Color Reproduction of Digital Camera Systems Using LED Spotlight Illumination

S. Fischer and T.Q. Khanh; Laboratory of Lighting Technology, Technische Universität Darmstadt; 64289 Darmstadt, Germany

Abstract

The use of LED spotlights has become more and more common in today's digital film and television production. In this context, the flexibility that comes along with the new LED technology offers a unique possibility to optimize the color reproduction of digital camera systems. In the following paper, an appropriate evaluation model should be proposed. It compares the reproduced image of a scene, depending on the spectra of the illuminating LED spotlights, to its direct perception under a reference illuminant and tries to minimize the perceived color differences by finding an optimal LED spectrum for each specific scene. The performance of this model will be tested using a set of 143 different surface colors and a measure for the quality of the color reproduction will be introduced.

Introduction

With the emergence of LED spotlights in digital film production a whole new experience of flexibility for directors, cinematographers and colourists has become possible. Depending on the atmosphere that should be created in a movie scene, specific characteristics, e.g., color temperature and white point, as well as the spectral distribution of the emitted light can be varied over a wide range. In combination with the digital film camera capturing the scene this flexibility further offers a unique possibility to optimize the color reproduction of the camera system.

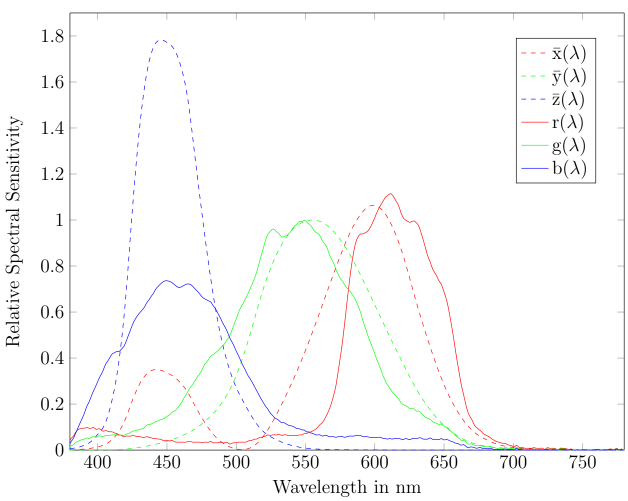


Figure 1. *Relative spectral sensitivities of the camera color filters (RGB) compared to the color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ of the CIE 1931 standard observer [1].*

Since the human perception and the spectral sensitivities of the digital camera differ significantly, which can be seen in Fig. 1, the issue of color reproduction has to be considered thoroughly in order to guarantee qualitatively good results in capturing realistic motion pictures.

The color reproduction of the digital camera system is mainly influenced by the spectrum of the illumination of the scene, the camera color filters, and the chosen white balance algorithm [2]. Perfect color reproduction means that directly perceived and reproduced colored scene objects look the same, so that arising color differences are negligibly small. However, this is usually not the case.

In order to reduce those color differences to a minimum and to obtain a measure for the quality of the color reproduction, an appropriate evaluation model is necessary. It compares the reproduced image of the scene, which depends on the spectra of the illuminating LED spotlights, to the direct perception of the scene under a reference illuminant and tries to minimize the perceived color differences in a device independent uniform color space (UCS) by finding an LED spectrum which is optimized for both the colored scene objects and the spectral sensitivities of the camera filter curves. Hence, the goal of this paper is to develop such an evaluation model to find the optimal LED-spotlight spectrum for each individual scene that should be captured by the camera system.

The paper is organized as follows. In Sec. 2 we give a short introduction to the possible colorimetric errors that can be defined when dealing with a digital camera system under various illuminations. Sec. 3 explains the proposed evaluation method whereas our first preliminary results are shown in Sec. 4. In Sec. 5 we finish the paper with some concluding remarks and an outlook on future developments.

Colorimetric Errors

In general, the RGB-sensor of a camera system does not fulfill the Luther-Ives-condition [3, 4, 5], i.e, the spectral response curves of the RGB-sensor cannot be described as a linear combination of the eye cone response functions. As a consequence the spectral sensitivity of the camera system differs significantly from the human perception described by the color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ of the CIE 1931 standard observer [1]. Several colorimetric errors can therefore be identified when comparing the direct perception of a scene to its reproduction under various illumination conditions. These errors are illustrated in Fig. 2 and are labelled by F1 to F5.

The error F1 describes the perceived color differences between the directly observed scene and its reproduction both under reference illumination. This error is given by the spectral sensitivity of the camera system and the applied color correction algorithm. The same holds true for the colorimetric error F3 which compares the direct perception of the scene under the test illu-

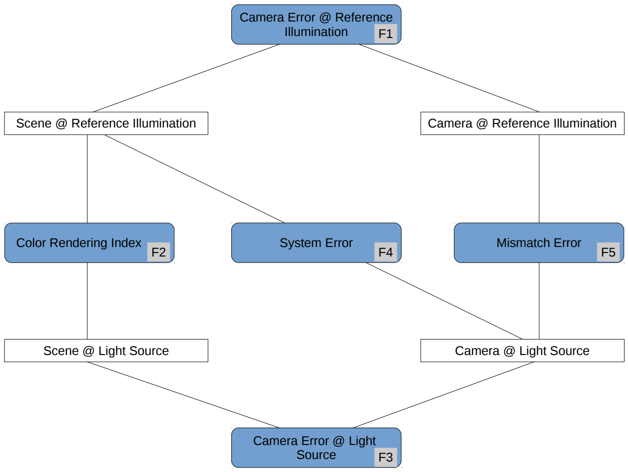


Figure 2. *Colorimetric errors that occur when comparing the direct perception of a scene to its reproduction under various illumination conditions.*

minant - in our case the LED spotlight system - to its immediate reproduction. If comparing the direct perception of the scene once with reference and once with test illumination a color difference F2 can be noticed which is basically described by the color rendering index CRI [6] of the test illuminant. On the side of the camera system, the equivalent is called mismatch error F5. Finally, the systematic error F4 is defined by the perceived color differences between the reproduced image of the scene, which depends on the spectrum of the test illuminant, and the direct perception of the scene under a reference illuminant.

For future developments, the main goal should be a simultaneous reduction of errors F1 to F5. However, for this work we focus solely on the systematic error F4 since it plays the most crucial role in color reproduction of digital motion pictures captured under LED spotlight illumination.

Evaluation Method

In order to find the optimal LED spotlight spectrum for each individual scene that should be captured by the camera system, we simulated more than 100 different realistic LED spotlight spectra with the same color temperature as the corresponding reference illuminant. The spectra were generated by assuming a 7-channel light engine consisting of 470 nm, 520 nm, 594 nm, 625 nm, 660 nm, cool white and warm white LEDs which were all spectrally measured and characterized at the Laboratory of Lighting Technology in Darmstadt. Such a spotlight system represents a good compromise between improved color reproduction properties and viability concerning its application in digital film and television production.

In the next step, a specific set of test colors is chosen, see Sec. 3.A, and the corresponding color stimuli for each LED spectrum are measured by the camera system resulting in raw RGB data for each test color and illumination condition. The raw data are then processed by the white balance algorithm described in Sec. 3.C and transformed into a UCS, which in our case is an extended version of the CIELAB color space being discussed in Sec. 3.B.

For each LED spectrum the perceived color differences between the reproduction of the test colors and their direct perception under reference illumination can be calculated in this color space, which corresponds to the systematic error F4 described in the previous section. Finally, we take the LED spectrum with the best color reproduction as the optimal one minimizing error F4. A mathematical criterion for good color reproduction is given later.

Gamut of Test Colors

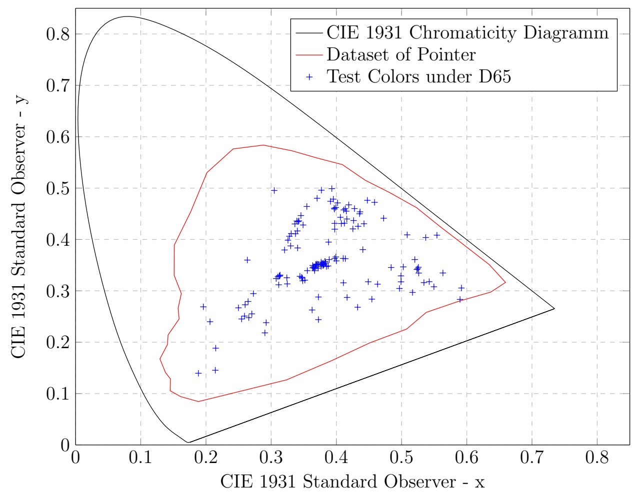


Figure 3. *CIE 1931 color coordinates of the test colors under reference illuminant D65 compared to the maximum possible color gamut of surface colors defined by Pointer [12] under various illuminations.*

In our evaluation model, we use a total number of 143 different surface colors of real objects as test colors which can be grouped into 11 blue objects, 37 green objects, 32 red objects, 7 yellow objects, 32 different skin colors, and the 24 color patches of the Macbeth ColorChecker. The spectral reflectivities of all of these surface colors were measured by the Laboratory of Lighting Technology at the Technische Universität Darmstadt [11]. In Fig. 3 their color coordinates under D65 illumination are shown together with the maximum possible color gamut of surface colors defined by Pointer [12].

Extended CIELAB Color Space

In order to quantify the perceived color differences between directly viewed and reproduced surface colors, an extended version of the well-known, device independent CIELAB [7, 8, 9] color space is used. This so-called DIN99 formula is standardized in DIN 6176:2001-03 [10].

In the CIELAB color space the simple Euclidean distance

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad (1)$$

is used to quantify the perceived magnitude of the color difference between two surface color stimuli. However, CIELAB color differences exhibit perceptual nonuniformities depending on the color region, e.g, color differences of less saturated colors are usually perceived more strongly than color differences in saturated regions even though they have the same Euclidean distance ΔE^*_{ab} [13]. In order to account for these nonuniformities and to improve the performance of the CIELAB color space while keeping the simple form of equation (1) for calculating color differences, a new color space transformation was introduced resulting in the DIN99 formula.

This transformation of the CIELAB color space can be divided into a lightness modification and a chroma transformation. First, the CIELAB lightness L^* is logarithmically transformed by

$$L_{99} = 105.51 \cdot \ln(1 + 0.0158 \cdot L^*), \quad (2)$$

which yields the DIN99 lightness L_{99}. Second, the CIELAB correlates a^* (red-green component) and b^* (yellow-blue component) - and therefore the CIELAB chroma C^*_{ab} and hue h^*_{ab} - are transformed via

$$e = a^* \cdot \cos(16°) + b^* \cdot \sin(16°), \quad (3)$$

$$f = 0.7 \cdot (b^* \cdot \cos(16°) - a^* \cdot \sin(16°)), \quad (4)$$

$$k = \frac{\ln(1 + 0.045 \cdot \sqrt{e^2 + f^2})}{0.045 \cdot \sqrt{e^2 + f^2}}, \quad (5)$$

$$a_{99} = k \cdot e, \quad (6)$$

$$b_{99} = k \cdot f, \quad (7)$$

where k is the so-called chroma compression factor. The Euclidean color difference in the extended CIELAB color space is then given by

$$\Delta E_{99} = \sqrt{(\Delta L_{99})^2 + (\Delta a_{99})^2 + (\Delta b_{99})^2}. \quad (8)$$

It could be shown by Cui et al. [14] that the performance and the results of the DIN99 color difference formula are comparable to the more complex CIEDE2000 formula. Further, the uniformity of the extended CIELAB color space compared to the original one is greatly enhanced.

Camera Color Measurement and Color Reproduction

As discussed before, camera color measurement and human perception differ significantly. From Fig. 1 we notice that the red and blue filter curves are much wider than the corresponding color matching functions $\bar{x}(\lambda)$ and $\bar{z}(\lambda)$, respectively. This mismatching cannot be corrected by a simple linear transformation and has a major influence on the color reproduction of the camera system.

In order to improve the color reproduction, a nonlinear white balance algorithm has to be included in our evaluation model which maps the raw RGB data of the camera system into the device independent XYZ color space performing a nonlinear color correction [15, 16].

For each test color, we first calculate the directly perceived color stimulus under reference illumination using

$$\begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix}_{n,\mathrm{direct}} = \int \begin{Bmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{Bmatrix} \cdot q_{e,n}(\lambda) \cdot E_{e,\mathrm{ref}}(\lambda)\, \mathrm{d}\lambda, \quad (9)$$

where $q_{e,n}(\lambda)$ is the spectral reflectivity of the nth test color and $E_{e,\mathrm{ref}}(\lambda)$ is the spectral irradiance of the reference light source. Further, we calculate the raw RGB data for each test color under LED illumination using the measured spectral sensitivities $r(\lambda)$, $g(\lambda)$, and $b(\lambda)$ of the camera color filters. Hence, we have

$$\begin{Bmatrix} R \\ G \\ B \end{Bmatrix}_{n,\mathrm{raw}} = \int \begin{Bmatrix} r(\lambda) \\ g(\lambda) \\ b(\lambda) \end{Bmatrix} \cdot q_{e,n}(\lambda) \cdot E_{e,\mathrm{LED}}(\lambda)\, \mathrm{d}\lambda, \quad (10)$$

where $E_{e,\mathrm{LED}}(\lambda)$ is the spectral irradiance of the LED light source under evaluation.

The raw RGB data of the test colors are then transformed into the XYZ color space by applying a 3×14 white balance matrix which is determined by equation (11) using a least-square optimization algorithm. Note that all 143 test colors are used for optimization.

Finally, the mapped camera raw data as well as the directly perceived color stimuli are transformed into the extended CIELAB color space and the color difference between the direct perception and the reproduction is determined for each test color using equation (8). The mean value $m_{\mathrm{CD}} = \Delta\bar{E}_{99}$ of the calculated color differences is taken as a criterion for good color reproduction. The smaller m_{CD} the better the color reproduction of the LED light source under evaluation. Hence, the above calculation steps have to be repeated for every simulated LED spotlight spectrum to find the one which is optimized for the test colors in the scene and the spectral sensitivities of the camera filter curves.

$$\min \sum_{n=1}^{143} \left(\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{n,\mathrm{direct}} - M_{3\times 14} \cdot \begin{pmatrix} R & G & B & RG & RB & GB & R^2 & G^2 & B^2 & R^3 & G^3 & B^3 & RGB & 1 \end{pmatrix}^{\mathrm{T}}_{n,\mathrm{raw}} \right)^2 \quad (11)$$

Optimization Results

In this section we apply the previously discussed evaluation method to minimize the perceived color differences between the direct perception and the reproduction of the test colors. We choose D65 to be the reference illumination. Further, the measured spectral sensitivities of the Photonfocus MV1-D1312C-40-G2-12 industrial camera shown in Fig. 1 are used as input for our calculations. During the evaluation process the mean value m_{CD} of the perceived color differences is determined for each simulated LED spotlight spectrum with 6500 K. The spectrum with the smallest value m_{CD} is then chosen to be the optimal one. In Fig. 4 the relative spectral power distribution (SPD) of the optimized spectrum is shown and compared to the relative SPD of the D65 reference illuminant.

For further comparison and in order to test the performance of the evaluation model, we also calculated the perceived color differences of the test colors under D65 illumination only, which corresponds to the error F1 described in Sec. 2 and is shown in Fig. 5(a). In this case, we obtain a mean value of $m_{\mathrm{CD}}^{\mathrm{D65}} = 0.83$. The maximum color difference observed is $\Delta E_{99,\mathrm{max}}^{\mathrm{D65}} = 3.61$.

As can be seen from Fig. 5(b) using the optimized LED spotlight spectrum leads to significantly smaller color differences for most of the test colors. We find a mean value of $m_{\mathrm{CD}}^{\mathrm{LED}} = 0.66$, which is a reduction of approximately 21% compared to the D65 illumination. Further, we observe a maximum color difference that is also reduced by approximately 13%, i.e., we have $\Delta E_{99,\mathrm{max}}^{\mathrm{LED}} = 3.14$. Additionally, resulting color differences of selected colored objects are shown in Tab. 1.

Table 1 – Resulting color differences of selected objects. D65 illumination only results (F1) are compared to the performance of the optimized LED spotlight spectrum (F4).

Colored Object	Error F1	Error F4
Purple Flowers	1.73	0.92
Maple Leaf 2	0.71	0.35
Maple Leaf 4	0.75	0.36
Buckhorn Plantain	0.94	0.58
Kiwi	1.41	0.89
Green Apple	0.74	0.51
Pink Peony	2.06	0.56
Pale Pink Rose	2.72	0.58
Red Polyester Jacket	1.42	0.93
Orange Apricot	1.47	0.83

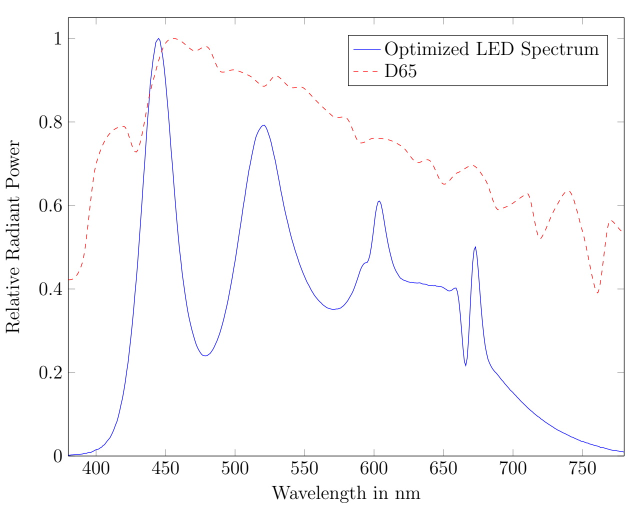
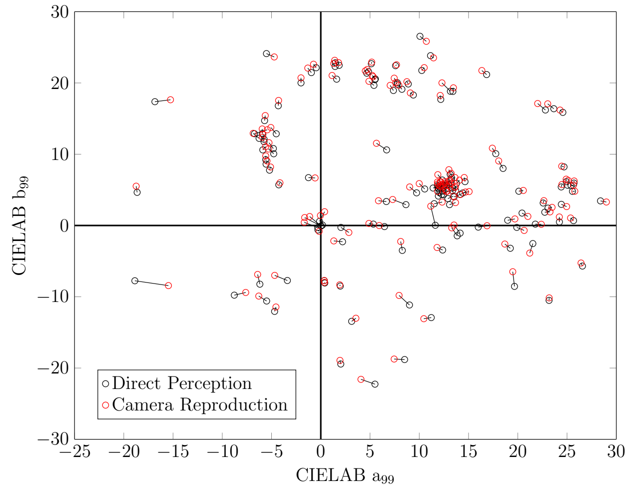
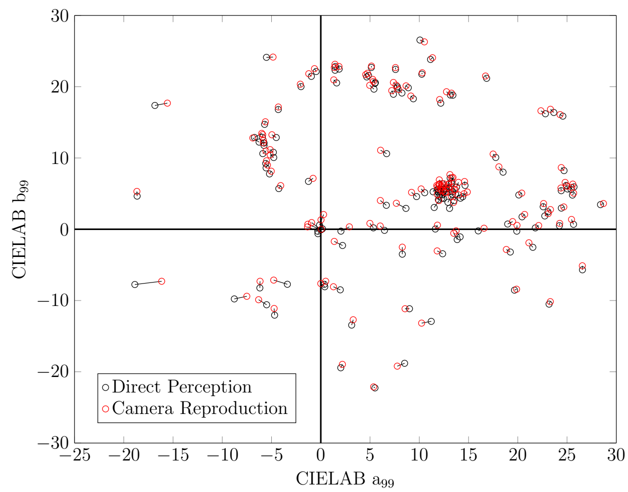


Figure 4. *Relative spectral power distribution of the 7-channel LED spotlight spectrum which has been optimized for the specific combination of test colors and camera sensitivity curves used in this work. For comparison, D65 reference illuminant is additionally shown.*



(a) Color differences between direct perception and reproduction of test colors under D65 illumination.



(b) Color differences between direct perception and reproduction of test colors with optimal LED spectrum at 6500 K.

Figure 5. *Resulting color differences of the 143 test colors used for optimization. Black points mark the DIN99 color coordinates of the directly perceived stimuli under D65 reference illumination while red points mark the color coordinates of the reproduction of those stimuli calculated for both D65 illumination (upper figure) and the optimized LED spotlight spectrum (lower figure). Note that the lightness component L_{99} is not shown here.*

Conclusion and Outlook

In this paper we proposed an evaluation model which compares the reproduced image of a scene under LED illumination to its direct perception under reference illumination and finds for this specific scene the optimal LED spotlight spectrum by minimizing the perceived color differences. The evaluation model is based on the DIN99 extension of the well-known CIELAB color space and includes a nonlinear white balance algorithm for color correction.

It could eventually be shown that the color reproduction of a digital camera system can be significantly improved when using this optimized LED spectrum for the illumination of the captured scene. The perceived color differences of most of the test colors could be reduced and the mean value of the color differences decreased by approximately 21% compared to the measurement of the test colors under reference illumination only. The same holds true for the largest observed color differences which could be reduced by approximately 13%.

So far, our proposed model still demands a pre-selection and time-consuming pre-simulation of the different LED spotlight spectra that should be evaluated. Consequently, we do not know if the spectrum found to be optimal by the evaluation model is really the absolute optimum for the specific scene under consideration. For future developments we will therefore design an iterative optimization algorithm which determines the theoretically optimal spectrum for an arbitrary set of test colors without any pre-simulation or pre-definition. We will then try to rebuild these theoretically optimized spectra with measured LED spotlight spectra in order to minimize the systematic error F4 under realistic conditions. In this context, a simultaneous minimization of the errors F1 to F5 could also be desirable.

References

[1] CIE Publication 015:2004, Colorimetry, 3rd Edition, Commission Internationale de l'Eclairage (2004).

[2] B. A. Wandell and L. D. Silverstein, Digital Color Reproduction, in The Science of Color, 2nd Edition, Elsevier (2003).

[3] R. Luther, Z. Tech. Phys. **8**, 540 (1927).

[4] N. Ohta and A.R. Robertson, Measurement and Calculation of Colorimetric Values, in Colorimetry: Fundamentals and Applications, John Wiley & Sons Ltd (2005).

[5] F. Martínez-Verdú et al., Color Res. Appl. **31**, 399 (2006).

[6] CIE Publication 13.3, Method of Measuring and Specifying Colour Rendering Properties of Light Sources, 3rd Edition, Commission Internationale de l'Eclairage (1995).

[7] G. Wyszecki and W. S. Stiles, Color Science: Concepts and Methods, Quantitative Data and Formulae, 2nd Edition, Wiley Classics Library (2000).

[8] M. D Fairchild, Color Appearance Models, 2nd Edition, John Wiley & Sons Ltd (2005).

[9] R. W. G. Hunt and M. R. Pointer, Measuring Colour, 4th Edition, John Wiley & Sons Ltd (2011).

[10] DIN 6176:2001-03, Colorimetric evaluation of colour differences of surface colours according to DIN99-formula, Beuth Verlag (2001).

[11] T. Q. Khanh et al., Farbwiedergabe von konventionellen und Halbleiter-Lichtquellen, Pflaum Verlag (2013).

[12] M. R. Pointer, Color Res. Appl. **5**, 145 (1980).

[13] H. Büring, Eigenschaften des Farbenraumes nach DIN 6176 (DIN99-Formel) und seine Bedeutung für die industrielle Anwendung, in 8. Workshop Farbbildverarbeitung, Ilmenau (2002).

[14] G. Cui, Color Res. Appl. **27**, 282 (2002).

[15] G. Hong, M. R. Luo, and P. A. Rhodes, Color Res. Appl. **26**, 76 (2001).

[16] F. Kimme et al., Appl. Opt. **52**, 8779 (2013).

Author Biography

Sebastian Fischer *received his M.Sc. in Physics from the Technische Universität Darmstadt, Germany (2014). Since then he has been working at the Laboratory of Lighting Technology in Darmstadt as a research assistant and PhD student. His current work is focused on digital cine technique and camera technology.*

Tran Quoc Khanh *is University Professor and Head of the Laboratory of Lighting Technology at the Technische Universität Darmstadt, Germany. He graduated in Optical Technologies and obtained his PhD in Lighting Engineering from the Technische Universität Ilmenau, Germany. Before being appointed as a professor, he gathered industrial experience as a project manager at ARRI Cine Technik in Munich, Germany.*