Optimal Real-time Digitization of Matrix-Headlights

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Abstract— This contribution discusses and compares different approaches and quality criteria for real-time digitization of automotive matrix-headlights. The digitization method enables hardware-in-the-loop evaluations of high-resolution lighting functions in the lighting laboratory at any time of day in real time to reduce the duration of real night test drives. The transformation of illumination to the virtual environment must be as fast and "accurate" as possible. This contribution presents a physics-based transformation strategy and compares different optimal parameterizations for different quality criteria for the image processing system. The scientific goal of this contribution is to define a numerical quantitative criterion for an "accurate" transformation. From the presented evaluation of the digitization of a real headlamp, an optimal quality criterion is derived, which can be used for the automatic calibration of the test bench and the optimization of the digitization process.

I. INTRODUCTION

Modern automotive matrix-headlights consist of many (up to over one million) individual light sources, also called pixels, arranged in a matrix [1], [2]. The headlamp control unit adjusts the individual light intensities of each pixel to adjust illumination to the current traffic situation, maximizing driver perception. The Individual control of the pixels enables lighting functions such as Glare-Free High Beam (GFHB), which minimizes glare for other road users by simply switching off parts of the light distribution. As the number of pixels or resolution increases, other adaptive lighting functions such as projecting symbols in front of the car become possible and allowing the car to communicate with its surroundings. A high-resolution headlight that behaves like a projector with this functionality is also called a pixel headlight or digital headlight.

The disadvantage of better adaptation quality with higher resolution is usually higher system complexity. This leads to an increasing number of error sources and optimization possibilities. To manage system complexity, more and longer tests are needed to ensure functionality. To make the evaluation of real hardware independent of time, of day, and of weather conditions a real-time Hardware-in-the-Loop (HiL) simulation has been presented in previous contributions [3]–[5]. The real-time capability is important for the HiL system to allow manual test drives with customers rather than simply showing them a video. The basic idea is to use an image processing system to measure the illumination of the matrix-headlamp in real time. A virtual light source loads the measured intensity distribution as its beam pattern to illuminate the virtual world as a real headlight would. Fig. 1 represents the entire HiL test bench, which is described in detail in the following chapter.

The previous contribution [3] presents the general approach and a possible calibration, but the transformation approach and quality criteria shown have a few drawbacks. The main problems are the failure to account for physical reflection laws, the use of a "weak" cost function (insensitive to some effects), and the empirical determination of the weights of the error function. The first and third problems may be small errors, but the second may result in a misaligned system requiring manual correction. For example, a mismatch between the origin of the real headlight and its virtual representation may not be detected in the previous contribution. This leads to longer setup times of the test stand and possible evaluation errors. Automated calibration and optimization of the test stand was therefore not possible.

In this contribution the presented problems are discussed and solutions are presented. This leads to a fully automatic calibration process of the image processing and the virtual light source by minimizing a "stronger" cost function (sensitive to all relevant effects) than in [3]. The transformation approach has been revised to be more physically based. The overall performance of the digitization was improved as the Root Mean Squared Error (RMSE) of the real-time digitization was reduced from $\approx 2.3\%$ [3], [4] to $\approx 1.6\%$ of the measurement range with the revised transformation without significant additional computation time and with the same number of parameters. The following chapter summarizes the real-time digitization method. In the next chapter, the major sources of error in digitization are presented and the physics-based transformation approach is developed to address the problems. Different quality criteria for digitization are presented and compared in theory in the next chapter. The final evaluation chapter uses the digitization of a real matrix-headlamp with 84 pixels to compare the approaches and quality criteria on a real device and gives hints for the optimal practical use of the HiL system.
II. HIL-SIMULATION WITH REAL-TIME DIGITIZATION

The basic idea of the real-time HiL evaluation of a matrix-headlamp is to control the Device Under Test (DUT) from a simulation and feedback the illumination as quickly and accurately as possible to the same virtual environment. The feedback is provided by a camera system that indirectly captures the illumination on a projection surface. An image processing system calculates from the color image $I_c \in \mathbb{R}^{r_u \times r_v \times 3}$ the intensity distribution $I_v \in \mathbb{R}^{r_u \times r_v \times 3}$, which contains the color information in 3 channels [3]–[5]. The number of pixels of the camera in both $u$, $v$ directions is respectively $r_u, r_v$. All operations in this contribution are performed in the same way for all color channels, so for simplicity the images are shown as grayscale (single channel) images. With the number of bits of the camera $n$, the range of a single element of $I_c$ is $I_c(u, v) \in [0, 2^n - 1]$. To archive real-time performance the computation is performed in parallel for each Texture-Element (texel) of the image on a GPU. The individual elements of the image are called texels in this contribution to distinguish them from the Picture-Element (pixel) of the spotlight and in accordance with Projective Texture Mapping [6], [7] for illumination simulation. In this method [8], the simulation engine calculates the illuminance $E_v$ from the digitized luminous intensities $I_v$ and the luminance $L_v$ from the illuminance using a material model [9]. The result is visualized to the user of the HiL system as shown in fig. 1. The simulation also generates the virtual sensor data (e.g., position and size of road users), from which the headlamp control unit generates the control data (e.g., the dimming values of the pixels) for the headlamp in order to adjust the illumination optimally to the current traffic situation. The main system components of the HiL test bench are shown in fig. 2.

![Fig. 2: Overview of the system components and signals of the HiL test bench. The parts that operate online during the HiL test are highlighted in green.](image)

The simulated illuminance $E_v$ is sent to an optimization and calibration unit, which compares it to a reference distribution $E_v, Ref$ to determine the error of the visualization. An automatic calibration process attempts to minimize this error by adjusting the system parameters. By inverting the simulation rule based on the photometric distance law, often called the inverse square law, the intensity distribution $I_v$ can be calculated from the simulated $E_v$ using the distance $d$ between the light origin and the object and the angle $\alpha$ between the beam direction of the light and the surface normal

$$I_v = E_v \frac{d^2}{\cos(\alpha)}.$$  

Thus, calibration process finds the optimal system parameters $x$ by minimizing an error function $f(x)$ that compares the digitized intensities with the reference intensities. A possible source for a reference is a goniophotometer that does not measure in real time the beam path of the matrix-headlamp just outside its photometric limit distance. Then the headlamp can be assumed to be a point light and the reference data is a valid source for the virtual point light used by Projective Texture Mapping. The goal of the digitization process is to achieve the same visual quality in real time as the non-real time reference measurement. The main problem is to describe the visual quality as a reliable number, which will be discussed in the following chapters.

III. PHYSICALLY BASED DIGITIZATION

The camera system measures the current illumination indirectly by capturing the illumination on a projection surface. This is shown in fig. 3. The advantage of the method is that the resulting intensities $I_v$ have the correct flat format with the two dimensions $u, v$ to be used directly in Projective Texture Mapping. No conversion from spherical coordinates is required.

![Fig. 3: Illumination of the headlamp on a projection surface.](image)

The digitization has four main sources of error, which motivates the presented transformation strategy:

- Interference Environment Illumination: The projected beam pattern may be directly or indirectly illuminated by interfering light sources. This leads to an incorrect beam pattern in shape and brightness. Possible solutions are to completely darken the room and to use a screen with a gain below one, which absorbs low levels of spurious illumination.
- Reflective Properties: For an ideal diffuse reflective surface, the luminance is independent of the observer’s viewing angle according to Lambert’s cosine law [10]. In this ideal case the intensity can in principle be reconstructed via (1). A real surface has reflections depending on the viewing angle (specular) and can absorb parts of the illumination, so a simple inversion of the distance law leads to errors. A model of the surface is needed to calculate the reflection.
- Discretization Steps and Noise of the Camera: These hardware parameters affect the differentiation of different brightness levels and the visibility of dark structures in the image. They also have a direct influence on the external shape of the light distribution.
- Frozen Superposition: Since a matrix-headlight consists of many small light sources (pixel), its illumination does not...
have a single point origin. For this reason, the appearance of the ray patterns varies with the distance \( d \) between the headlamp and the screen more than a simple scaling of size. Inhomogeneities such as groove darkening at the edges or yellow and blue color changes due to chromatic aberration vary with distance. The reason for this is a variable overlap of the individual illuminations of the pixels, which changes with the distance. The projection screen freezes these overlaps so that the simulated beam spread, which is based on the shape on the screen and it deviates from reality.

One approach to correct these errors is to use look-up tables [11] for the correction parameters. These parameters like factor and offset for each texel and intensity value can be determined by minimizing an error function. The advantage is that the errors can be reduced to zero for at least one reference image. The disadvantages are the required memory and possible difficulties in interpreting and adjusting the correction if the result is not satisfactory, which is caused by the large number of parameters.

The abstract quality criterion for the HiL simulation is that the lighting in reality and in the simulations "looks and feels" the same and has the same visual expression. What this means for the digitization process is that the intensity distributions of the digitization and the reference must be exactly the same. If it is not possible for both distributions to be the same, which in reality is often caused by the sources of error shown, the decision must be made as to which important aspects of "good" illumination are preferentially optimized. The choice is very subjective and dependent on the evaluation scenario, so that a transformation without the possibility of manual traceable adjustment can lead to problems in the application.

This chapter will present a traceable transformation and the next chapter will discuss the quality or error criteria. The presented approach is based on conventional image correction ideas and the inversion of ray propagation in combination with the reflection properties of the surface. The general approach to describe reflections, motivated by the well-known material models in computer graphics [9], is to separate the reflection into a diffuse and a specular component. The parameter vector \( \mathbf{x} = (x_1, x_2, \ldots , x_{16})^T \in \mathbb{R}^{16} \) of digitization with single parameters \( x_i \) consists of 16 entries and the transformation has three steps. Fig. 4 gives a schematic overview of the different corrections of the transformation. The diffuse correction, as part of the inversion of the martial model, is independent of the viewing angle and thus the position in the image assuming Lambert’s cosine law [10]. The specular correction depends on the relative position to the center of the image, which can be shifted to account for the observer angle of the camera. The inversion of the reflection is multiplied by the inversion of the beam propagation of the headlamp, which depends on the relative position of the headlamp to the surface according to the photometric distance law.

The physical rules are formulated below to depend on the \( u, v \) image coordinates and few parameters \( \mathbf{x} \). These parameters are interpretable and an optimizer can identify them automatically.

\[
\Delta u = \frac{(u + x_4 - r_u/2)}{\max(r_u, r_v)/2}, \quad \Delta v = \frac{(v + x_5 - r_v/2)}{\max(r_u, r_v)/2}. \quad (2)
\]

All normalized distances are always limited to \([-1, 1]\). The inversion of ray propagation also uses a normalized distance \( \Delta u_R, \Delta v_R \) to the center of illumination

\[
\Delta u_R = \frac{(u + x_1 - r_u/2)}{\max(r_u, r_v)/2}, \quad \Delta v_R = \frac{(v + x_2 - r_v/2)}{\max(r_u, r_v)/2}, \quad (3)
\]

where \( x_1, x_2 \) represents the difference of the origin positions of the camera and the headlight. The normalized distance \( d \) between the origin of the light and the surface and the incident angle \( \alpha \) between the beam direction of the light and the surface normal are

\[
\alpha = \arctan \left( \sqrt{\Delta u_R^2 + \Delta v_R^2} / x_{15} \right), \quad (4)
\]

\[
d^2 = \left( \Delta u_R^2 + \Delta v_R^2 \right) / x_{15}^2 + 1, \quad (5)
\]

where \( x_{15} \) is the aspect ratio of the sensor to the focal length of the camera. This sets the angle of view and thus the length of an imaginary "z-axis" of the image where \( x_{15} \) lies. The correction divisor is a multiplication of the distance law with the addition of a factor for the diffuse correction and a polynomial function for the specular correction,

\[
f_{u,v,refl} = (x_6 + x_6 |\Delta u| + x_7 |\Delta u|^2 + x_7 |\Delta v| + x_7 |\Delta v|^2) / \sqrt{d^2 \cos (\alpha)}. \quad (6)
\]

This can be seen as the use of a general material model whose parameters are determined during calibration. The assumption for the specular correction is that the specular reflection properties are symmetric in all four directions from the displaced origin \((x_4, x_5)\), no individual correction parameters were chosen for the directions. It is also possible to use material descriptions such as [9]. Each texel \((u, v)\) of the acquired image \( I_u \) is divided by an individual divisor \( f_{u,v,refl} \) to calculate the result \( I(u, v) \in [0, 2^n − 1] \) of the first step

\[
I(u, v) = I_u(u, v) \times 14 / f_{u,v,refl}(x). \quad (7)
\]
As \( I \in \mathbb{R}^{n \times r \times 3} \) is an intermediate value, it could have values outside the range of \( I_{c} \), but in this paper it is always restricted to \([0, 2^{n} - 1]\). The whole described process can be seen as an identification and online inversion of a material model like [9], with \( f_{u,v,\text{ref}} \) as the structure and \( x \) as the parameter of the model.

The second step is a classic image processing step to adjust the dynamic range of the image and suppress noise in the areas outside the ray pattern. The result of the first step \( I(u, v) \) undergoes a thresholding operation to zero for all \( I(u, v) \leq x_{0} \). For uniform and low ambient noise the thresholding operation combined with scaling in the next step can suppress its influence and create a completely dark area outside the beam pattern. The noise from the camera in dark areas can also be suppressed. Afterwards \( I_{u,v} \) is adjusted

\[
I(u, v) = \left( \frac{I(u, v) - x_{10}}{2^{n} - 1} \right)^{x_{11}} (2^{n} - 1) x_{12} + x_{13},
\]

where \( n \) is the number of bits of the camera.

The third step of the transformation is loading \( I_{v} \) into a virtual point light source that uses the image as input for Projective Texture Mapping. The light source requires a maximum intensity value \( I_{v,\text{Max}} \) to translate the utilization of the camera’s sensor pixels in \( I \) into a concrete intensity value. \( I_{v,\text{Max}} \) can be determined during optimization as an additional parameter or during calibration, which is explained in the next section. The light source also has an aperture angle \( 2 \times x_{3} \), which scales the size of the light distribution of the image in the virtual world. The final intensity of the virtual light \( I_{v} \), propagating in the relative \((u, v)\) direction of the light is

\[
I_{v}(u, v) = I_{v,\text{Max}} I(u + x_{1}, v + x_{2})/(2^{n} - 1).
\]

The parameters \( x_{1}, x_{2} \) shift the image against the difference of the origin of the camera and the headlight, so that the origin of the virtual headlight and that of the real headlight are equal. For this, the viewing direction (optical axis) of the camera and the headlight must be parallel, which can be achieved by mounting the camera directly above the headlamp.

The first step of calibration [3], which must be done before identifying \( x \), is to manually or automatically adjust the photographic lens to use the full range of the camera by capturing the reference light distribution. If the maximum intensity of the reference is known, this is \( I_{v,\text{Max}} \) for the virtual source. A second goal is to maximize the sharpness of the image. The next step is to set the exposure time. If the headlamp generates its illumination with Pulse-Width Modulation (PWM), the exposure time must be a multiple of the period of PWM. If the period is not known, it can be determined by minimizing the difference between images of the same reference illumination of the matrix-headlight.

IV. QUALITY CRITERIA OF THE DIGITIZATION

To make the evaluation of the quality of the digitization independent of the quality of the test drive simulation, the digitized intensity is compared with a reference. The headlamp in the test stand must be controlled in the same way as in the reference measurement, so that the input is identical in both cases. Both intensity distributions are projected with a cubic subtexel interpolation as a light distribution onto a virtual wall whose normal vector is exactly opposite to the optical axes of the light source. The wall has \( r \) discrete texels in its two dimensions. The three-channel color input was converted to one channel representing intensity so that the reference intensities \( I_{v,\text{Ref}} \in \mathbb{R}^{r \times r} \) and the digitized \( I_{v} \in \mathbb{R}^{r \times r} \) always have the same number of texels and the same data format if the number of data points or the coordinate system of the inputs differ.

The final step of the calibration identifies the optimal parameters \( x^{*} \) by minimizing an error function \( f(x) \) between \( I_{v} \) and \( I_{v,\text{Ref}} \). One approach is to minimize the squared difference between the histograms \( H = (h_{1}, h_{2}, \ldots h_{2^{r}})^{T} \in \mathbb{R}^{2^{r}} \) of the two distributions [3]. For this purpose, the total intensity maximum of both distributions is determined and then the number of texels \( h_{i} \) with values within a brightness interval is counted. In this paper, the total intensity range is divided into \( 2^{n} \) intervals. This is to compensate for the influence of a possible higher measurement resolution in the reference measurement. With weight vector \( w = (w_{1}, w_{2}, \ldots w_{2^{n}})^{T} \in \mathbb{R}^{2^{n}} \), the histogram error \( e_{\text{hist}} \) is

\[
e_{\text{hist}} = \sqrt{\frac{1}{\sum_{i=1}^{2^{n}} w_{i}^{2}} \sum_{i=1}^{2^{n}} w_{i}^{2} (h_{i} - h_{i,\text{Ref}})^{2}}, \]

between the counts of the digitization \( h_{i} \) and the reference \( h_{i,\text{Ref}} \). At infinite resolution (texel count), histogram error is invariant to translations and rotations of the same image, since it only counts and does not evaluate the position of the values. Also, values within an interval are treated as equal, which can lead to robustness to noise beyond the interval.

Another possible metric is the RMSE, which compares the values of texels at the same position. The error \( e_{\text{se}} \) is

\[
e_{\text{se}} = \sqrt{\sum_{i=1}^{r} \sum_{v=1}^{r} w_{u,v}^{2} (I_{u,v} - I_{v,\text{Ref}})^{2} / \sum_{i=1}^{r} \sum_{v=1}^{r} w_{u,v}^{2}}.
\]

Here \( w \in \mathbb{R}^{r \times r} \) is a weight matrix with the individual elements \( w_{u,v} \). The RMSE is sensitive to errors in translation and rotation of the same image because it evaluates the position of the values. By comparing the absolute values, the same percentage error in bright areas is more important than in dark areas, which could focus the calibration on optimizing only the bright center of the ray pattern. By squaring the deviation it is expected that focus the calibration on the bright center of the ray pattern. By squaring the deviation it is expected that

The Mean Absolute Relative Error (MARE) sets the error in relation to the reference on a texel. This error \( e_{\text{re}} \) is

\[
e_{\text{re}} = \frac{\sum_{i=1}^{r} \sum_{v=1}^{r} w_{u,v} (I_{u,v} - I_{v,\text{Ref}})}{\sum_{i=1}^{r} \sum_{v=1}^{r} w_{u,v}}.
\]

Reference values of zero are replaced by small values during division. The disadvantage of MARE is that noise has a higher impact in dark areas than in bright ones. The magnitude of the
relative error was chosen over the quadrature to minimize the influence of small noise in areas without reference intensity in the error measure, which produces large relative errors even though it is not visible.

The weights \( \mathbf{w} \) can be chosen according to personal and subjective preferences. A possible objectified method would be to choose the weights in such a way that the percentage deviations \( e_{\text{per}} \) are weighted according to their conspicuousness. This is done by multiplying the error by the area in which it occurs

\[
A_i \cdot e_{\text{per}} \cdot I_{c,\text{Max}}/(2^n - 1) \cdot i \quad \forall i = 1, 2, \ldots, 2^n \tag{13}
\]

where \( A_i \) is the number of texels with values within the interval. This can be interpreted as the error luminosity, which is intended to mimic the visibility of the error. The weights can be calculated with

\[
w_i = 1 - \frac{A_{2^n}(2^n - 1)}{A_i(i - 1)} \quad \forall i = 2, 3, \ldots, 2^n. \tag{14}
\]

The weights are intended to give higher priority to conspicuous errors in order to achieve a better visual impression in the presence of limited correction possibilities. For \( w_1 \), a subjectively good value is 0.5, as it reasonably extrapolates the behavior of subsequent values. From these data points, the parameters of a weight function which is a 3rd order polynomial are determined. To better represent the weights in dark regions below a threshold \( i_{\text{Thr}} \), a separate root function is used for the dark region. The weighting function \( w_f(i) \) with the parameters \( a_i \) is

\[
f_{w_f}(i) = \begin{cases} 
    a_3i^3 + a_2i^2 + a_1i + a_0 & \text{if } i > i_{\text{Thr}} \\
    a_4\sqrt{i/i_{\text{Thr}}} + a_5 & \text{if } i \leq i_{\text{Thr}}
\end{cases} \tag{15}
\]

Fig. 5 shows the weights for different intensities for a high beam distribution created by 84 pixels. The light distribution is shown in fig. 4.

![Fig. 5: Weights for different intensity levels for high beam distribution created by 84 pixels.](image)

The calculated weights correspond to the personal subjective feeling that for the overall impression of a light distribution, especially the shape, the large dark areas at the edge are somewhat more important than the small bright area in the center. Since the weights depend on the reference light distribution they must be calculated individually for each reference and no generally valid parameters \( a_i, i_{\text{Thr}} \) can be given. To ensure that areas outside the ray pattern are always completely dark, the error of texels at the edges of \( I_c, I_{\text{Ref}} \) should be weighted significantly higher (e.g. \( I_{c,\text{Max}}/100 \) for the RMSE) than in the rest.

V. EVALUATION

The goal of the evaluation is to find the best quality criteria for digitization in order to optimize the transformation in further work. Image processing is done in CUDA C++ [12] with OpenCV [13] and its denoising approach [14]. Optimization is performed with a genetic algorithm [15] in its default configuration, which terminates the optimization after \( \approx 300 \) generation, since no significant improvements were achieved in the last generations. The reference is a high beam distribution from a matrix-headlight with 84 pixels. Table I shows the obtained parameters \( x \) for each quality criteria, which are the RMSE of the histogram and the intensities as well as the MARE without and with weights.

<table>
<thead>
<tr>
<th>Qual. Cr.</th>
<th>( x_1 )</th>
<th>( x_2 )</th>
<th>( x_3 )</th>
<th>( x_4 )</th>
<th>( x_5 )</th>
<th>( x_6 )</th>
<th>( x_7 )</th>
<th>( x_8 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hist</td>
<td>21.29</td>
<td>25.03</td>
<td>5.90</td>
<td>5.12</td>
<td>-0.93</td>
<td>0.77</td>
<td>0.54</td>
<td></td>
</tr>
<tr>
<td>RMSE</td>
<td>-31.50</td>
<td>-53.49</td>
<td>10.89</td>
<td>-6.05</td>
<td>-0.09</td>
<td>-0.51</td>
<td>1.03</td>
<td></td>
</tr>
<tr>
<td>MARE</td>
<td>-28.46</td>
<td>-54.45</td>
<td>9.84</td>
<td>9.70</td>
<td>0.09</td>
<td>-0.38</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>w. Hist</td>
<td>18.49</td>
<td>-11.24</td>
<td>25.92</td>
<td>-4.85</td>
<td>-4.89</td>
<td>-0.93</td>
<td>0.64</td>
<td>0.51</td>
</tr>
<tr>
<td>w. RMSE</td>
<td>-27.52</td>
<td>-54.36</td>
<td>21.16</td>
<td>-8.87</td>
<td>-5.86</td>
<td>-0.94</td>
<td>0.56</td>
<td>1.20</td>
</tr>
<tr>
<td>w. MARE</td>
<td>-28.46</td>
<td>-54.45</td>
<td>22.56</td>
<td>-8.05</td>
<td>9.70</td>
<td>0.08</td>
<td>-0.38</td>
<td>0.62</td>
</tr>
</tbody>
</table>

The comparison of the shift of the light origin \( x_1, x_2 \) shows that for the histogram error other parameters are optimal than for the others. The parameters for the intensity errors are similar to each other and agree with empirically determined parameters (done by manually shifting the beam pattern until it overlaps). This proves the translation invariance of the histogram and makes the error useless as a quality criterion, because it does not detect this significant effect.

The aperture angle of the light \( x_3 \) and the Angle Of View (AOV) of the camera witch determined \( x_{15} \) match empirical results and the specifications of the hardware. In particular, \( x_{15} \), which is close to the true 0.5 calculated from the camera parameters, is an indication of "reasonable" optimization. Thus, minimizing the RMSE and MARE of intensities is expected to find parameters that are physically correct. There will be differences mainly in the modeling of the reflection, which arises from the problem and correction of the fixed superposition in the distance of the projection surface. This problem causes the groove-like darkening in the upper and lower parts of the ray pattern, resulting in the corresponding errors (in red) in fig. 6.

Without weights, the 95% quantile of the Mean Absolute Error (MAE) is \( \approx 62\% \) lower when the process is optimized with the RMSE compared to the MARE, but the result is noisier, especially at the edges of the beam pattern (see fig. 6 a and b). The RMSE is lower when optimized with the RMSE with 1.59% to 2.05% of the measurement range compared to the optimization with the MARE, but the MAE is similar with 1.01% to 0.98%.

Fig. 6 (c and d) also shows the results of the optimization with weights. Using the weights equalizes the 95% quantile of
absolute error of the weighted RMSE (now only ≈ 8% lower) to the weighted MARE. The RMSEs are 1.67% and 2.06% and the MAEs are 0.89% and 0.98%. The results of optimization with the weighted MARE are 23% better in the weighted MARE criterion, but 22% worse in the weighted RMSE criterion than the digitization optimized with the weighted RMSE. In addition, the use of weights improves the noise reduction for the RMSE.

The detailed difference of the results is shown in fig. 7. The main differences are the size and the area around the maximum of the beam pattern. The result of the optimization with the weighted RMSE is smaller than that of the weighted MARE and the reference. The result of the weighted MARE is also smaller than the reference. The differences at the outer edge are in the range up to the lower 3 discretization steps of the 8-bit camera used, but the differences are visible in the headlight simulation. A disadvantage of the weighted MARE is that the error in the area around the maximum of the intensities is larger than in the results of the weighted RMSE.

As shown in this chapter no presented quality criterion is better suited to optimize the digitization of headlights and to classify different transformation approaches. In general, minimizing the MARE (with or without weighting) leads to a better digitization of the dark parts of the beam pattern than the RMSE, which can be seen from the errors in the dark areas in the unweighted case. The disadvantage is a larger error in the bright area, which can be more visually noticeable because the center of the light distribution is primarily directed to the road and not to the surroundings, which could distract from errors in the outer area. It follows that digitization procedures for matrix-headlights should not be evaluated by any of the presented criteria alone and without context, and a trade-off and prioritization between the error in bright and dark areas must always be made when setting up the HiL-system.

VI. CONCLUSION & OUTLOOK

This paper presents a novel digitization approach for automotive matrix-headlights based on the inversion of physically based laws of light propagation and reflection in real time. The calibration can be done automatically by minimizing an error function, but for matrix-headlights there is no simple error function that leads to the best results in all optimality criteria of a matrix-headlight. In general, weighted MARE is good when the focus is on the outer shape and weighted RMSE when the inner bright area is more important.

This paper focuses on a reference beam pattern (high beam) to compare numerical error functions rather than the quality and robustness of the transformation approach. By using the defined quality criteria, it will be possible to optimize and evaluate different digitization approaches in future work.

REFERENCES