Optimizing LSF Shape for Robust and Uniform Backlighting of Automotive Displays with Direct-Lit Local-Dimming

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ABSTRACT

In this paper, radial LSFs for direct-lit BLUs are modelled with three parameters and can render different shapes for a same influence. Diverse LSF shapes are analyzed in terms of robustness in production as well as power saving capabilities regarding local-dimming. Characteristic measures for an optimum shape are proposed.

1 INTRODUCTION

The demand for high visual quality is still increasing. Especially in the field of automotive displays the image quality and power saving are crucial to meet the very high requirements for valuable displays. On the other side, the costs must be low to compete against other technologies like edge-lit LC- or OLED displays.

To reach the goals, BLU design may enhance the positive effects of an appropriate local-dimming algorithm [1]. This BLUs or rather the underlying LEDs with their light-spread-function (*LSF*) should be analyzed to reach a good trade-off between robustness and power saving.

For that reason, mathematical models, like the Gaussian function or a superposition of them exist to model the shape of the LSFs and are e.g. assumed in [2] and [3]. But a lot of parameters would be needed to meet the real behavior. Therefore, in section 2 a model is proposed for modelling the LSFs for analysis. It will also be shown, that the shape, despite of a constant maximum influence, is crucial for a uniform light distribution and also for the robustness against variation in the production.

2 LSF MODEL

Due to the reasons mentioned above, a new model with just 3 parameters (*A, B, C*) was presented in [4]. It was shown, that the model can match radial light distributions very well. Fig. 1 demonstrates a real LSF as well as a fitted model. Also, the remote region is matched very accurately. This part cannot be neglected for a dependable local-dimming algorithm.

The equations 1 to 3 describe the 1-dimensional part for values ≥ 0. This model is also used for the simulations in this paper.

$$\mathrm{M}_1(x) = \frac{1+e^{-A\cdot B}}{1+e^{A\cdot(x-B)}} \text{ with } x, B \in \mathbb{R}_0^+ \wedge A \in \mathbb{R}^+ \qquad \text{Eq.1}$$

$$\mathrm{M}_2(x) = x \cdot e^{-\frac{x}{C}} \text{ with } x \in \mathbb{R}_0^+ \wedge C \in \mathbb{R}^+ \qquad \text{Eq.2}$$

$$\mathrm{M}_{\text{total}}(x) = \mathrm{M}_1(x) - \mathrm{M}_2(x) \cdot \left.\frac{d\mathrm{M}_1(x)}{dx}\right|_{x=0} \qquad \text{Eq.3}$$

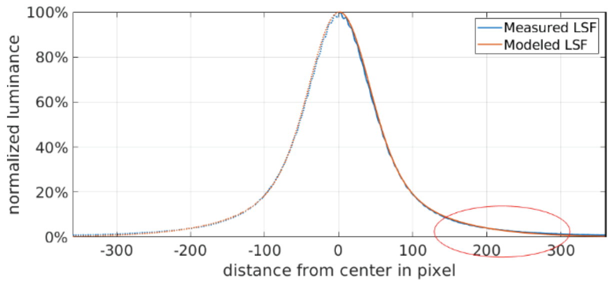

Fig. 1 Real (measured with ELDIM UMaster) and modeled LSF from [4].

3 BACKLIGHT SIMULATION

In the previous work [4] the LSF shape was analyzed for a constant Full-Width-Half-Maximum to pitch (FWHM/pitch) ratio (≈ 1.5, see also [5], [6]) as depicted in Fig. 2 on the left. An LED number of 600 was chosen for the simulation. The resulting relative light contributions (*influences*) were substantially different as well as the power saving rates despite constant FWHM.

The best tradeoff has a maximum influence of ≈ 25%-35%. It has been shown that the influence is the most crucial value of a BLU for local-dimming. Therefore, in this paper the influence will be fixed at 30%, while the width of the LSF shape will be varied.

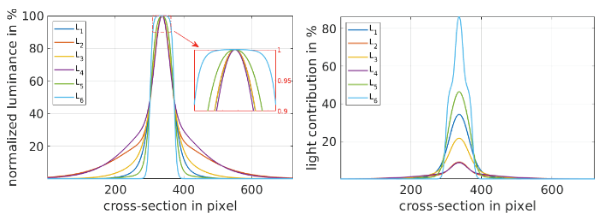

Fig. 2 Simulation from [4] with constant FWHM/Pitch ratio but different influences.

3.1 Simulation Setup

For the simulation in this paper an LED number of 9x24 = 216 is chosen for a typical 1920x720 automotive panel. This resolution is used as the underlying grid $P = \{(x,y)^T \mid x \in [0,1919] \wedge y \in [0,719]\}$ for the simulation precision. For the mentioned reason and further investigations, the maximum influence is kept constant at 30%. That means, for the center point

$(x_0, y_0)^T$ of the LSF of the $\text{LED}_{r,c}$ where r is the LED row and c is the LED column (alternatively LED_l, with l is the linearized LED number) the following equation is given:

$$\frac{\mathbf{LSF}_{r,c}(x_{0,l}, y_{0,l})}{\sum_{n=1}^{\text{nLEDs}} \mathbf{LSF}_n(x_{0,l}, y_{0,l})} = 0.3 \qquad \text{Eq.4}$$

To keep the absolute LSF shapes of the 216 LEDs identical, the influence constraint is just valid for the center of the screen. In this simulation, 6 different LSFs ($M_1$to M_6), which will be used for simulation and analysis in this paper, are selected out of the huge amount of possible solutions with the model from section 2 by selecting appropriate parameters A,B and C.

3.2 Influence of Model Parameters

The 6 LSFs are shown in Fig. 3 with a normalized luminance. They are sorted ascending according to their FWHM. For an efficient local-dimming the crosstalk must be considered [1], therefore the influence is very important and fixed according to equation 4. The influences of the 6 LSFs are shown in Fig. 4. Due to the fixed maximum influence the shapes are very similar to the shapes of normalized luminance. In this figure the constant influence is clearly visible.

In fact, this shape similarity is just observed at very far distances from the edges. It is obvious, that LEDs near display edges may have a higher influence on a certain area of the panel.

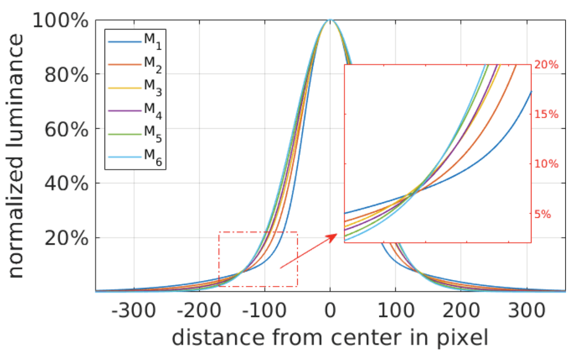

Fig. 3 Selected LSFs with different parameters.

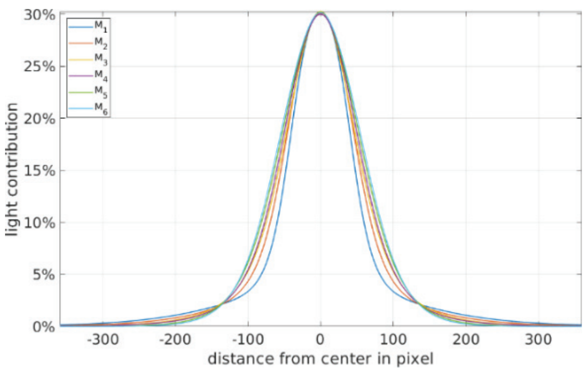

Fig. 4 Resulting influence from the absolute light distribution.

The resulting all-on backlights are depicted in Fig. 5 which are represented by $\mathbf{BL}_{\text{all}} = \sum_{n=1}^{nLEDs} \mathbf{LSF}_n$. The scale is normalized and emphasized by the Gamma function with γ = 2 for a better visualization.

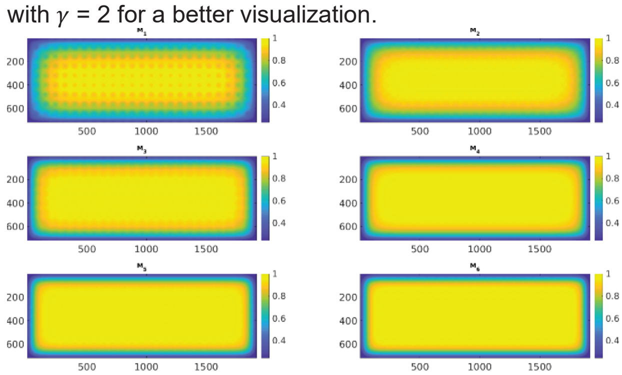

Fig. 5 Resulting all-on images in false colors.

The different uniformity can be observed directly. For uniformity measurements, different methods exist as e.g. described in [7] and can be additionally applied. In addition to the constraint of a fixed maximum influence, two non-uniformity values can be calculated to select appropriate model, namely U_1 and U_2. For the sake of simplicity let $\text{pos}(L_{r_c c_c})$ describe the position of one centrally located LED L_{central}, then

$$U_1 = \frac{\sum_{p \in Pixel} \mathbf{BL}_{\text{all}}(\text{pos}(p))}{|Pixel| \cdot \mathbf{BL}_{\text{all}}\left(\text{pos}(L_{r_c c_c})\right)} \qquad \text{Eq.6}$$

The second uniformity measure considers the fact, that for the diagonal distance between two adjacent LEDs the following inequality is true. The according measure points are visualized in Fig. 6.

$$\|\text{pos}(L_{r,c}) - \text{pos}(L_{r,c\pm1})\|_2 < \|\text{pos}(L_{r,c}) - \text{pos}(L_{r\pm1,c\pm1})\|_2 \qquad \text{Eq.7}$$

That means, that the luminance is expected to vary more on the diagonal path. For that reason, U_2 is calculated as follow

$$U_2 = \frac{\mathbf{BL}_{\text{all}}\left(\left(\text{pos}(L_{r_c-1,c_c-1}) + \text{pos}(L_{r_c,c_c})\right)/2\right)}{\mathbf{BL}_{\text{all}}\left(\text{pos}(L_{r_c,c_c})\right)} \qquad \text{Eq.8}$$

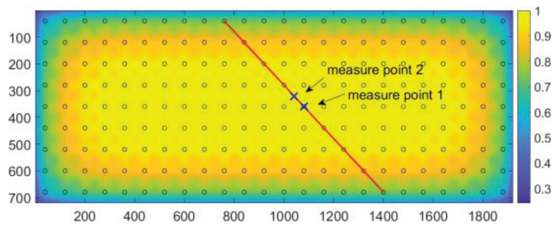

Fig. 6 Visualization of the diagonal cut and measure points for uniformity calculation.

As mentioned, the highest variation in luminance is on the diagonal line between the led center. Therefore, a diagonal cross section as indicated in Fig. 6 with the red line is plotted for every LSF selected in Fig. 7. One can observe high variation particularly for model M_1. The LED locations can easily be correlated to the oscillations of the plots. The higher the FWHM/pitch ratio (r_{50}), the more uniform the results look like. M_4 to M_6 result in a uniform backlight. Next the different shapes are evaluated for robustness in production.

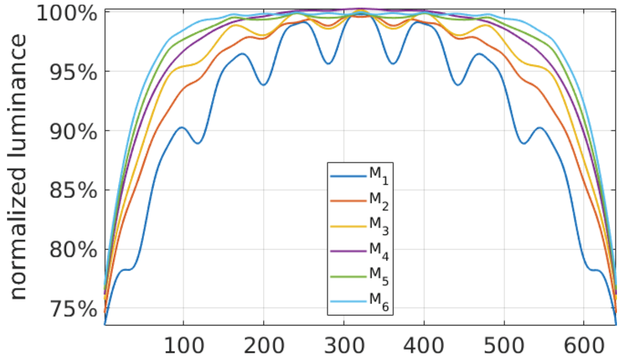

Fig. 7 Diagonal cross-sections through the all-on of the six LSFs.

4 ROBUSTNESS CONSIDERATIONS

During the production process, e.g. assembling, soldering etc. some inaccuracies may be introduced. So, the LED position may not be 100% exact. Also, the LSF can vary due to some imperfections in diffusor or LED mounting. The ability to produce uniform backlight despite of the mentioned inaccuracies in this context is called as *robustness*. First the LED misplacement is investigated.

4.1 Impact of Inaccurate LED Placement

The aspect of possible deviation of the LED position compared to the optimal grid shall be considered. This LED position variation is called as position *jitter*. A random jitter of $\pm 4\%$ of the LED pitch is imposed to the 6 BLUs. One exemplary result is demonstrated in Fig. 8 for M_2 and M_4.

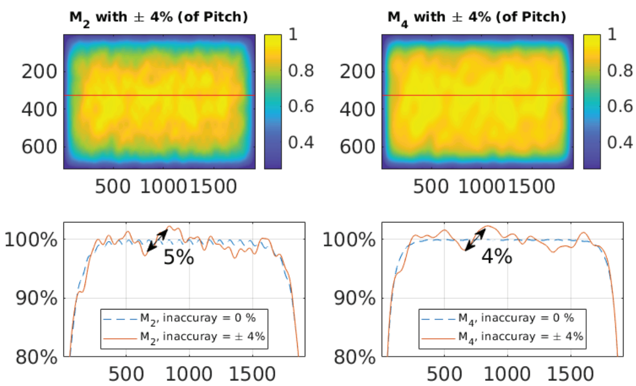

Fig. 8 Impact of inaccurate LED placement on uniformity with random jitter.

On the upper images the resulting all on backlights are shown with the same LED placement. Visually the right backlight looks more uniform compared to the left. Also, the peak-peak deviations on the cross sections is lower for M_4. So, the impact of the jitter is different for different LSFs.

The human eye is very sensitive to high contrast deviation. Therefore, the mean gradients of the deviations ($\bar{G}$) resulting from the inaccurate LED placement are analyzed and calculated as described in the following:

$$\mathbf{BL}_{\mathrm{dev}}^{\mathrm{rel}}(x,y) = \frac{\mathbf{BL}_{\mathrm{all}}^{\pm 4\%}(x,y)}{\mathbf{BL}_{\mathrm{all}}(x,y)} - 1, \forall\, (x,y)^T \in P \qquad \text{Eq.9}$$

In addition, the mean deviation to the corresponding backlight is denoted as $\bar{D}$ (blue line) and is depicted together with $\bar{G}$ (red line) in Fig. 9. It can be stated, that the values $\bar{G}$ and $\bar{D}$ are still decreasing for bigger FWHM/pitch ratios (r_{50})

$$\bar{G} = \frac{\sum_{(x,y)\in P}\left(\left|\frac{\partial}{\partial x}\mathbf{BL}_{\mathrm{dev}}^{\mathrm{rel}}(x,y)\right| + \left|\frac{\partial}{\partial y}\mathbf{BL}_{\mathrm{dev}}^{\mathrm{rel}}(x,y)\right|\right)}{|P|} \qquad \text{Eq.10}$$

$$\bar{D} = \frac{\sum_{(x,y)\in P}\left|\mathbf{BL}_{\mathrm{dev}}^{\mathrm{rel}}(x,y)\right|}{|P|} \qquad \text{Eq.11}$$

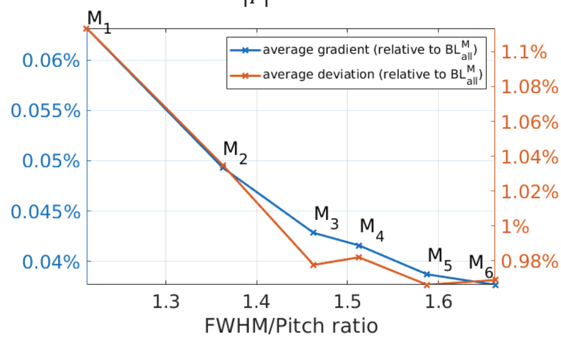

Fig. 9 FWHM/Pitch ratio vs. $\bar{D}$ (red) and $\bar{G}$ (blue).

For the human perception and quality, a low $\bar{G}$ leads to a less disturbing appearance of the backlight. Next, the impact of the variation of the LSF shape is analyzed.

4.2 Impact of LSF Shape Variation

In addition to LED positions jitter, the shape itself may be distorted by different impacts. This effect is demonstrated in Fig. 10. This behavior is modelled by adapt the model parameter B by a small percentage. This results in slightly changes of r_{50} and a small change in the tail of the models.

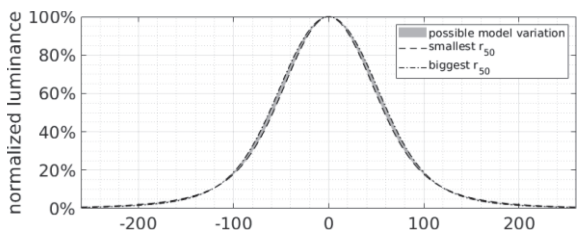

Fig. 10 Simulated model shape variations for M_6.

One random jitter is applied to the models M_4 to M_6 which results in the left images of Fig. 11. In these examples, the most uniform model M_6 seems to be the most prone to this kind of shape variation of the LSF. On the right plot, the relative deviations according Eq.9 are plotted for the vertical cross sections indicated on the left images.

This example demonstrates the impact of slight LSF shape changes on the uniformity. To generate the above random deviations, the parameter B of the LSFs is varied as depicted in Fig. 12. For each LSF, the parameter is changed in a relative fashion and not as an absolute value. The y-axis shows the sum of absolute deviations of the whole backlight for the different LSFs (analog to Eq.11). For this kind of variation, the value r_{50} is not correlated to the average deviation.

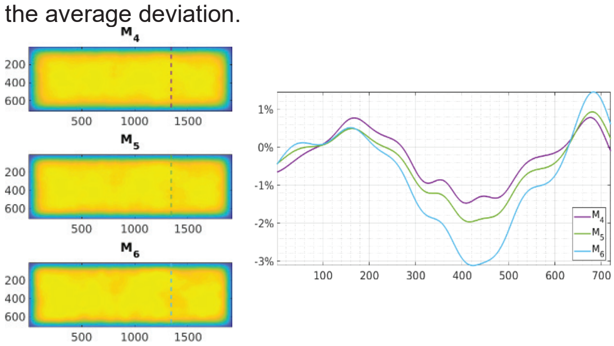

Fig. 11 Impact of variation of the LSFs on the uniformity and relative deviations to the corresponding backlight.

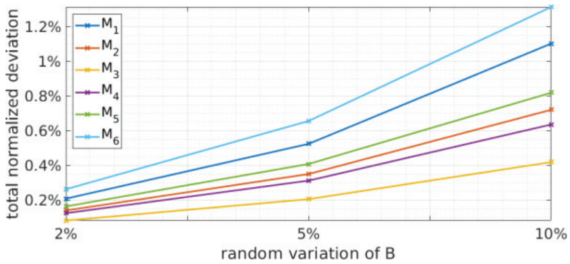

Fig. 12 Averaged deviation vs. the variation of the LSF.

5 RESULTS AND CONCLUSIONS

In this paper, the LSF of a direct-lit BLU is analyzed with the introduced LSF model with just 3 parameters. The influence was kept constant for this analysis. Additionally, the impact of LSF shape on *robustness* has been simulated. The maximum influence of an LED was kept at 30% for all models.

To estimate the efficiency regarding power saving, the SSC algorithm [1] was applied for an automotive testset based on 6 LSFs. The results are depicted in Fig. 13. The different colored lines are induced by adaption of the algorithm to different hardware complexity as described in [5] for efficient crosstalk modelling during the LED optimization process.

It can be stated, that for LSF with the same maximum influence and smaller r_{50} values, the power saving rate is slightly lower and differs for the different SSC adaption. For higher r_{50} the results are very similar and therefore, the hardware costs can be kept low. Thus, in combination with the results from [4], for a constant maximum influence, the r_{50} can be selected higher, for an efficient local-dimming and a uniform backlight. To achieve also a high robustness against production variations, the LSF shape shall be considered, too.

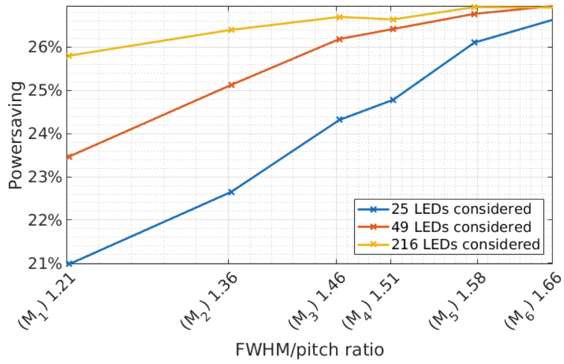

Fig. 13 Powersaving vs. FWHM/pitch ratio.

Based on the analysis in this and a previous paper [4], it is recommended that the LSF shall have a maximum influence at ca. 30% and a r_{50} of ≥ 1.5. A high uniformity, robustness against variation in production as well as good local-dimming results can be achieved.

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