of each display, to choose an independent color space in which we will do matching operation and to decide what the best technique depending on the color profile information is [3]. The question is "do we use LUT or a display model approach?" for the color matching? Because of hardware and space limitation, the display model approach has been chosen for that project.

In the next sections, we will present our mixed technology display system, the test version we used to test our color matching workflow and the proof of concept version we used to present to our existing and potential customers. Then we will introduce the display model, the color matching technique and experimental results.

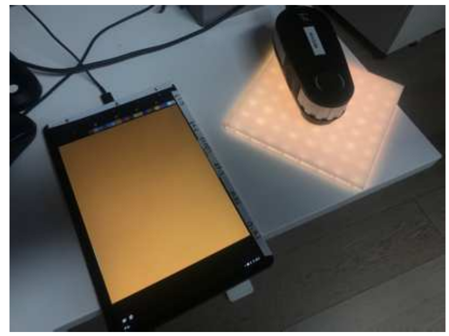

Figure 1. *Picture of our mixed display mock-up. On the left the tablet S6, on the right the LED tile. You can also see the color measuring device i1pro positioned on the LD.*

Mixed display technology system

Our mixed display technology system combines in its simplest form two display technologies: an LCD or OLED display with backlight control, 8bits per color channel and LED lights. The LED lights are under the form of a tile covered by regularly spaced RGB LED with 8 bits per color channel, a fixed backlight, each light source independently controllable, it can be understood as a display surface with a smaller ppi than a regular display.

In both versions we did display the same images on both display parts, measure the color responses, evaluate the differences in CIEuv distance and construct the transformation matrices based on RGBW CIExy measurement.

These first operations are to characterize the regular display (or RD) and the LED display (or LD), to retrieve each gamut boundaries and response curves (or RCs). A typical RC for a standard display is expected to have a *gamma* shape of value $\in \{2,3\}$. An interesting observation for our system is that the LD part is at first combining lighting technology element, therefore the RC present a linear relationship, consequently the same RGB digital command value present different colors than on RD.

Mock-up version

The mock-up version is made of a tablet Samsung S6 and an 8 by 8 RGB LED tile (REF SMARTLED). The LD has a white diffuser placed on the top of it, Figure 1 shows a view of the mock-up. We can observe that the visual impression between the two displays is really different. For the final version another diffuser will be used on the top of both displays.

We choose the 24 color combinations of the ColorChecker as test colors, see Figure 2. Both displays are set to their maximum screen brightness and after studying the spatial uniformity of both

Figure 2. All ColorChecker patches presented as an image where each patch is displayed and measured from top to bottom, left to right.

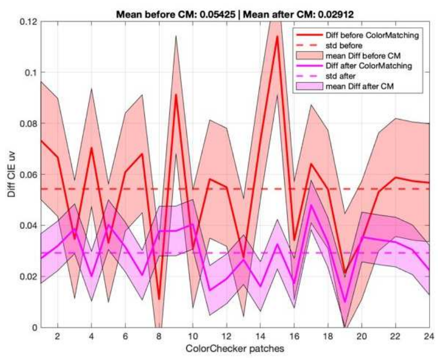

Figure 3. Delta CIE uv distance bewteen the ColorChecker patches displayed on each display, before and after color matching correction applied to LD. From left to right the points correspond to the colored patches, the last 6 from right to left correspond to the grayscale ramp in the ColorChecker chart.

displays, we choose for both their centers as measuring location, for the LD it corresponds to a spot located between four LEDs.

Figure 3 shows the CIE Delta uv distances before (average of $\Delta_{uv} = 0.05425$) and after color matching ($\Delta_{uv} = 0.02912$) when comparing the 24 patches of the ColorChecker. Only the RGB combinations for the LD have been modified by the color matching operation.

Prototype version

The prototype version visible in Figure 4 was built to illustrate how we can make usage of any cockpit surfaces, to increase the display size to convey more information, to add a new immersive experience to the car driver and passengers. It presents several challenges for its characterization, calibration and control, achieving seamless transition between display technologies. For example, the maximum brightness of the LD is five times bigger than the RD and no back light control is possible of the LD on that setup.

If the work here focuses on the color matching, it comes after the work of the designers, architect, material engineers, UX specialists and more. For example, the cover glass layer has different properties depending of the RD or LD area, meaning the color measurement can only be done when the setup is fully assembled.

A video sequence has been created, showing successively RGBW colors, then a grayscale ramp from black to white, then the 24 color patches of the ColorChecker (e.g. in Figure 4, the system shows a frame turned blue). The purpose of the grayscale measurement is to retrieve the RC of each display.

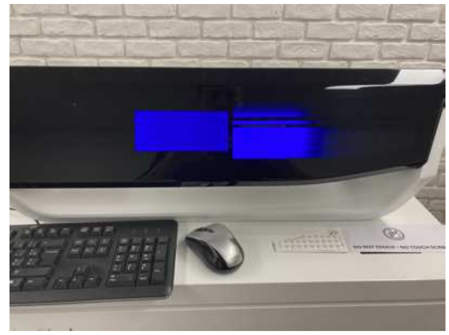

Figure 4. Picture of our demo display as it is presented to customers. Only a part of each display areas is turned on in that illustration, but we can observe the effect of having a common glass cover over the two displays, giving a seamless impression between the two display technologies.

In Figure 5, you can observe the normalized RC of the RD (in blue) and LD (in red), respectively the gamma value are 2.6 and 1, those values will be needed for the color matching operation described in the next section. Figure 6 allows to visualize how the same RGB values for each ColorChecker patch produce different colors. We can also observe that the RD behaves like a calibrated display, the blue diamonds are nicely spread over the display gamut and the white point is close to a $D65$ reference. On the other hand the red circle shows a very concentrated set of points.

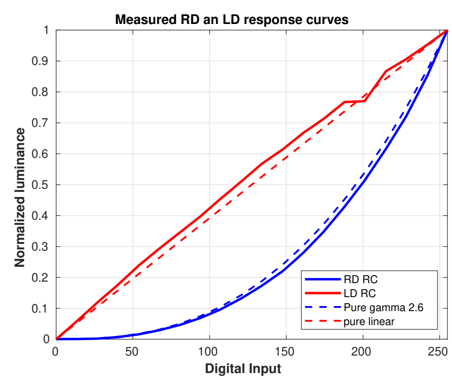

Figure 5. The normalized response curves of each display. RD has a gamma of 2.6 *and LD a gamma of* 1.

Color Management

To solve the color distortion between the two display parts we had to implement a color management solution to our system. One approach could have been to use a workflow related to ICC profile and having a color management module dedicated for the color transformation. Because of the hardware resources allocated to this system we had to use an alternative, but a parameter remains similar: a reversible transformation from display color space to an independent color space (ICS), we did choose the CIE XYZ color space as ICS.

Display model

We use the matrix display model [5, 1] that predict the color $c = [X,Y,Z]^T$ for a given pixel $p = [r,g,b]^T$ where $r,g,b \in \{0,1\}$:

$$c = \mathbf{M}.p^{\gamma} = \mathbf{M}.[r^{\gamma}, g^{\gamma}, b^{\gamma}]^T \quad (1)$$

where $\gamma \in \{1,3\}$ describes the display response curve with a gamma shape.

M defines the transformation matrix from device space to independent color space and each column stands from the display primaries red, green and blue as follows:

$$\mathbf{M} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_b & Z_b \end{bmatrix}, \quad (2)$$

and using the CIE chromaticity values notation as follow:

$$x = \frac{X}{X+Y+Z}, y = \frac{Y}{X+Y+Z}, z = \frac{Z}{X+Y+Z} \quad (3)$$

we can rewrite

$$\begin{aligned} x_r &= \frac{X_r}{X_r+Y_r+Z_r} = \frac{X_r}{C_r}, \\ y_r &= \frac{Y_r}{X_r+Y_r+Z_r} = \frac{Y_r}{C_r}, \\ z_r = 1 - x_r - y_r &= \frac{Z_r}{X_r+Y_r+Z_r} = \frac{Z_r}{C_r} \end{aligned} \quad (4)$$

where $C_r = X_r + Y_r + Z_r$, similarly for x_g, y_g, z_g and x_b, y_b, z_b with $C_g = X_g + Y_g + Z_g$ and $C_b = X_b + Y_b + Z_b$. Using the last previous equations we can rewrite Eq. 2 as follows:

$$\mathbf{M} = \begin{bmatrix} x_r C_r & x_g C_g & x_b C_b \\ y_r C_r & y_g C_g & y_b C_b \\ (1 - x_r - y_r)C_r & (1 - x_g - y_g)C_g & (1 - x_b - y_b)C_b \end{bmatrix}, \quad (5)$$

and finally as we also know each display white (X_w, Y_w, Z_w) we can rewrite C_r, C_g, C_B as follows:

$$\begin{aligned} C_r &= \frac{(Y_w/y_w)[x_w(y_g - y_b) - y_w(x_g - x_b) + x_g.y_b - x_b.y_g]}{D} \\ C_r &= \frac{(Y_w/y_w)[x_w(y_b - y_r) - y_w(x_b - x_r) + x_r.y_b - x_b.y_r]}{D} \\ C_r &= \frac{(Y_w/y_w)[x_w(y_g - y_b) - y_w(x_g - x_b) + x_r.y_g - x_g.y_r]}{D} \end{aligned} \quad (6)$$

where

$$D = x_r(y_g - y_b) + x_g(y_b - yr) + x_b(y_r - y_g) \quad (7)$$

In our setup we obtain the following matrix values for the RD:

$$\mathbf{M_{RD}} = \begin{bmatrix} 0.3824 & 0.3249 & 0.1894 \\ 0.1763 & 0.7388 & 0.0849 \\ 0.0105 & 0.0404 & 0.9892 \end{bmatrix}, \quad (8)$$

and LD:

$$\mathbf{M_{LD}} = \begin{bmatrix} 0.4912 & 0.1240 & 0.2744 \\ 0.2573 & 0.5412 & 0.2014 \\ 0.0093 & 0.0881 & 1.6697 \end{bmatrix}, \quad (9)$$

We did evaluate the performance of the forward display model by comparing for each display the ColorChecker measurement versus the simulated $CIEXYZ \rightarrow uv$ using the display model. For the LD we obtain an average $\Delta_{uv} = 0.0089$ and for the RD $\Delta_{uv} = 0.0044$. Figure 7 and Figure 8 present in $CIEuv$ diagrams the measurements and simulations.

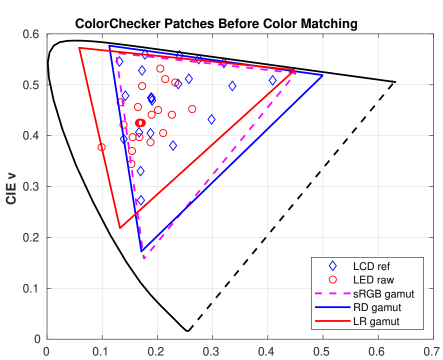

Figure 6. *The figure above shows the ColorChecker patches for each display before applying color matching. Their respective gamut boundaries is also highlighted together with the sRGB gamut, in a CIEuv diagram.*

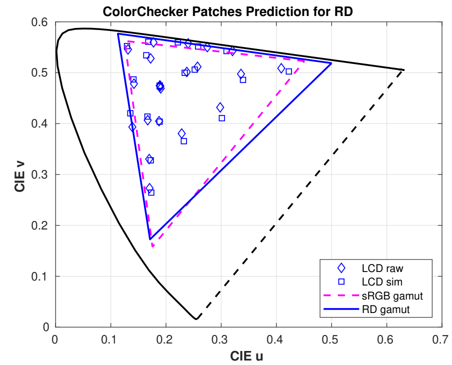

Figure 7. *Comparison of the ColorChecker measurement on the RD and the CIEuv simulation using model described in Eq. 1 to Eq. 7 and matrix values as in Eq. 8.*

Color matching

The color matching operation will modify the RGB values for the display we want to correct the color. In our scenario only the LD is modified as the RD is set as reference. Therefore the transformation matrix is defined as follows:

$$\mathbf{M_{CM}} = \mathbf{M_{LD}^{-1}}.\mathbf{M_{RD}} \quad (10)$$

with the following values obtained:

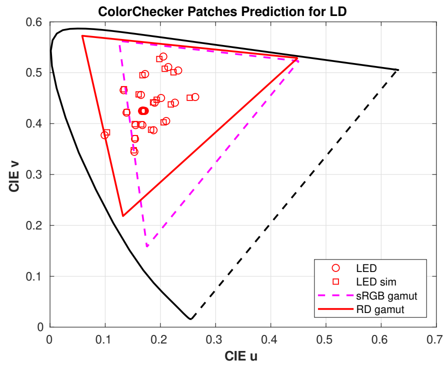

Figure 8. *Comparison of the ColorChecker measurement on the LD and the CIEuv simulation using model described in Eq. 1 to Eq. 7 and matrix values as in Eq. 9.*

Figure 9. *All ColorChecker after color matching has been applied using Eq. 12 patches presented as an image where each patch is displayed and measured from top to bottom, left to right.*

$$\mathbf{M_{LD}} = \begin{bmatrix} 0.7887 & 0.3819 & 0.0776 \\ -0.0510 & 1.1987 & -0.1023 \\ 0.0046 & -0.0412 & 0.5974 \end{bmatrix}. \tag{11}$$

This transformation is assumed to be applied in linear domain, therefore we need to use the RC information about each display to get the right values:

$$p' = (\mathbf{M_{CM}}.p^{-\gamma_{RD}})^{\gamma^{LD}} \tag{12}$$

and

$$p' = \left[r', g', b'\right]^T, \tag{13}$$

Essentially the transformation in Eq. 12 estimates the CIE XYZ values produced by display 1 (here the RD) for a given RGB combination and uses the inverse model of display 2 (here the LD) to estimate the corresponding R'G'B' combination to produce that same CIE XYZ values.

Figure 9 presents an image visualization of the ColorChecker patches after color matching applied. Because the LD is much brighter than the RD, the new RGB values are very low, but once used as digital commands for the LD, the colors appeared correctly.

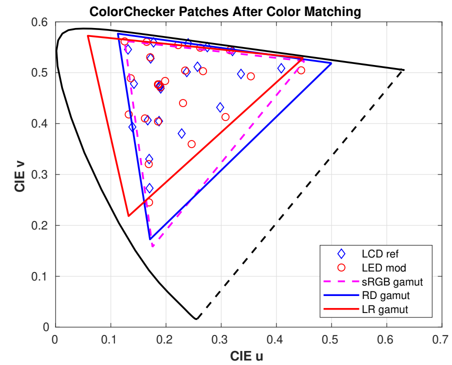

Figure 10. *The figure above shows the ColorChecker patches for each display after applying color matching to the LD. The gamut boundaries for each display is also highlighted together with the sRGB gamut, in a CIEuv diagram.*

Results and Discussion

The Figure 10 presents the ColorChecker patches in a *uv* diagram after the color matching transformation has been applied. Compared to Figure 6, we can see the red circles for the LD being closer to the blue diamonds. Also we could visually judge that the colors on both parts of the display were much closer.

The Euclidean distance in CIE *uv* space was used to evaluate the before/after effect of the color matching as it is commonly used when evaluating display performances. Results are presented in Figure 11, average $\Delta_{uv} = 0.0653$ before correction and $\Delta_{uv} = 0.01464$ has been obtained.

Other metrics have been considered such as Euclidean distances in CIELab space, but the relative large luminance difference between the two display technologies produced big numbers. Big numbers that do not reflect the real visual improvement the color matching brought to the system, e.g. $\Delta E_{ab} > 9$ mostly located on the *CIEL* axis.

The approach we did follow requires to modify only the LD RGB values. But the gamut mapping method could have been applied to the RD only or to both displays where a third color gamut will have been selected (i.e. the common color gamut between those displays or a reference virtual display with e.g. sRGB and a known gamma value).

That's one of the major difficulties in evaluating the color matching between two different technologies, a regular display RD and lighting technology LD turned into a display, to find the right metric. Another difficulty comes from the continuous evolution of the prototype, and therefore the need to develop guidelines, workflow to quickly characterize, calibrate and evaluate the color matching.

The goal of such installation is to extend the regular display size and to give a feeling of immersion, e.g., any surface of the cockpit as a display surface. Once the display is calibrated and color matched, it is the work of the graphic and UX designers to propose, tune, develop a natural use of the system.

Acknowledgments

We would like to thanks our colleagues from the different locations on planet earth who work on different aspects of the project. We did work here in Montreal on the final display cal-

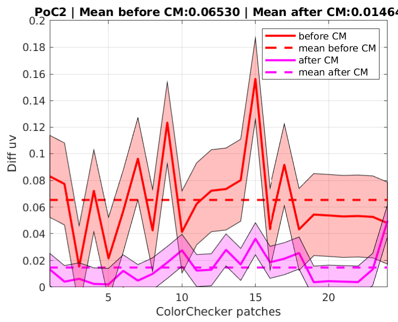

Figure 11. *Delta CIE uv distance between the ColorChecker patches displayed on each display of our prototype, before and after color matching correction applied to LD. From left to right the points correspond to the colored patches, the last 6 from right to left correspond to the grayscale ramp in the ColorChecker chart*

ibration and color matching, but different departments and skills were involved, from display makers, materials expert, software and hardware architects, designers.

References

[1] David Rogers, Procedural elements for computer graphics, McGraw-Hill, Inc., 1986, pg. 618-619.

[2] Alain Pagani and Didier Stricker, Spatially uniform colors for projectors and tiled displays, Wiley Online Library, J. of the Society for Information Display, 15, 2007.

[3] Morovič, Ján , Color gamut mapping, John Wiley & Sons, 2008

[4] Greg Ward, Hyunjin Yoo, Afsoon Soudi and Tara Akhavan, Tara, Exploiting wide-gamut displays, Color and Imaging Conference, Society for Imaging Science and Technology, 2016

[5] William B. Cowan, An inexpensive scheme for calibration of a colour monitor in terms of CIE standard coordinates, ACM SIGGRAPH Computer Graphics, 1983,ACM New York, NY, USA