

# A Phase-coded Aperture Camera with Programmable Optics

Jieen Chen<sup>1</sup>, Michael Hirsch<sup>2</sup>, Rainer Heintzmann<sup>3</sup>, Bernhard Eberhardt<sup>4</sup>, Hendrik P. A. Lensch<sup>1</sup>

<sup>1</sup> Department of Computer Science, Universität Tübingen, Germany

<sup>2</sup> Department of Empirical Inference, Max Planck Institute for Intelligent Systems, Tübingen, Germany

<sup>3</sup> Leibniz Institute of Photonic Technology, Jena, Germany

<sup>4</sup> Computer Animation Department, Stuttgart Media University, Germany

## Abstract

We propose a novel computational imaging system that enables the generation of Point Spread Functions (PSFs) of user-specified geometry. Key ingredient of our system is a phase-coded aperture which manipulates the phase distribution of the pupil function by inserting a phase modulator. We use a reflective phase-only liquid crystal-based Spatial Light Modulator (SLM) for phase modulation. Via encoding a grayscale image on the SLM, the refractive index of each cell can be altered. Phase patterns of PSFs with different shapes are optimized by the Gerchberg-Saxton algorithm. A number of non-trivial, complex shaped PSFs has been captured. We further demonstrate how such a system can realize refocusing through encoding a Fresnel lens phase pattern to shift the focal plane.

## Introduction

Imaging systems under partially coherent illumination can be described as linear systems and as such are fully characterized by their response to a point light source. This response is known as the Point Spread Function (PSF) since the image of a point light source would typically get dispersed and extend over several pixels on the imaging plane.

While in traditional imaging systems the PSF – as being a consequence of the optical design – is considered fixed, in computational imaging systems ways are studied that enable deliberate PSF manipulation.

Pupil plane coding is often used for modulating PSFs of an imaging system. For example, amplitude-coded aperture techniques modify the transmittance of the pupil to explore the PSF pattern. Especially when defocus exists, the amplitude-coded aperture can be employed for depth map measurement. However, the energy distribution cannot be fully controlled. In contrast, phase-coded aperture techniques manipulate the phase of an optical wavefront. By modulating the phase at different spatial locations, light experiences different degrees of delay. By doing so the wavefront phase distribution can be controlled and therewith its corresponding PSF. Phase-coded aperture techniques explore this property to control PSFs. More applications could potentially arise by providing freedom of manipulating PSFs into arbitrary shapes.

We propose a phase-coded aperture setup for PSF engineering using a Spatial Light Modulator (SLM). By placing the SLM at the pupil plane of a camera lens, we explore the Fraunhofer diffraction relation between a PSF and its complex pupil function. We generate phase patterns encoded on the SLM using a standard phase retrieval algorithm to produce PSFs of arbitrary shape.

Our described system can a) produce a PSF following a target shape, b) does use the temporal ability of the SLM to obtain a better fit by altering the pattern sent to the SLM over time, and c) even

allows for changing the PSF of the system during capture. As one particular application we show how our setup can be used to realize refocusing by encoding a phase pattern of a Fresnel lens on the SLM.

## Related Work

A Point Spread Function (PSF) is the intensity impulse response of an optical system. In computational photography applications the illuminant light is in most cases incoherent to a level far beyond the size of the detection pupil. As a consequence the PSF is determined by the square of the amplitude impulse response function [1]. At the same time the captured image can be computed by convolution of the PSF with the emitted intensity. The PSF is often used as a measure for the quality of an imaging system since the PSF captures the deviations from an ideal optical system, i.e. optical aberrations [2] such as chromatic aberrations and misfocus.

Pupil plane coding is a computational approach for engineering PSFs [3] by placing optical elements at the pupil plane. The pupil plane is the surface where all the chief rays from different object points cross the optical axis and pivot about. This allows for a uniform modulation of the incoming wavefront. A well-known approach is coded aperture, which uses an optimized occluder pupil pattern to preserve high frequency in case of defocus. Levin et al. [4] insert a patterned occluder within the aperture of the lens of a conventional camera which creates corresponding pre-designed PSFs at different depths. By estimating the deconvolution filter and introducing a sparse prior, image and depth are simultaneously recovered. Cossairt et al. [5] places an optical diffuser at the pupil plane. Due to light scattering, the PSFs of their system is invariant to the focal plane, which preserves high frequencies across different depths. A subsequent deconvolution is implemented to recover an image with extended depth of field.

Phase-coded aperture, often referred to as wavefront coding, places a phase modulator at the pupil, e.g. a plate of glass with a 3D profile or a Spatial Light Modulator (SLM) at, or close to the pupil plane of a photographic lens. The complex pupil function can be modified by optical aberration theory [2] or phase retrieval algorithms [6]. Herewith the shape of PSFs can be modulated.

The most known technique is wavefront coding for extended depth of field [7]. By designing a cubic shape 3D profile of the phase plate, the incoherent wavefront is altered and the PSFs become independent of the misfocus function. An image with extended depth of field is then recovered by a deconvolution of the intermediate image. Chi and George et al. [8] propose a lensless phase-coded aperture imaging system by combining a phase-only screen and a detector array. In [9], a phase-coded aperture lens is realized by a diffractive optical element to shape the PSFs.

A Spatial Light Modulator (SLM) is a real-time device

containing a microscopic pixel array that is capable of spatially modifying the incoming wavefront in response to optical or electrical control signals. Amplitude, polarization and phase of the complex optical wave distribution can be modified using SLMs. SLMs are widely used in display, holography, adaptive optics and optical computing. There are various types of SLMs, which operate by varying the pixel cell height or the refractive index of the cell [1]. With the latter type, pure optical phase modulation can be achieved by placing a linear polarizer in front. Phase profiles can then be encoded to manipulate the wavefront. For this reason, SLMs are widely used in adaptive optics applications in astronomy and biology to correct optical aberrations [10, 11]. In [12], a programmable diffractive lens phase profile is encoded on a SLM for ophthalmic applications. The reflectance display of Glasner et al. [13] uses a liquid crystal on silicon(LCoS) SLM to fabricate BRDFs. Carles et al. [14] uses an SLM as an adaptable phase mask for wavefront coding.

## PSF Engineering

PSF engineering can be achieved by modulating the pupil function. We use the phase-coded aperture approach to manipulate the PSF distribution by employing a phase-only SLM as a phase mask. This phase modulating SLM in the pupil plane acts similar to an optical lens: however, instead of spatially varying the thickness of a glass plate, we encode the SLM with a grey level image to program the refractive indices of the cell array. We use a standard phase retrieval algorithm to compute the phase pattern that is deployed on the SLM. Before we describe our phase estimation in more detail we will first revise the relation between the pupil function that we are going to modulate and the resulting PSF.

### Fraunhofer approximation

The PSF of an incoherent imaging system is the squared magnitude of the amplitude response function. Therefore the phase term of the response function provides an additional degree of freedom to optimize the PSF distribution.

According to the Fraunhofer approximation [1] the PSF of a diffraction limited optical system is obtained as the Fourier transform of the exit pupil function. The PSF of this system can be formulated as

$$I_f(x, y; \lambda) = \frac{A^2}{\lambda^2 f^2} \left| \iint_{-\infty}^{\infty} \mathcal{P}(x_0, y_0) \exp \left[ -j \frac{2\pi}{\lambda f} (xx_0 + yy_0) \right] dx_0 dy_0 \right|^2 \quad (1)$$

where  $A$  is a constant denoting the amplitude,  $f$  is the focal length and  $\mathcal{P}(x_0, y_0)$  is the complex pupil function. The complex generalized pupil function of a modulated system is

$$\mathcal{P}(x, y) = t_A(x, y) \exp[jW(x, y)] \quad (2)$$

where  $W(x, y)$  is the wavefront deformation function introduced by the SLM, and  $t_A(x, y)$  is the amplitude transmittance associated with the limited size of the lens pupil.

### Phase modulation

The PSF modelling problem can be seen as one of designing a proper function  $W(x, y)$ . For phase estimation we use the

commonly used Gerchberg-Saxton method [15]. An overview of our processing pipeline is shown in Fig. 1. We initialize the pupil function with a random phase and amplitude function. Within a single iteration, first the pupil function amplitude is set to be uniform within the pupil and zero outside. And the phase function remains as initialization. Then the wavefront is propagated to the image plane applying the Fraunhofer diffraction theory by Fourier transformation. At the image plane, the result of this transformation is calculated. We calculate the target amplitude function from the intensity pattern of the target PSF and substitute the calculated amplitude function with the target. The phase term of the wavefront distribution remains the same. Then it propagates back to the pupil plane by inverse Fraunhofer propagation through inverse Fourier transformation. After multiple iterations, we obtain the phase distribution of the pupil function. The algorithm error decreases due to Parseval's theorem.

We found both in the simulation and experiment that the generated single phase pattern does not produce a smooth PSF pattern. The main reason for this is that the iteration algorithm only finds approximated results with speckles. To alleviate the above mentioned effects, we generate an entire sequence of phase frames. In particular, we generate 60 frames of phase images with different initialized random pupil functions and combine them into a one second video featuring a frame rate of 60Hz. The video is then played back on the SLM and repeated during image capture.

## Experimental setup

To achieve PSF modulation, we use a liquid crystal on silicon PLUTO-VIS-016-HR by Holoeye Inc. It consists of a  $1920 \times 1080$  refractive liquid crystal cells on a silicon reflective layer with  $8\mu m$  cell pitch. A linear polarizer must be added in front of the SLM, because phase-only modulation applies only for polarized light. The maximum modulation range of the SLM is  $6.7\pi$  at  $532nm$ . The SLM operates as a display device employing a frame rate of 60Hz. By displaying an 8 bit grayscale image, the refractive index of each cell is changed by digital pulse code addressing. Each gray value of the displayed image relates to an addressing voltage, which drives the molecular orientation of the liquid crystal cell to switch its refractive index. We use a voltage-to-phase mapping for gamma correction. The limitation of the SLM is the addressing scheme. It is pulse code-based and hence produces temporal discrete electronic pulses to accumulate a certain averaged Z orientation of the parallel-aligned liquid crystal molecules. Therefore a phase jittering effect exists due to timing and orientation mismatch between different molecular orientations.

We designed a simple imaging setup having the SLM placed in front of a telephoto lens. We set the object at the far field, and use the small field of view of the telephoto lens to make the non-uniform phase coding negligible.

Our experimental setup is illustrated in Fig. 2. We put an artificial star with an aperture diameter of  $70\mu m$  at a distance of  $1.72m$  from the SLM surface to fulfill the far field condition of the Fraunhofer approximation [1]. We place a spectral filter in front of the star aperture to produce monochromatic illumination. The spectral filter is a VariSpec VIS-07-35. It has a  $35mm$  aperture and 33 color bands from  $400nm$  to  $720nm$  with a step-size of  $10nm$  and a bandwidth of  $7nm$ . In our experiments we used the  $550nm$  band. Then a linear polarizer is set between the star target and the SLM surface to enable phase-only modulation. The modulated light is

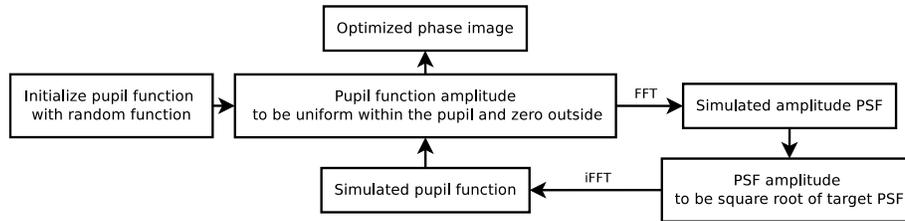


Figure 1: Overview of our optimization procedure for the pupil phase function.

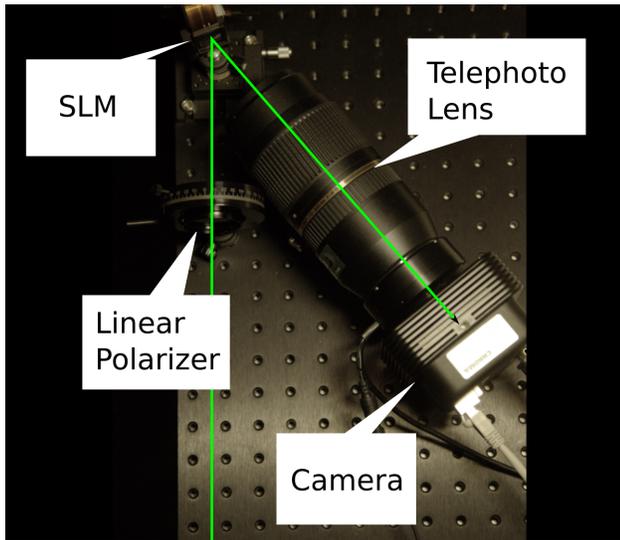


Figure 2: Imaging setup with SLM and a telephoto lens

captured by a camera with a telephoto lens. We use a Tamron 70-300mm  $f/4-5.6$  zoom lens. We employ a DVC4000C camera with a Bayer color filter array for image capturing. We pick the focal length 125mm to magnify the spiral PSF with a width less than 100 pixel. Finally, we capture all images with a HDR pipeline following [16] which uses an optimal weighting function under the assumption of compound-Gaussian noise.

## Results

We now demonstrate results for generating PSFs of various shapes and geometry. We show the optimized phase pattern and illustrate the limitation of displaying a static phase image rather than playing back an entire sequence of phase images. We also include a robustness analysis by comparing the PSFs obtained by using phase videos at different frame rates. We demonstrate a refocusing application with this system.

### Captured PSFs and optimized phase pattern

In Fig. 3 (a)-(e) we show various images of PSFs generated through phase modulation with our imaging setup. Note the large variety and the complex shapes that can be realized with our setup. All of these images have been logarithmically scaled for better visibility. The prominent central peak is caused by zeroth order diffraction of the SLM cell array and the non-modulated reflection. If necessary, it could be removed by subtracting an image with neutral phase pattern. The vertical strikes are caused by the diffraction of the non-modulating reflective SLM frame. Fig. 3 (g) shows an optimized phase pattern for a spiral PSF obtained by the Gerchberg-Saxton algorithm. In Fig. 3 (f) we present an image

of a real scene with LEGO bricks captured with the spiral-shaped PSF depicted in Fig. 3 (e). The lego scene is monochromatically illuminated by the same color filter illuminated from a broadband light source filtered by the same color filter that has been used for PSF capture. At careful inspection one can read off the spiral PSF at isolated highlights.

We can also vary the PSF pattern in a sequence of image capturing. We present an animation of an animated spiral PSFs in Fig. 4<sup>1</sup>. We produce a phase video for generating each frame of the PSFs. One can observe the smoothly shrinking sequence of the PSFs.

### PSF stability analysis

Experimentally we observed that the captured image of a generated PSF exhibits unwanted discontinuities as shown in Fig. 5 (a). These discontinuities are highly dependent on the initial phase function of the pupil function. Therefore one can increase the PSF stability by averaging the energy distribution caused by the phase modulation. Deploying the advantage of the SLM to play back videos, we generate a sequence of images to produce phase images produced by varying the initialization. During image capture, we repeatedly play back the video on the SLM. The resulting PSF can be thought of as a temporal average over the individual played-back video frames. Fig. 5 (b) shows the PSF obtained by playback of a phase video containing 60 frames over a duration of one second. Note the much improved smoothness in appearance through temporal averaging.

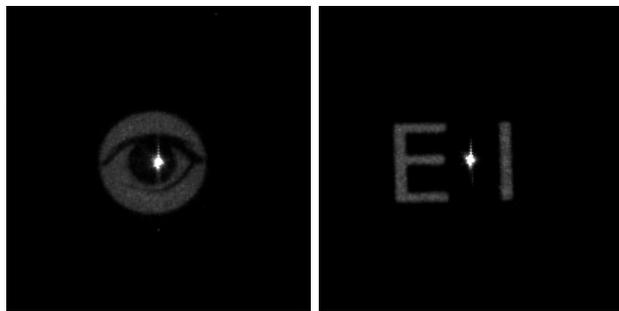
To analyze the stability of this procedure, we created multiple phase videos of different frame rates. We captured PSF images and compared the PSF smoothness. To this end we chose the 60fps phase video to be the ground truth PSF, which is depicted in Fig. 5 (b). We compute the mean square error between the ground truth PSF and the resulting PSFs obtained by phase videos with a varying frame rate of 5fps, 10fps, 15fps, ..., 55fps. Integration time was one second in all cases. We show the result of this comparison in Fig. 5 (c). The discontinuities decrease quickly with an increased frame rate and level off at a frame rate of 30fps.

### Refocusing

By modulating the phase term of an optical wavefront, its propagation will be redirected. A Fresnel lens phase pattern is a quadratic phase transformation function modulo the phase modulation range as shown in Fig. 6 (c). By adding a Fresnel lens phase pattern, the incoming wave is converged to a different focal plane from its original focal plane. In this experiment, we compare the images captured by displaying an uniform grayscale image and a Fresnel lens grayscale image on the SLM.

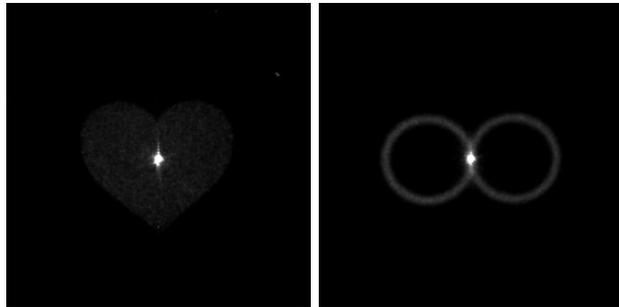
In practice, our refocussing technique is demonstrated in

<sup>1</sup>Please use Adobe Acrobat Reader for display of the animated image.



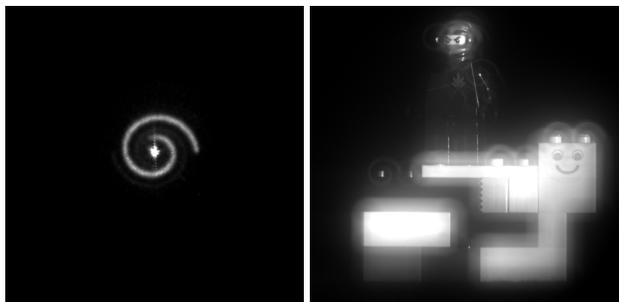
(a) Eye

(b) EI logo



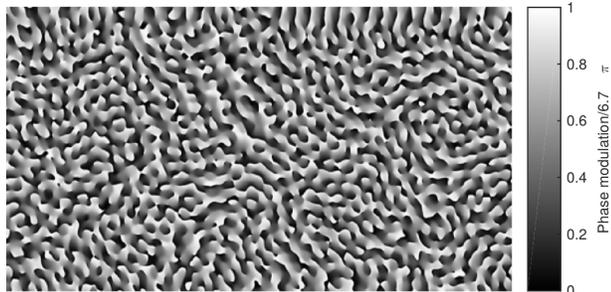
(c) Heart

(d) Infinity symbol



(e) Spiral

(f) Real scene captured with (e)



(g) Optimized phase pattern for the spiral PSF shown in (e). Note the spatial discontinuities.

Figure 3: Captured PSFs

Fig. 6. Three Lego bricks are placed at three different distances from the SLM. The camera is manually focused on the farthest object. We encode a uniform level grayscale image on the SLM to reflect the incoming light without any modulation. Fig. 6 (a) shows a captured image by encoding an uniform zero level gray image to the SLM. We then encode a Fresnel lens on the SLM to shift the focal plane to the Lego figure. We show the result in

Figure 4: Time-varying PSF in form of an animated spiral. Please use a pdf viewer that allows for animated image playback such as Adobe Acrobat Reader.

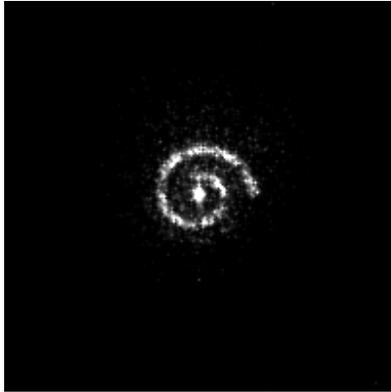
Fig. 6 (b). One can observe especially from the arm and the head of the Lego figure, a desired high frequency edge is reproduced by refocusing. One can also observe a halo effect on each object. This is caused by the residual non-modulated light.

## Discussion and Future work

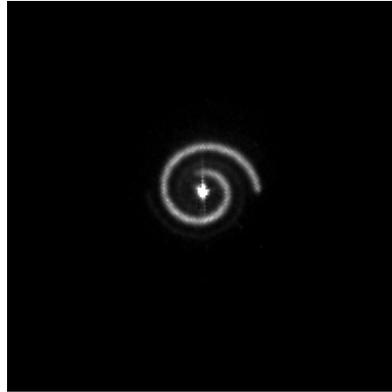
The main limitation of our current technique is twofold: the PSF contains speckles and a central peak. Smooth PSF patterns can be achieved by encoding a phase video to perform temporal averaging, of course at the cost of additional exposure time that is needed for image capture. The central peak of the PSFs are caused by the non-modulated reflection, zeroth order diffraction. The observed speckles are produced due to existence of interference. However, the temporal cost can be reduced by using the residual PSF as the target to compensate the PSF discontinuities in the future. In the future, one could try to obtain a smoother SLM pattern by exploiting transport theory as done for the design of caustics pattern [17]. The central peak response can be eliminated by capturing PSFs by encoding uniform level phase images onto the SLM and with a subtraction thereafter. The possibility of generating PSFs of user-specified geometry might result in novel deconvolution applications such as spatial-spectral multiplexing or motion blur removal. Even light field applications could be generated by encoding micro-lens array patterns on the SLM.

## Conclusion

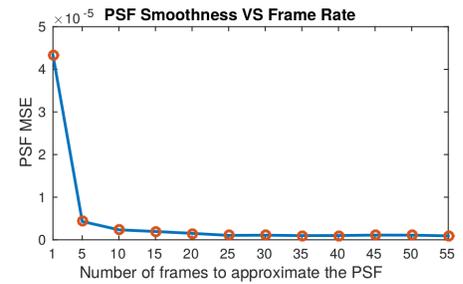
We introduced a novel phase-coded aperture technique that allows the generation of user-specified PSF geometry on a photographic camera. Using the standard Gerchberg-Saxton method, we produced 8 bit grayscale images to encode the phase pattern on the SLM to realize phase modulation. The resulting system allows for full control of the PSF even over time. This ability might enable a number of interesting novel imaging applications. We demonstrated its practical use in the case of digital refocusing. The possibility of generating PSFs of user-specified geometry might result in novel deconvolution applications such as spatial-spectral multiplexing or motion blur removal. Even light field applications could be generated by encoding micro-lens array patterns on the SLM.



(a) PSF when displaying a single static phase on the SLM



(b) PSF when averaged over 60 phase patterns displayed on the SLM



(c) PSF reconstruction error vs number of temporally averaged frames

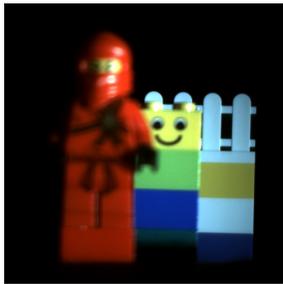
Figure 5: PSF stability analysis

## Acknowledgements

This work was partly supported by "Kooperatives Promotionskolleg Digital Media" at Stuttgart Media University and the University of Tübingen.

## References

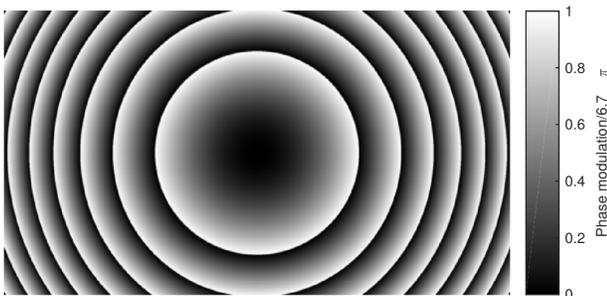
- [1] Joseph W Goodman. *Introduction to Fourier optics*. Roberts and Company Publishers, 2005.
- [2] W. Smith. *Modern Optical Engineering, 4th Ed*. McGraw Hill professional. McGraw-Hill Education, 2007.
- [3] Changyin Zhou and Shree K Nayar. Computational cameras: convergence of optics and processing. *Image Processing, IEEE Transactions on*, 20(12):3322–3340, 2011.
- [4] Anat Levin, Rob Fergus, Frédo Durand, and William T Freeman. Image and depth from a conventional camera with a coded aperture. In *ACM Transactions on Graphics (SIGGRAPH)*, 2007.
- [5] O. Cossairt, C. Zhou, and S.K. Nayar. Diffusion Coding Photography for Extended Depth of Field. *ACM Trans. on Graphics (SIGGRAPH)*, 2010.
- [6] James R Fienup. Phase retrieval algorithms: a comparison. *Applied optics*, 21(15):2758–2769, 1982.
- [7] Edward R Dowski Jr and W Thomas Cathey. Extended depth of field through wave-front coding. *Applied Optics*, 34(11):1859–1866, 1995.
- [8] Wanli Chi and Nicholas George. Phase-coded aperture for optical imaging. *Optics Communications*, 282(11):2110–2117, 2009.
- [9] Yifan Peng, Qiang Fu, Hadi Amata, Shuochen Su, Felix Heide, and Wolfgang Heidrich. Computational imaging using lightweight diffractive-refractive optics. *Optics Express*, 23(24):31393–31407, 2015.
- [10] R.K. Tyson. *Principles of Adaptive Optics, Fourth Edition*. CRC Press, 2015.
- [11] Joel A Kubby. *Adaptive Optics for Biological Imaging*. CRC press, 2013.
- [12] María S Millán, Elisabet Pérez-Cabré, Lenny A Romero, and Natalia Ramírez. Programmable diffractive lens for ophthalmic application. *Optical Engineering*, 53(6):061709–061709, 2014.
- [13] Daniel Glasner, Todd Zickler, and Anat Levin. A reflectance display. *ACM Transactions on Graphics (SIGGRAPH)*, 2014.
- [14] G Carles, G Muyo, S Bosch, and AR Harvey. Use of a spatial light



(a) Defocused lego figure



(b) Refocused lego figure



(c) Phase pattern of a Fresnel lens

Figure 6: Refocusing by implementing a Fresnel lens phase pattern

modulator as an adaptable phase mask for wavefront coding. *Journal of Modern Optics*, 57(10):893–900, 2010.

- [15] Ralph W Gerchberg. A practical algorithm for the determination of phase from image and diffraction plane pictures. *Optik*, 35:237, 1972.
- [16] Miguel Granados, Boris Ajdin, Michael Wand, Christian Theobalt, Hans-Peter Seidel, and Hendrik PA Lensch. Optimal HDR reconstruction with linear digital cameras. In *CVPR*, 2010.
- [17] Yuliy Schwartzburg, Romain Testuz, Andrea Tagliasacchi, and Mark Pauly. High-contrast computational caustic design. *ACM Transactions on Graphics (SIGGRAPH)*, 2014.

## Author Biography

*Jieen Chen received his BS in Optical Information Science and Technology (2012) from Shandong University and his master of Photonics (2015) Friedrich Schiller Universität Jena. He is now a PhD candidate in Eberhard Karls Universität Tübingen. His research work focuses on Programmable Optics in Computational Photography.*

*Michael Hirsch is a Senior Research Scientist at the Max Planck Institute for Intelligent Systems in Prof. Bernhard Schölkopf's department of Empirical Inference and is leading a research group on computational imaging. His research interests cover a wide range of signal and image processing problems in scientific imaging as well as computational photography. Dr Hirsch studied physics and mathematics at the University of Erlangen and at Imperial College London. He received a Diploma in theoretical physics in 2007, before joining Prof. Dr. Bernhard Schölkopf's research group at the Max Planck Institute for Biological Cybernetics in Tübingen, Germany. After his doctoral studies he worked as a post-doctoral researcher at University College London from 2011 to 2014.*

*Rainer Heintzmann holds the Nanobiophotonics Professorship for Physical Chemistry of Institute of Physical Chemistry in Friedrich-Schiller-Universität Jena. He is also the head of Microscopy Research Unit in Leibniz Institute of Photonic Technology. He finished his diploma in University of Osnabrück. He had his PhD in Physics in Applied Optics and Information Processing in University of Heidelberg. He spent two years (2000-2001) as a postdoctoral fellow at the Max-Planck-Institute for Biophysical Chemistry, Department of Molecular Biology. From 2002 to 2004, he was the head of "Multidimensional Microscopy" research group in the Department of Molecular Biology at MPI for Biophysical Chemistry. He was the head of the Biological Nanoimaging research group in Randall Division of King's College London from 2004 to 2015. His research focuses on imaging cellular function at high resolution. His group develops techniques to measure multidimensional information in small biological objects such as cells, cellular organelles or other small structures of interest. A further interest is in computer-based reconstruction methods.*

*Bernd Eberhardt received a masters degree in mathematics from the University of Massachusetts at Amherst and a Diploma in Mathematics at the University of Tübingen. In 1994 he received a PhD in Mathematics from the University of Tübingen and finished his habilitation in computer graphics in 2001 under the guidance of Dr. Wolfgang Strasser. Currently, Dr. Eberhardt is full professor at the Stuttgart Media University, Germany and head of the computer animation department. His research interests include computer animation, visualization, computer graphics and image processing as well as computer vision. His main research areas are in physically based modeling, motion capture and motion control and image based rendering.*

*Hendrik P. A. Lensch holds the chair for computer graphics at Tübingen University. He received his diploma in computer science from the University of Erlangen, in 1999. He worked as a research associate at*

*the computer graphics group at the Max-Planck- Institut für Informatik in Saarbrücken, Germany, and received his PhD from Saarland University, in 2003. He spent two years (2004 to 2006) as a visiting assistant professor at Stanford University, USA, followed by a stay at the MPI Informatik as the head of an independent research group. From 2009 to 2011, he was a full professor at the Institute for Media Informatics at Ulm University, Germany. In his career, he received the Eurographics Young Researcher Award 2005, was awarded an Emmy-Noether-Fellowship by the German Research Foundation (DFG) in 2007 and received an NVIDIA Professor Partnership Award in 2010. His research interests include 3-D appearance acquisition, computational photography, global illumination and image-based rendering, and massively parallel programming.*