Experimental validation of extended depth-of-field imaging via spherical coding

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Abstract: We prototyped a spherical coded triplet imaging system and verified its extended depth-of-field imaging capabilities.

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1. Introduction

Spherical aberration in optical imaging systems is a consequence of using spherically curved lens surfaces to form an image. Spherical surfaces are easy to grind and polish but are not ideal for image formation. In an imaging system, the effect of spherical aberration is to blur the image, reducing image contrast. Long ago it was also noted that spherical aberration makes focussing an optical system difficult [1] as the system has a larger focal depth, albeit with lower contrast. Recently, this property of spherical aberration was identified as a mechanism for achieving extended depth-of-field (EDoF) imaging for microscopes in a joint digital-optical system architecture [2]. We call this approach *spherical coding*, a reference to the original digital-optical architecture *wavefront coding* pioneered by CDM Optics [3], operates by adding controlled amounts of spherical aberration to an optical design such that the optical modulation transfer function (MTF) has reduced contrast, but larger depth-of-field. The blurry captured images are subsequently sharpened via digital image processing.

We describe our prototype a spherical coded triplet imaging system. First, we describe the electro-optical image system design and the image processing we used to restore the images. Second, we experimentally verify the extended depth-of-field imaging capabilities of our system and provide example images visualizing the residual artifacts inherent to the spherical coded imaging architecture.

2. Spherical coded prototype imaging system

To be effective as an EDoF imaging system, the optical design must a system to have large amounts of spherical aberration while minimizing the other aberrations. We limited our design to the use of standard off-the-shelf (OTS) catalog lens elements thereby greatly limiting the optical design flexibility. Consequently, our $f = 10mm$ design was limited to a full-field-of-view of 32 degrees and f-number of $F\#2.7$. The optical design targeted the green channel ($\lambda = 550nm$) of a Sony XCD-710CR having 1/3 inch XGA CCD with 4.65 μm pixels. Because we use only the green channel image, the effective pixel pitch is 9.3 μm pixels (Nyquist rate of 54 lp/mm). The back focus of the lens is controlled using the C-mount threading on the camera housing.

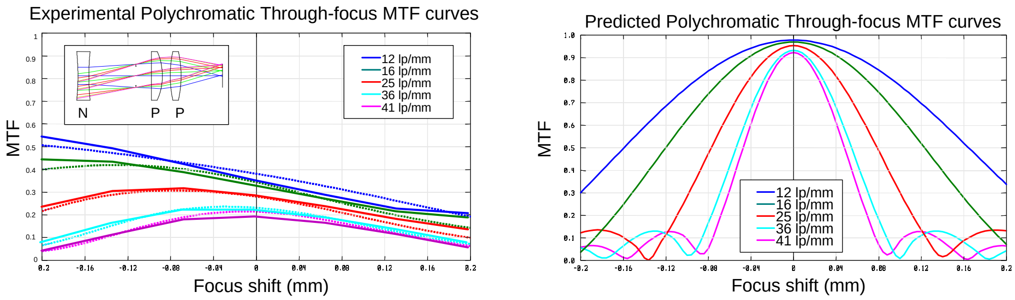

Fig. 1. The graph on the left compares the measured through-focus MTF (solid) curves at several spatial frequencies with the predicted through-focus MTF curves (dashed) predicted by Zemax for the spherical coded triplet shown inside the graph. We observe that the measured through-focus MTF curves show very nearly match the predicted performance. The graph on the right shows the through-focus MTF curves for an aberration-free system demonstrating the improved contrast value, yet shallow depth-of-focus.

The final design follows a negative-positive-positive (NPP) architecture having 12 waves of spherical aberration at $F\#2.7$. The NPP design form expands the beam prior to the positive image-forming lenses so as to accentuate the spherical aberration. This design form has minimal remaining aberrations with the exception of distortion. The significant distortion, nearly 5 percent, is induced by the initial negatively powered surface on the object side of the lens. The through-focus MTF graph on left side of Fig. 1 contains a diagram of the spherical coded NPP triplet lens design based on stock BK7 lens elements.

Using barrel rotation as our back focal distance control, we acquire seven images of a slanted edge target at different barrel rotations corresponding to a total range of ± 0.2 μm. Then, we measure the MTF curves using the ImaTest software [4] based on the slanted-edge MTF test to obtain measurements of the through-focus MTF curves at five different spatial frequencies. The left graph of Fig. 1 compares the experimentally measured through-focus MTF curves (solid) with those predicted (dashed) using the Zemax lens design software package. The measured through-focus MTF curves match the predicted values reasonably well over the range of spatial frequencies. Also, the through-focus MTF curves demonstrated the very broad depth-of-focus for the spherical coded imaging system. In this case, the system preserves contrast for a very large focal depth corresponding to nearly ± 3.5 waves of defocus aberration. As a point of reference, the graph on the right side of Fig. 1 shows the through-focus MTF curves for a similar 10mm focal length system free of all aberrations. The maximum contrast is much higher than the spherical coded system but shows a very shallow depth-of-focus.

EDoF imaging depends on digital image processing to restore the lost contrast in the image due to spherical aberration. We employ simple spatially-invariant linear filters to restore the image contrast. To prevent oversharpening of the final image, we compute the optimistic MTF surface defined by

$$H_o(\omega_1, \omega_2) = \max_i |H_i(\omega_1, \omega_2)|, \tag{1}$$

where $H_i(\omega_1, \omega_2)$ is the measured OTF function for the ith focus position. This does not present a problem since the OTF has constant phase. We then use this optimistic MTF function to design a single sharpening filter according to

$$R_o(\omega_1, \omega_2) = \frac{1}{|H_o(\omega_1, \omega_2)| + s^{-1}} \tag{2}$$

where s is the signal-to-noise (SNR) for our $F\#2.7$ imaging system at 5 ms exposure setting. We approximate this to be about 35 dB. The left side of Fig. 2 shows a slice through the spatial frequency response of the the rotationally-symmetric simple high-pass sharpening filter.

3. EDoF Experiments

We visualize the quality of the EDoF images obtained by the spherical coded imaging system by imaging a modified Siemens star target located at about 1.7 meters from the camera. We acquire images using 5 ms exposures at five different back focal distances separated by 0.067 μm. We apply our sharpening filter $R_o(\omega_1, \omega_2)$ to these images. The right side of Fig. 2 shows an example of a captured star chart image. The overall image shows the significant distortion present in the spherical coded imaging system.

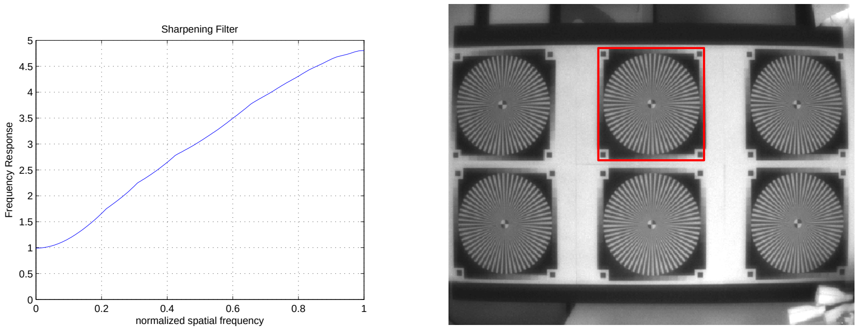

Fig. 2. The graph on the left shows a slice through the spatial frequency response of our rotationally-symmetric digital sharpening filter. The image on the right shows an example of the set of Siemens star target objects used to evaluate the image quality and the cropped portion shown in Fig. 3

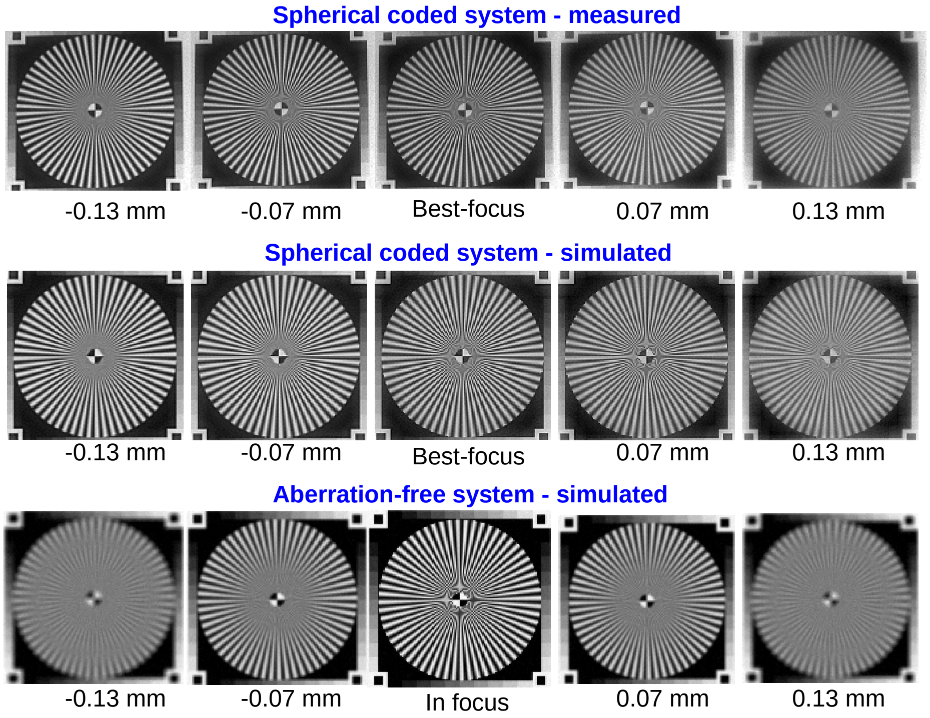

Fig. 3. The five image columns visualize the through-focus performance for a Siemens star target. The top row shows the actual measured images on the spherical coded prototype after digital sharpening. The middle row shows the simulated images based on the nominal triplet design using our images simulator similar to that of [5]. The bottom rows show the simulated images of an aberration-free optical system.

The top row of Fig. 3 compares the cropped sharpened star target images at the five different back focal depths. The top row shows the target images captured by the spherical coded triplet system after sharpening. The system shows reasonably good contrast throughout the focal volume, although at 0.13mm, the poor contrast at low spatial frequencies is noticeable. The middle row shows a similar set of images produced by our image simulation engine similar to that of [5] which is based on the actual Zemax nominal design. The simulated images match the predicted images quite well validating our simulation engine. The bottom row shows the simulated images for an aberration-free optical system. We include this simulation to visualize the poor depth-of-focus of a well-corrected optical system.

4. Conclusion

We described our prototype version of a spherical coded EDoF imaging system based on an NPP triplet optical system. We describe a simple approach to designing digital filters to restore contrast and show example images captured by our system verifying the EDoF properties of spherical coding. The image processing used in the EDoF imaging is rudimentary suggesting that more sophisticated algorithms might eliminate the artifacts produced using only a single sharpening filter. Further investigation into the design of sharpening filters which are robust to manufacturing variations could prove valuable for practical high-volume manufacturing of spherical coded systems.

References

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