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MACCLED: Mixed Adaptive Color Correction System for Outdoor LED Displays

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Abstract. The colors displayed on an outdoor LED Display appear incorrectly most of time due to the contieously changing ambient lighting conditions. In this paper, we demonstrate the MACCLED (Mixed Adaptive Color Correction) system that correct the displayed colors on the LED display based on the readings from both ambient color sensor and a photometer. The performance of the system is then analyzed through conducting a series of psychophysical visual experiments. The resulting z-score of each ambient conditions is then compared to select the optimum adjustment of system parameters.

Keywords: LED display, color appearance, ambient lighting, chromatic adaptation, incomplete adaptation, mixed adaptation.

1. Introduction

The color perception in photopic vision mode is a very complex process, which combines millions of cells in both the human eye sensor and the nervous system [1]. The Human Vision System (HVS) applies a sophisticated process called the chromatic adaptation to track ambient white point as a reference used in predicting the colors. This process can be explained by the independent sensitivity adjusting or gain control of the three cone responses in order to eliminate the effect of the illumination color and to preserve the appearance of a seen object. When we watch a softcopy image on a display device, the HVS becomes affected by both ambient white point and the display white point. The resulting perceived image is then regenerated inside the HVS based on an adapted white point relative to the both luminance sources.

Previous studies done by N. Katoh, M.D. Fairchild and others show that this point is somewhere between 40% to 60% relative to the display white point [2]. The resulting colors from this mixed and incomplete chromatic adaptation suffers from great discrepancies when compared to the original colors intended to be displayed. However, the results also become more dramatic when the display is installed in outdoor environment. Figure 1 shows how the lighting conditions white point, measured in correlated color temperature (CCT) in outdoors keep changing continuously from one severe state to another.

In the framework of this research, we derived a model for correction of colors displayed on outdoor LED displays. This model states that the corrected input color to the display in RGB space R_{LED},G_{LED} and B_{LED} is a function of the original target color R_T,G_T and B_T and can be expressed as below:

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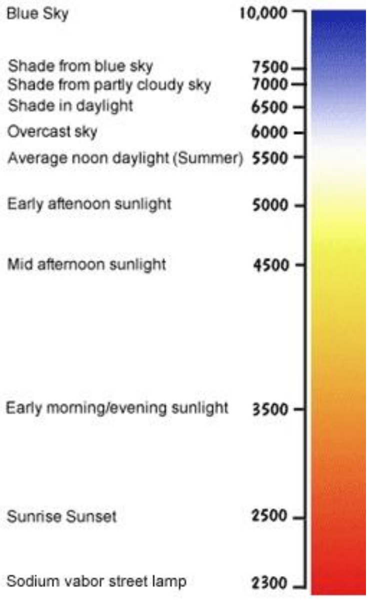

Fig. 1: Ambient white point in CCT through the day

$$\begin{bmatrix} R_{LED} \\ G_{LED} \\ B_{LED} \end{bmatrix} = \eta \cdot \begin{bmatrix} R_T \\ G_T \\ B_T \end{bmatrix} \tag{1}$$

where η is the correction matrix calculated as:

$$\eta = \beta_{LED}^{-1} \cdot M_{CAT02}^{-1} \cdot \begin{bmatrix} L''_{n(LED)} & 0 & 0 \\ 0 & M''_{n(LED)} & 0 \\ 0 & 0 & S''_{n(LED)} \end{bmatrix} \cdot M_{CAT02} \cdot \beta_{LED} \tag{2}$$

and β_{LED} is the device dependent transfer matrix from the RGB to XYZ space for that LED display. β_{LED} is calculated through the LED display characterization process, M_{CAT02} is the chromatic adaptation matrix used in the CIECAM02 color appearance model and $L''_{n(LED)}$, $M''_{n(LED)}$ and $S''_{n(LED)}$ are the cone signals of the intermediate adapted white point between the ambient white and the LED display. Since both β_{LED} and M_{CAT02} are constant matrices, equation 1 corrects the input colors to be displayed depending only on the adapted white point. In the following, we introduce a real-time system for outdoor LED displays color correction based on the above equations.

2. Analysis of Model Parameters

The algorithm for color adaptation is based on the following input parameters included in equation 2 and listed in Table 1 below:

Table 1: Model Input Parameters

X_{LED}, Y_{LED} and Z_{LED}	Original color stimulus desired for output by the LED display
X_{AMB},Y_{AMB} and Z_{AMB}	Ambient light color stimulus
K_x, K_y, and K_z	Reflectance factors of the LED display surface
$Y'_{n(LED)}$	The absolute (nominal) luminance of the display white point
L_A	The LED display adapting field luminance in cd/m^2
R_{adp}	Adaptation factor to the white point of the LED display

The parameters X_{LED}, Y_{LED} and Z_{LED} can be calculated from the LED display RGB input by linear transfer matrix β_{LED}. Ambient lighting components X_{AMB}, Y_{AMB} and Z_{AMB} can be obtained by direct measurements form the display location. Kx, Ky, and Kz are device dependant constants that can be obtained by measurements from display surface. $Y'_{n(LED)}$ is a constant parameter of each LED display. L_{AMB} can be measured or calculated from Y_{AMB} depending on screen position. Finally the adaptation factor R_{adp} is a constant whose value depends on the average time the observers will focus their retina to the screen area, as the adaptation degree increases with the display exposure time as showed in Figure 2.

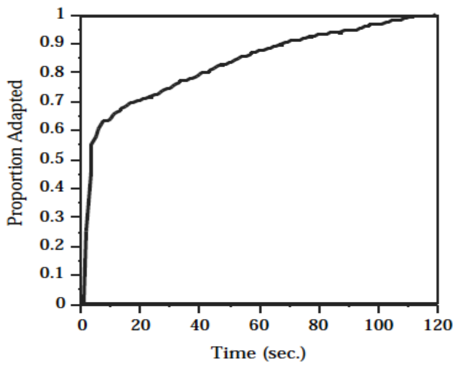

Fig. 2: Time course of chromatic adaptation [3]

Hence we can consider this phenomenon to be directly depending on screen installation nature. The intermediate calculated model variables are:

- $R_T G_T B_T$ is the desired Target color intended to be realized from the LED display as obtained from the displayed media RGB stream. This input is mainly in the CRT color space. Most modern LED displays use a linear color space conversion matrix α (3x3 matrix) to transfer these values into LED color space, noting that LED color space gamut is much wider than the limited CRT's color gamut.
- β_{LED} is a 3x3 conversion matrix from $(RGB)_{LED}$ color space to XYZ color space. β_{LED} is a device dependent matrix calculated in the factory for each LED display by the arithmetic mean values measured for many display points.
- Adapted white point $L''_{n(LED)}$, $M''_{n(LED)}$ and $S''_{n(LED)}$ is calculated from forward model input parameters listed in table 1. The adapted white point depends mainly on the ambient lighting conditions and the relation between the installed display and light sources. Time analysis of its value shows the slow changing nature of these variables under assumption that the average exposure time of most observers is range limited, which is directly related to the display installation geographical properties.

Based on the above analysis we are now able to construct an adaptive system that recalculates the display colors in real time for much accurate color appearance.

3. Adaptive Color Correction System

In order to achieve the real time nature of the system with smallest delay possible in calculations, we divided the system in two parallel dataflow paths namely: a) η calculations b) R_{LED},G_{LED} and B_{LED} calculations. This allows us to exclude the slow varying η from the real time data path. This is a crucial requirement to our system if we take into consideration that most modern LED displays use an RGB data throughput of more than 200MB/s while η may stay constant for more than 30 minutes at day time. Based on this we divided the system into two subsystems namely A and B, in which subsystem B is mainly a real time multiplier. We estimated L_A as 20% of the absolute luminance of the adapting field measured by the photometer. In addition, the value of F, the lightness contrast factor of degree of adaptation in the CIECAM02 standard [2] was substituted as:

$$F = \begin{Bmatrix} 1.0 @ {}^{L_A}\!/_{L} > 20\% \\ 0.9 @ 2\% < {}^{L_A}\!/_{L} < 20\% \\ 0.8 @ {}^{L_A}\!/_{L} < 2\% \end{Bmatrix} \tag{3}$$

Our system employs a photometer sensor to measure the display adapting field luminance in cd/m^2 needed to calculate the D factor in the CIECAM02 standard [2], and a true color XYZ color sensor to measure ambient light. Figure 3 represent our proposed system.

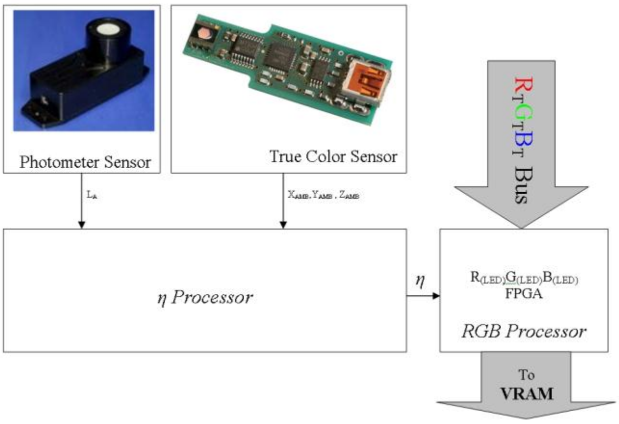

Fig. 3: System block diagram

We choosed to use MTCS-C2 true color RGB sensor. This Sensor use RGB Tri-Stimulus method, imitating the human eye's natural color perception according to DIN 5033, Part 2 – color measurement; standard solorimetric systems – CIE 1931 tri-stimulus value function. We used pre-calibrated units to CIE Illuminant D65. So the readings at noontime with CCT of 6500°K represent the nominal values of the sensor readings. The sensor board also incorporates a microcontroller unit which providedd us with the capability to integrated the X_{AMB},Y_{AMB} and Z_{AMB} calculation.

4. Experimental Work

In order to investigate the system performance we conducted a series of visual experiments. The experiments aimed to compare between original non modified image displayed on a LED display and a corrected image using our system while changing the ambient lighting condition and the value of R_{adp}.

4.1 Experiment Setup

We followed the CIE guidelines [4], the ASTM standard guide for designing and conducting visual experiments and the CIE/TC8-04 guidelines to insure experiment comparability [2]. The experiment setup was prepared as follows:

- A Long dark room with eliminated ambient light entrance.
- A 512 x 512 resolutions with 3.2mm pixel size LED display was used. The display was calibrated and characterized at a white point of 6500K CCT. The display was made using high contrast black LED elements. This LED display as most outdoor display has a very wide dynamic luminance range from 0.01 Cd/m2 to a maximum of 4800 Cd/m2 at 6500K. The LED display brightness was automatically adjusted to suit the surrounding luminance level. We adjusted the experiment images to be surrounded by 100% white proximal field of two pixels then five pixel wide (20%) uniform gray background. The Display was characterized with a Minolta CS-1000 spectroradiometer normal to the screen at 0° viewing angle. The resulting matrix has average error of characterization for the Macbeth colorchecker of 0.62 ± 0.53 ΔE^*_{ab}. With maximum error of 1.84 ΔE^*_{ab}. The display luminance was set to equal L_A using the reading from the photometer sensor.
- Observer seat located 12 meters away form the LED display to suit the display pixel density. In order to avoid viewing angle dependency which is evident on the display at off-axis viewing angles, the experimental arrangement were prepared to forces observers to view a limited region of the front area at angles very near to 10° (θ =10°) by the use of binocular limiter.
- Two digital sensors were used to measure ambient color conditions and photometer to measure the adapting field luminance. The two sensors were carefully positioned by setting the photometer just above the display and the color meter is placed behind the observer to measure ambient light.
- For the matching target, we used a color sheet image as a hardcopy with area 73x73cm (similar to displayed area). The hardcopy was printed using characterized and calibrated HP L65500 printer. The hardcopy were placed attached beside the LED display but can be moved around the display as asked by the observer.
- For the ambient lighting, we used a high power controlled lighting utilizing ten units of 290W LED lamp arrays. Each of these lamps has three controllable CCT modes namely 2300°K, 5000°K and 6500°K used to simulate different ambient lighting conditions. As originally designed to be used in street lighting, the setup configuration of lamp arrays inside the room was powerful enough to achieve a maximum illuminance level of 18600 Lux when measured behind the observer seat at one meter above ground level. In addition, it can be dimmed down to 0.5 Lux. This was crucial to simulate outdoor environment inside the experiment area. The lamps were installed in a manner that inhibits them from being visible by the observer and eliminates casting shadows or glare from the display or hardcopy surface.
- A Remote consol notebook was used to manage the experiment operation with a three keys mouse device used by the observer for scrolling the test images and confirm selections.

In this experiment twenty normal color vision observers, 12 females and 8 male, ages ranging from 17 to 22 years were participated. Figure 4 shows the experiment setup used. Before conducting the experiments, a set of trials were made to judge the best distance L (to match CIE 10° observer) and watching time needed. The results obtained from trials lead us to limit the range of R_{adp} from 0.4 to 0.6 in order to minimize the running cycles.

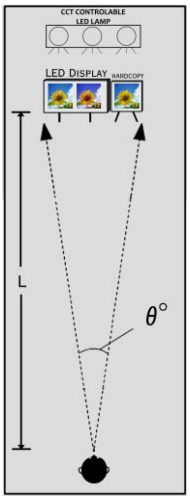

Fig. 4: Experimental Setup

4.2 Experiment Procedure

The aim of this experiment was to determine the best value of R_{adp} to suit our LED display. As most previous experiments showed that the best R_{adp} value range from 0.4 to 0.6 we limited our trials on this experiment to this range to minimize the running cycles. The ambient lighting was adjusted in each phase of the experiment until we achieved average illuminance of 10000 Lux when measured behind the observer seat. This is similar to a normal day in the winter-time. This experiment was carried on three phases with 2300°K, 5000°K or 6500°K CCT selected. A group of four images shown in Figure 5 were used in the experiments plus the color checker (2005 model). There were no problems concerning the color gamut, as the LED display color gamut is much wider than the hardcopies. The images combined to form six pairs with random order. The observer could ask to move the hardcopy up or down as he/she desired, but not over the screen next to the softcopy image. In this way, the observer had to move his eyes at some distances for the image comparisons.

Fig. 5: Pictures used in the experiments

No time restrictions were given to the observer. We used Thurstone's law of comparative judgment in converting ordinal-scale visual decisions to interval psychophysical scale. Using Thurstone's law case V the average results are calculated using 95% confidence interval limited by:

$$\mu \pm \frac{1.96\sigma}{\sqrt{N}} \tag{4}$$

where μ is the result mean value, *N* is the number of observations for each pair and σ is the standard deviation.

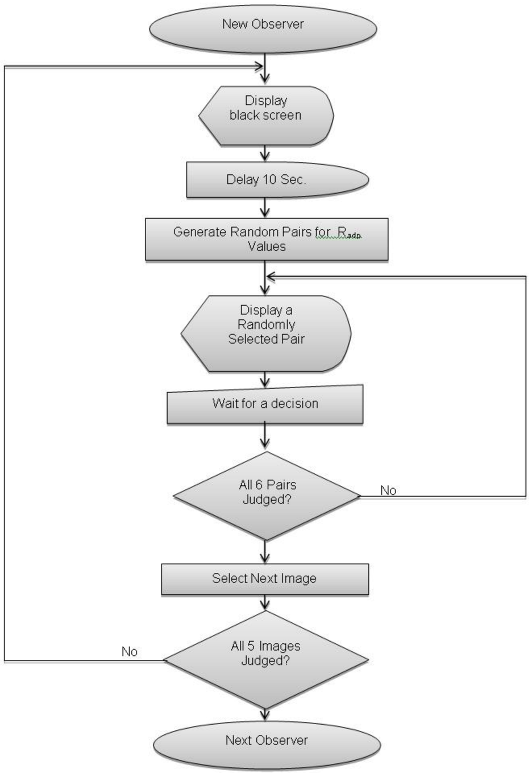

Fig. 6: Flowchart for each phase of the experiments

Each phase was repeated five times with each of the testing images and the color checker. The observers were asked to use the mouse device to scroll the display and to select one image out of the reproduced images pair as follows, with only one pair of images being displayed at a time, as many times as he/she wished:

- Original non-modified image.
- Reproduced image with R_{adp} set to 0.40
- Reproduced image with R_{adp} set to 0.50
- Reproduced image with R_{adp} set to 0.60

The order of the regenerated images pairs was randomly changed with each image. A black screen was shown between the scrolling for ten seconds and the observer was asked to remove their focus from the display to avoid any memory effect. Then he/she selects the better matching image. Figure 6 shows a flowchart for each phase of this experiment. In the following, we show the interval scale values calculated from the paired comparison data according to the Law of Comparative Judgment were we used Thurstone's law of comparative judgment in converting ordinal-scale visual decisions to the interval psychophysical scale. Thurstone's Case V scaling model was applied when converting to Z-score with 95% confidence intervals. The used images were denoted Color Checker, Surfing, Swan, Fruits and Sunflower.

5. Results and Discussions

5.1 2300°K Ambient Condition

This very warm ambient lighting condition simulates dawn and sunset times and lighting condition at night when the street light is a sodium-vapor lamp. The average results of the five images are shown in Figure 7 below. These results show clearly a significant improvement in the adapted images compared to the original non-modified one. This experiment results confirm the past results obtained by TC8-4 and Katoh [2][5] in their work with CRT and LCD monitors. The closest modified image obtained at adaptation ratio R_{adp} set to 0.6 , i.e. the HVS is 60% adapted to the LED display and 40% to the ambient lighting condition.

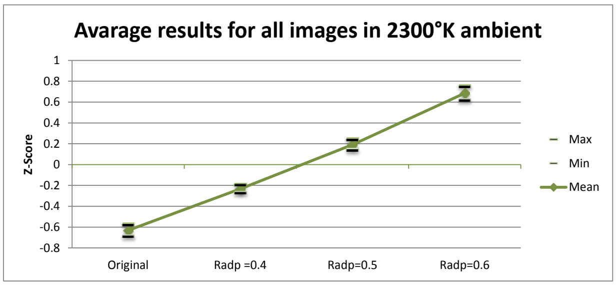

Fig. 7 Average results for all images in 2300°K Ambient

The resulting average score was matching what we predicted as the HVS has enough time for the adaptation process to be completed. We obtained a continuous enhancing in the resulting regenerated image score as the value of R_{adp} increased. However, we found the average score varies from one image to another based on the presence of saturated colors in each image.

5.2 5000°K Ambient Condition

This condition simulates normal daytime or standard D50 light source. Figure 8 shows the average results for the five images under the 5000°K CCT lamp. As the light source of 5000°K CCT is near ideal source for color rendering, we notice less improvements in the obtained Z scores, as the adapted images colors appear more close to the original hard copy. Again, the results showed noticeable variation in the Z-score with each image, which implies that the image contents also affects the adaptation state of HVS.

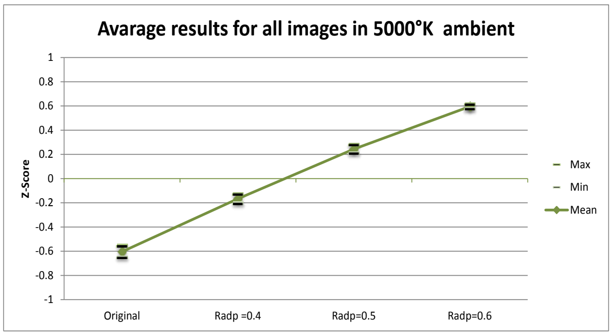

Fig. 8 Average results for all images in 5000°K Ambient

5.3 6500°K Ambient Condition

The bright white LED lamp arrays we used simulated the daylight source. As the display white point was calibrated at 6500K CCT, we expected that the generated images would be close to hardcopy original with minimum modifications with no much improvement in adaptation if compared with previous results obtained under 2300K and 5000K lamps. This is due to the fact that display white point was set to 6500°K which matches the ambient environment. Figure 9 shows the average results in 6500°K Ambient.

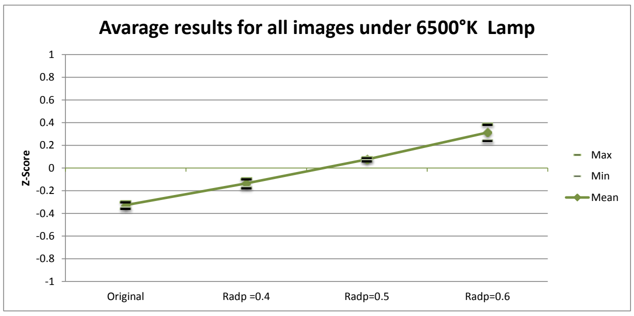

Fig. 9 Average results for all images in 6500°K Ambient

The regenerated images still have major improvement here when applying our system; however, this improvement can be justified by the correction of Hue shift and fading from the flares due to the experiment high luminance environment (Bezold-Brucke hue shift and Hunt effect). Finally, the average results for all conditions are shown together in figure 10.

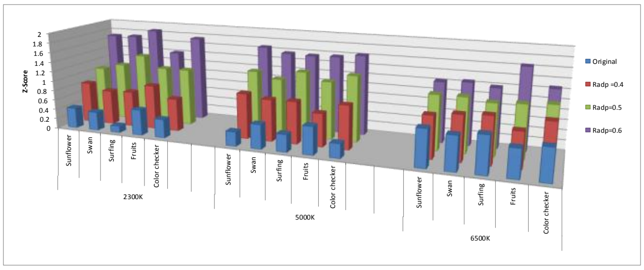

Fig. 10: Z-score results for the three testing conditions

The results obtained from the paired comparison between original raw images displayed in the ordinary manner without any processing and modified images based on our equations show significant improvement in the modified images in the three lighting conditions. The experiment investigated the performance of the model in near steady state where the observer had enough time to adapt to the LED display. The psychophysical scale results showed that the corrected images were preferred (looks more matching to an original hardcopy) over the original raw image with a Z-score varying from 0.3 to 0.7 depending on the ambient condition. Figure 11 shows the z-scale values against the ambient color temperature.

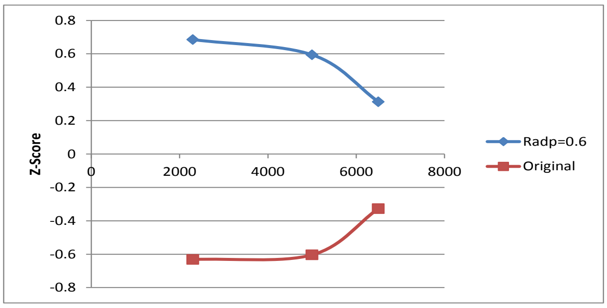

Fig. 11 Z-score for Radp and the original none modified images under deferent CCTs

The results from comparing the performance using different values for the adaptation ratio R_{adp} show that the best value for R_{adp} is 0.6 (or the observer's eyes are 60% adapted to the LED display) at our setup. This results matchs with previous experiments conducted by the TC8-4 [2], Naoya Katoh [5] and others for the effort they made concerning other technologies of self luminance displays. However we had a better results with approximately R_{adp}=0.7 when the observer seat is moved towards the display. This is understandable as the display image starts to fill the background of the observer vision. The results concerning this phenomenon are extremely important, and suggest future study to estimate the relation between R_{adp} and viewing distance and/or display size. In addition we found that when using properly calibrated true color sensor to measure ambient white point, our proposed system is capable of making great improvement dynamically on the color appearance of displayed images under varying ambient lighting conditions and taking into consideration reflection component from the display surface.

6. Conclusion

In this paper, we developed an adaptive system to correct the colors generated in outdoor LED displays. We conducted psychophysical experiments to compare corrected images using our system to non-modified images. The results showed significant improvements in the displayed colors compared to the original ones. The experimental results also confirmed that the LED display at steady state of adaptation is not different from other self-luminance displays and the HVS will be 60 % adapted to the display. Further work could be carried out for carefully examining the system performance in transient state of adaptation when the observer will have only limited time to look at the LED display in outdoor environment.

7. References

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