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Paper

Modeling of LCD Reflection Characteristics and Simulation Method of LC-displayed Images Under Daylight Conditions

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Abstract It is known, that daylight reflection on an LCD significantly degrades the visual quality and readability of a display. Methods to mitigate this problem like daylight image enhancement are mainly based on the assumption that the reflection is linearly dependent of the daylight intensity. It was found out by extensive measurements that the reflection also depends on the gray-value of a pixel and thus image contents [1]. The reflection at a white image may exceed two-times of that at a dark image. In this paper, the reflection is modelled as a function of the transmission value of a (sub)pixel and is decomposed into three parts, namely a constant part for the surface reflection, a linear term for the LC-cell and a square term for the reflection of the BLU. This refined and, regarding the daylight direction, generalized model leads to an excellent agreement with measurements.

Keywords: LC Reflection, Readability, Legibility, Sunlight Compensation, Daylight Compensation.

1. Introduction

Daylight, particularly strong sunlight, causes various effects on displays which significantly deteriorate the image quality of a display.

Direct sunlight or bright ambient light may cause e.g. glare on the display, reduce the legibility and since legibility is a necessary prerequisite for readability also affect readability. This can usually be mitigated by using anti-glare coatings on the screen or positioning the display in a way that minimizes the amount of direct sunlight or bright light that falls on it.

High luminance of daylight can also reduce the contrast of the display, making it harder to distinguish between different shades of color. This can be addressed e.g. straightforwardly by increasing the maximum backlight brightness and using ambient light sensors to adjust the display brightness automatically to the environment. Other techniques for improving overall appearance of images in daylight conditions may also be required to address this issue. Tone mapping, color correction and calibration techniques can be used to adjust the color gamut and color temperature of the display to compensate the effects of daylight on displays [2].

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There exist multiple requirements, standards and certifications for displays to fulfil regarding their behavior under daylight and ambient light conditions.

The IEC 62087 is e.g., a standard that sets out procedures for evaluating the visual performance properties of displays under various lighting conditions, including daylight and ambient lighting. It defines requirements such as luminance, contrast, and color accuracy and offers guidance on measuring tactics and how to evaluate display performance under various lighting conditions.

The VESA Display HDR standard is a certification program that rates the performance of displays based on their ability to display HDR content in various lighting conditions. The certification requirements for peak brightness, contrast, and color gamut which are evaluated under different lighting conditions, including daylight and ambient light. Other organizations, such as SID, also provide guidelines and recommendations for display performance under various lighting conditions.

Speaking in general, display manufacturers have an essential interest in satisfying these standards, not only to ensure a high quality of their products, but also to serve markets where displays will be safety relevant devices.

In the case of automotive applications, daylight can have a significant impact on the readability of safety-relevant information. As mentioned before, it can affect among others the contrast, visibility, and color accuracy of the information and therefor may cause severe problems [3][4].

Similar standards and guidelines from the International Organization for Standardization (ISO), the Society of Automotive Engineers (SAE) and the Automotive Industry Action Group (AIAG) exist therefor for automotive displays. To mention a few, ISO 15008:2017 specifies visual performance requirements for luminance, color, contrast and reflection under varying lighting conditions, including low-light and daylight conditions for automotive displays. ISO 9241-303:2011 specifies e.g. requirements for visual ergonomics in automotive displays on factors like display layout, text legibility and contrast, which can also affect readability under daylight. Further guidance can be found in ISO 9241-307:2008, that covers topics as display layout, text legibility, icon design or color coding.

Overall, there are a multitude of independent hardware and design related parameters, where each of them might have an impact on certification processes for different standards. The readability of safety-relevant information on automotive displays under different lighting conditions is critical for driver and passenger safety and should be safeguarded for many ambient conditions. It is therefore recommended for display designers, to consider the impact of daylight and ambient light on display performance, especially for HMIs that make use of a full range of gray values (gv) and which have safety-relevant content.

So far, impacts of design changes have to be measured physically. This comes not only with a certain time commitment, it also binds resources and may also deliver measures with a large measurement inaccuracy for critical parameters as e.g. local contrast, particularly for content, that makes use of a continuous gray-value range. A reflection model might therefore speed up the complete design process, e.g. of HMIs, by eliminating the necessity for some interim measurement steps, leading to a more efficient design processes. A reflection model might also improve the development of daylight image enhancement techniques for displays [5][6]. Thus, the physical aspects of daylight reflection on LCDs will be highlighted by analyzing the physical structure of an LCD Display and identifying reflection sources and, driven by this understanding, a gray value depended reflection model will be derived and applied to an automotive display.

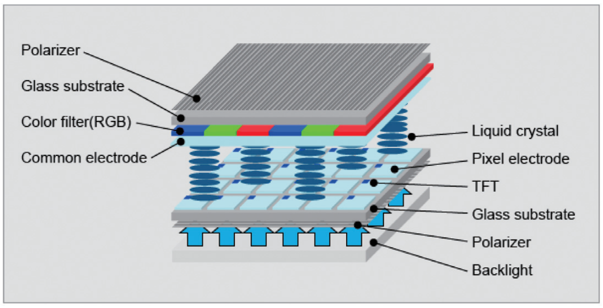

Fig. 1 TFT LCD structure (j-display.com).

2. Daylight Reflection on LCDs

An LCD consists of an LED backlight unit (BLU) and an LC-Panel. An exemplary embodiment is shown in fig. 1. Both in turn consist of individual layers which serve different functions.

At the bottom of a (direct-lit) BLU one can find an LED matrix, as a light source. The reflector is located above the LEDs and helps to direct the emitted light towards the observer. The light passes a diffuser layer, which helps to scatter, spread and distribute the emitted light evenly across the surface of the display.

The light passes subsequently the light guide layer and additionally several optical layers, like brightness enhancement layers, polarizing layers, or remote phosphor sheets, before it enters the LC panel. There it usually has to pass polarizers, glass substrates, a color filter, an LC layer and an alignment layer, until it reaches the observer in front of the display.

Overall, this stack consists of a number of functional sheets and layers with different optical properties. They are designed with the intention to display a specific image. Nonetheless, this stack is also translucent for light, as incoming daylight, entering the stack from the opposite direction. Ambient or daylight enters the display at the LC panel surface. Different types of reflections, like specular reflection, diffuse reflection or retroreflection will occur. In addition, light waves will scatter and diffract, depending on their wavelength. Light will also partly be absorbed, leading to a change in temperature and consequently to a change of optical properties.

A multi physical simulation including raytracing might, under the condition of properly modelled optical properties of the single layers, lead to detailed simulations, but might also not be a viable solution for practical use cases. Therefore, a lumped reflection model for LCDs will be introduced in this paper, which can be used for a pixelwise simulation of an LCD under daylight conditions.

3. LC Reflection Model

When considering reflections, the relative positions of the light source, display surface and observer are relevant. In the first approach, the observer can be assumed right in front of the display. The relative position of the light source, e.g. the sun, can be described with the azimuth angle θ and the elevation ϕ. These values are illustrated in fig. 2.

Having a closer look on the reflections, that reach the observer, one can identify different modes of reflections, which will be considered below.

The first mode will be the one of specular reflections of light, that gets reflected without entering the LC layer, and thus is independent of the gray value, but proportional to the ambient light L_{AMB} and also depending on azimuth and elevation.

Its luminance Y_{CON} can be formulated to

$$Y_{CON} = f_{CON}(\theta,\phi) \cdot L_{AMB} \tag{1}$$

The proportionality to L_{AMB} is denoted as $f_{CON}\,(\theta, \phi)$.

As mentioned in the previous section, daylight that is entering the display will enter the LC panel via the cell apertures and thus a gray value dependence of the reflection will occur to some extent. In that case, one can distinguish between two cases. In the first one, the light might get reflected inside the LC layer. It is conceivable, that the liquid crystal molecules inside the layer will cause a reflection. Since the LC molecules can be considered as evenly distributed, light that gets reflected this way will pass in mean one time the LC layer which means that a gray value dependent reflection will occur in the subpixels. The luminance Y_{LC} of this reflection can be formulated as

$$Y_{LC} = \sum_{i\,\epsilon\,\{r,g,b\}} f_{i,1}(\theta,\phi,gv_i) \cdot L_{AMB} \tag{2}$$

Where

$$f_{i,1}(\theta,\phi,gv_i) \approx f_{i,1}(\theta,\phi) \cdot gv_i^{\gamma} \tag{3}$$

for each color channel $i \in \{r, g, b\}$, with the gray value $gv_i \in [0, 255]$ and display gamma γ. $f_{i,1}$ considers the linear transmission values of the r, g and b subpixels, respectively.

A substantial portion of the light will also pass the LC layer with direction to the inside of the display. The rays will interact with the inner layers and sheets of the display, follow complex path of reflections, scatterings and diffractions and got either absorbed, or eventually reversed in their direction at the reflector of the BLU and pass the LC layer again. A portion of that light will be directed to the observer. Since it passes the LC layer twice, the luminance Y_{DISP} of that portion can be modelled as

$$Y_{DISP} = \sum_{i\,\epsilon\,\{r,g,b\}} f_{i,2}(\theta,\phi,gv_i) \cdot L_{AMB} \tag{4}$$

where

$$f_{i,2}(\theta,\phi,gv_i) \approx f_{i,2}(\theta,\phi) \cdot gv_i^{2\gamma} \tag{5}$$

The reflected light will be the sum of all three terms. Hence, the reflection model consists of three parts, namely a constant, a linear and a square term, as just described.

$$Y_{REFL} = Y_{CON} + Y_{LC} + Y_{DISP} \tag{6}$$

4. Measurements of LCD Reflection

Daylight reflection on an LCD is measured in a dark room. The setup is shown in fig. 3. As a light source, a D65 illuminant with a maximum brightness of 62k lux

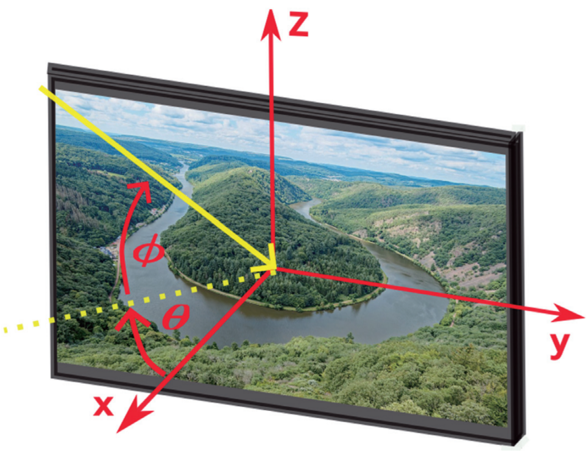

Fig. 2 Azimuth and elevation of the light source.

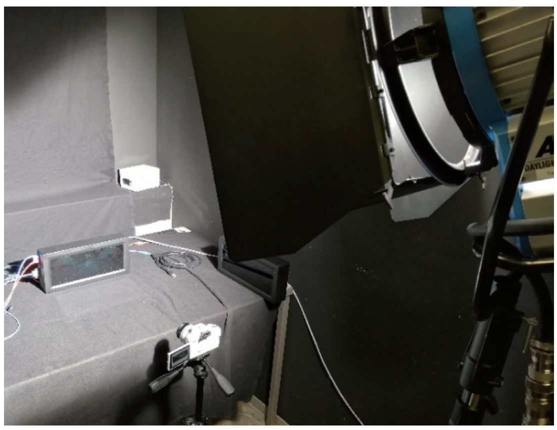

Fig. 3 Setup of LCD, daylight lamp and measurement devices.

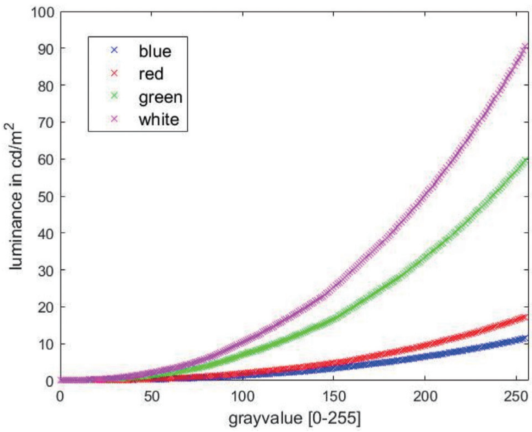

Fig. 4 LCD Luminance for uniform images, BLU on, Daylight off.

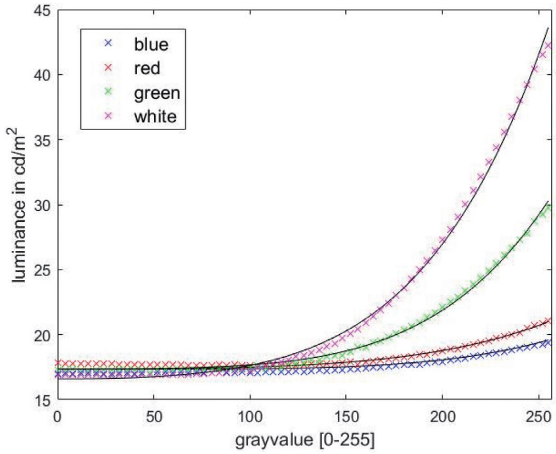

Fig. 5 Luminance for uniform images, BLU off, Daylight on.

has been placed at an azimuth and elevation of 45°/45° relative to an automotive display (12.3", 1920RGB720), to simulate a typical condition for incident light.

The display is measured by a spectroradiometer (Photo Research SpectraScan PR-740). Photographs captured by a consumer camera are used for various comparisons, both placed in front of the display at angles 0°/0°.

Multiple measurement series have been conducted for the electro-optical transfer function (EOTF) and have been analyzed. Red, green, blue and gray uniform images at varying gray values were measured for different lighting situations at fixed angle.

The results with the BLU turned on and the daylight turned off are plotted in fig. 4. The results are an expected gamma curvature with .

The reflection can be measured, with the BLU turned off, while the daylight lamp is turned on. The LCs are controlled independently with the BLU turned off. The measurement is therefore purely affected by the reflected daylight. The reflection model can be used to fit these curves. A good agreement between the measurements (crosses) and the model function (lines) is given in fig. 5. The model parameters are listed in Table 1.

Table 1 model parameters.

parameter	value
γ	2.354
f_{CON}	$2.7980 \cdot 10^{-4}$
$f_{R,1}$	$3.7935 \cdot 10^{-11}$
$f_{R,2}$	$8.5226 \cdot 10^{-16}$
$f_{G,1}$	$5.7161 \cdot 10^{-11}$
$f_{G,2}$	$8.5226 \cdot 10^{-16}$
$f_{B,1}$	$1.6823 \cdot 10^{-11}$
$f_{B,2}$	$2.3258 \cdot 10^{-17}$

It can be shown, that for small gv a major part of the reflected light is caused by the direct reflection from surface layers. An offset value of ~17.4 nits for all four measurements can be obtained. It is assumed that the slight variation of these offsets at gv = 0 is due to temperature variations during the measurements. Nevertheless, for large gv the total share of gv-dependent reflection increases significantly up to ~61% of the total reflected light (fig. 6).

The share of the reflection mechanisms on the total reflection is shown in fig. 6 for uniform gray images with gv = r = g = b. The amount of reflections from inside the LC layer (parameter $f_{i,1}$; *II in* fig. 6) is for small and medium gray values smaller by orders of magnitude compared to the reflections coming from inside the display (parameter $f_{i,2}$; *III in* fig. 6), which is to be expected, as the BLU surface is deliberately made reflective.

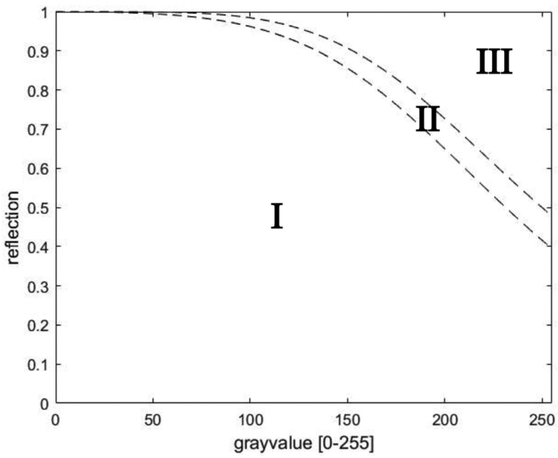

Fig. 6 Shares of reflection mechanisms (I: direct, II: LC, III: Display).

In a third series (fig. 7), both the daylight lamp and BLU are turned on. The curves of the previous measurements can be summed up to match with the

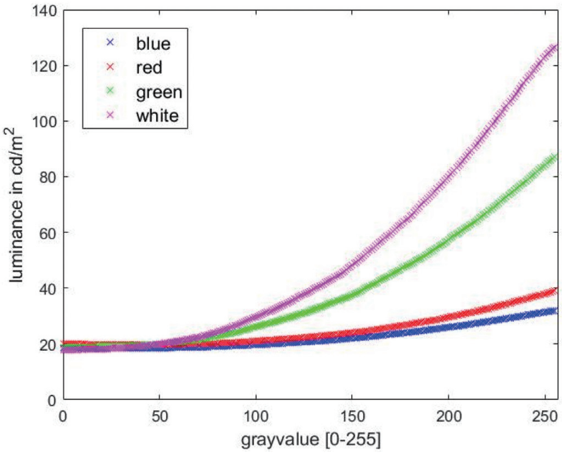

Fig. 7 Luminance for uniform images, BLU on, Daylight on.

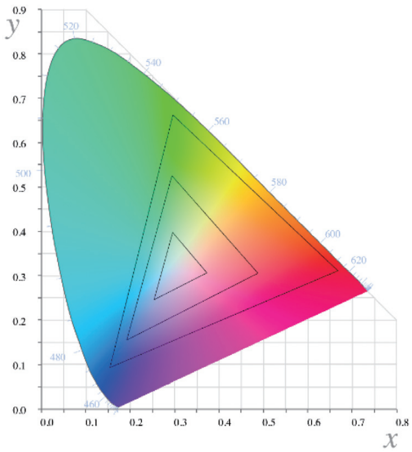

Fig. 8 Gamut comparison.

curves of the measurements in the third series shown in fig. 7. This confirms the consistency of the measurements as well as of the model.

In fig. 8, three gamut measured are depicted. The large triangle represents the native gamut of the LCD, without distortion by any reflection. The inner triangle is the gamut solely generated by the daylight reflections. The triangle in between is the gamut for the case, when daylight lamp and BLU are on, and the reflection is superposed with the initial unicolor image. This case is accordant to a real operation under daylight condition. Beyond, the shrunk gamut, the color contrast particularly for lower and median gv is diminished by the incoming daylight.

5. Simulation method of image under daylight

With the measurements in the last section, the consistency and reasonability of the proposed reflection model has been proven for a specific light source at certain angles for uniform images.

Doing so, with the obtained parameter from table XYZ, a realistic simulation of an arbitrary image under a defined lighting condition can be performed. This will help e.g. to probe a specific HMI design, whether specifications like ISO 9241 and/or ISO 15008 are fulfilled or not.

While the reflection may be assumed spatially invariant, the LCD emits pixelwise individually. The tristimulus values X, Y, Z for each pixel are

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{LCD} = Y_{BL} \cdot \begin{pmatrix} R_X & G_X & B_X \\ R_Y & G_Y & B_Y \\ R_Z & G_Z & B_Z \end{pmatrix} \cdot \begin{pmatrix} t_R \\ t_G \\ t_B \end{pmatrix} \qquad (7)$$

The matrix parametrises display properties, t_i are the normalized transmission values which depend on the gray values of the subpixels and Y_{BL} is the display brightness, e.g., 800 nits.

The formula for the calculation of the tristimulus values can be considered as a linear transformation. Thus, the tristimulus values of two superposed spectra can simply be added, to get the total tristimulus values. The observer receives the intended light, superposed with the reflection of the daylight. Therefor the observer receives

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{TOTAL} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{LCD} + \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{REFL} \qquad (8)$$

The luminance Y of the reflected light is as described and modelled. X and Z values of the reflected light can subsequently be determined. It is assumed, that the chromaticity (x, y) is unaltered at varying ambient light, as the chromaticity is fixed at D65.

The resulting total tristimulus values can be used, to calculate the simulated image. The simulated image is an image, that can be displayed without daylight, which shows how this image would be perceived under daylight. It is calculated pixelwise by inversion of equation (9) with $(X, Y, Z)_{TOTAL}$ as the input.

$$\begin{pmatrix} t'_R \\ t'_G \\ t'_B \end{pmatrix} = \frac{1}{Y_{BL}} \cdot \begin{pmatrix} R_X & G_X & B_X \\ R_Y & G_Y & B_Y \\ R_Z & G_Z & B_Z \end{pmatrix}^{-1} \cdot \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{TOTAL} \qquad (9)$$

An inverse gamma function may be applied to the transmission values t'_R, t'_G and t'_B to calculate the accordant RGB values and thus construct the perceived image under daylight.

Images that are simulated using this method and compared e.g. with images taken under daylight conditions with the consumer camera, can be expected as similar to human perception. This means that the simulation may deliver comparable results about images displayed under daylight. This may make a pixelwise luminance measurement, which is difficult and not dependable, in many cases obsolete. It may also simulate effects of daylight image enhancement method. Thus, this simulation method may be applied for various purposes like evaluation of legibility or estimation of image enhancement methods.

6. Conclusion

Three shares for reflection from an LCD have been identified. Incident light can be reflected independent of gray values in outer layers of the display, dependent of gray values inside the LC layer and from inside the display. While for low gray values the reflection is dominated by the outer layers and nearly constant, the reflection will increase from medium and higher range with the gray value of a pixel. Incoming light will be reflected by the LC layer itself and the light passing through the LC layer will be reflected by the BLU plate which is due to its nature reflectiveness. This part may exceed the reflection by the outer layers. With the understanding of the reflection mechanisms, the expected influence of the angle of incidence may be investigated in future work. The reflection model may deliver a pixelwise simulation of an image displayed under daylight. It may assist a development of more detailed image enhancement method for mitigating the quality deterioration caused by daylight.

For each subpixel, the quotients of the model are individual which may be ascribed by the property of each color filter. The model presented in this paper is based on a D65 light source. For future research, a varying color temperature shall be considered and the reflection model may be amended by further interactions.

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