Optical design in the digital age: Integrated optimization of the imaging chain

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Can optical design be significantly simplified in terms of size and complexity if software based aberration correction on distortion or color fringes is applied? Integrated optimization of optics and image processing in one design tool is the key to tailored solutions. We are showing potentials and limits of a priori lens data based corrections.

1 Introduction

Imaging is a multi-step process starting from capturing an illuminated object scene to watching a final image on screen or paper with the human eye. Optical imaging is one part of this imaging chain. But many other steps like the sensor characteristics and image processing contribute vitally to the final image. Therefore it is necessary to include these aspects into the development of an optical system. Typically this is done in a two-step-process starting with optical design and introducing image-processing afterwards. Here we show that an integrated optimization of optics where the quality of the final image is already available in the optical design software leads to tailored systems with reduced complexity.

2 Two product examples including digital image processing

Image processing is widely used in digital compact cameras. Fig. 1 shows the raw image of a typical zoom-lens for these products in the wide-angle position. A strong barrel distortion of about -20% is visible. The discrete structure of the sensor is highlighted in the blue box.

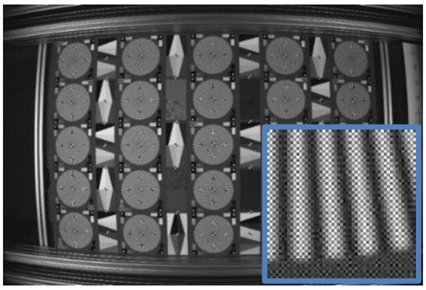

Fig. 1 *Raw image of a digital compact camera*

This raw image is post-processed in the camera to correct distortion, relative illumination up to 2 or 3 f stops and color fringes to come to improve the image quality.

In mobile phone cameras relative illumination is also digitally corrected, whereas distortion is usually already corrected in optical design. In Fig. 2 you see a cut through a lens module of a mobile phone camera.

Fig. 2 *Layout of a mobile phone*

3 Digital aberration corrections and side-effects

In general, <u>color fringes</u> [2] can digitally be reduced by shifting the individual color channels relative to one another. Fig. 3 shows simulated edge-spread-functions for the RGB-channels. Each of these channels represents a certain spectral range which depends on the image sensor and the illumination of the object scene. In the top half of Fig. 3 the edge-spread-functions have exactly the same slope. Therefore the blue and red color fringe can be perfectly removed (Fig. 3 top right). Usually, wavelength dependent aberrations lead to different slopes in the RGB-channels (Fig. 3 bottom left). Shifting these channels produces residual color fringes (Fig. 3 lower right).

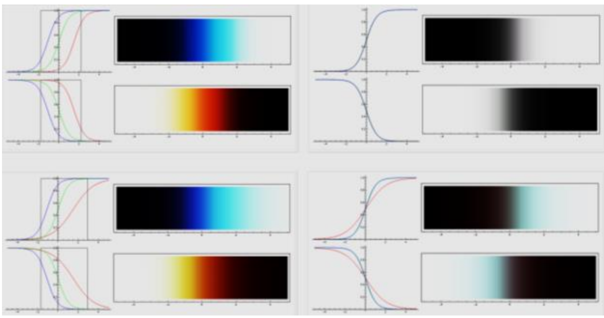

Fig. 3 *Color fringe correction: constant slopes (top left/right) and different slopes (bottom left/right)*

<u>Distortion</u> correction [1] is strongly related to resolution. In Fig. 4 strong barrel distortion is obvious. The red grid visualizes the pixel structure of the sensor. In the center of the field (small distortion) we see

circles with sufficient pixel sampling. At the corner of the field (high distortion) the circles are compressed in tangential direction. This can be regarded as a change in magnification over image height. To get the same object resolution, higher spatial frequencies in image space must be resolved. In addition, the pixel sampling decreases remarkably. Consequently software correction of barrel distortion introduces a tangential MTF drop.

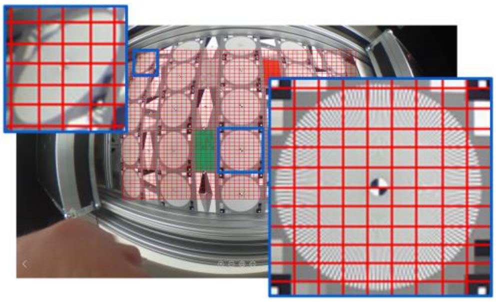

Fig. 4 *Field dependent resolution for systems with strong barrel distortion*

Relative illumination and distortion are also interrelated. In Fig. 5 (left) a homogenously illuminated sensor is shown. Barrel distortion shifts the corner closer to the center of the field (Fig. 5 middle) and therefore increases relative illumination. Pincushion distortion decreases the relative illumination (Fig. 5 right). In camera lenses shading arises mainly at higher apertures due to vignetting.

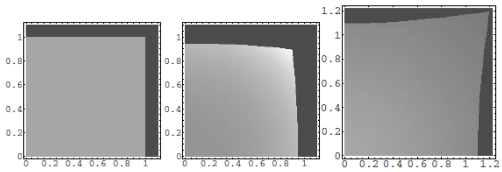

Fig. 5 *Effect of distortion on illumination [3]*

Another simple possibility is the amplification of the signal in the corner of the field. Side-effects are quantization artefacts and increased noise levels.

4 Design study with integrated optimization

In classical optical system optimization the task of the lens designer is to create an optical design performing near the final image quality. In digital optical co-optimization however lens performance can be reduced giving the freedom to reduce size or costs. Now we include additional steps of the imaging chain like the software corrections mentioned in chapter 3. Thus it is possible to analyze and optimize a lens system directly regarding the image performance after image processing. Therefore it is called integrated optimization.

To evaluate the potentials of the integrated optimization an optical design study for a f/2.8 super-wide-angle zoom lens with a field of view of 2w=110°…70° for cinematography is set up: Design 1 is pure optical design, design 2 is developed with integrated optimization. Both designs have the same basic structure (e.g. zooming groups) and object field of view. The quality of the aerial image of design 1 and the final image in design 2 needs to be comparable.

Results:

	Design 1: pure optical	Design 2: integrated optimization
Complexity	24 lenses including 3 aspherical lenses and 8 special glasses	14 lenses including 3 aspherical lenses and 3 special glasses
Diameter X OAL	78mm X 247mm	76mm X 201mm
Relative illumination	wide and tele 20%	wide 36% tele 44%
Distortion	wide -3% tele +4%	Optical: wide -19% and tele -8% Digitally corrected: wide and tele 0%
MTF 20lp/mm on axis	wide 90% tele 85%	wide 88% tele 87%
Wide over field:		
MTF 10lp/mm	60%	62%
MTF 20lp/mm	29%	40%
Tele over field:		
MTF 10lp/mm	88%	86%
MTF 20lp/mm	63%	63%

Fig. 6 *Comparison of results*

Optical color fringes for design 2 are large. They are digitally removed with very small residuals (Fig. 7)

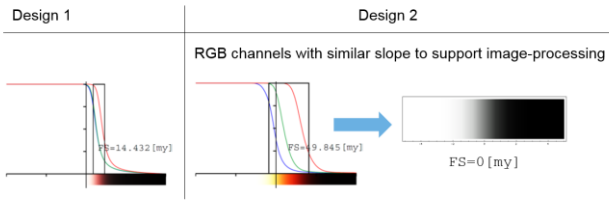

Fig. 7 *Color fringes pure optical (left) and integrated optimization (right)*

5 Summary

Image-post-processing has side-effects and should not be used blindly on bad lenses. Integrating image post-processing steps into the optical design software in terms of analyzing and optimizing helps to develop tailored optical systems with good overall image quality at reduced size and optical complexity.

References

[1] W.. Hugemann: „Correcting lens distortions in digital photographs“ in *EVU Conference (Vol. 19), Prague* (2010)

[2] S. Kang, „ Automatic Removal of Chromatic Aberration from a Single Image,“ in *IEEE Conference on Computer Vision and Pattern Recognition, Minneapolis, Minnesota, USA, 1-8* (2007)

[3] V. Blahnik, V. „Teilkohärente objekthöhenabhängige Abbildungstheorie“, Dissertation, TU Braunschweig, (2002)