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INSTITUT FÜR  
TECHNISCHE OPTIK  
UNIVERSITÄT STUTTGART



Universität Stuttgart

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ANNUAL REPORT 2009/2010



## Active Optical Systems and Computational Imaging

Stable 3D trapping using axially extended intensity distributions .....	36
<i>Supported by: BMBF (FKZ 13N8809)</i>	
<i>Project: "AZTEK"</i>	
Dynamic correction of aberrations using a combination of stochastic optimization and gradient-based measurement .....	37
<i>Supported by: BMBF (FKZ 13N8809)</i>	
<i>Project: "AZTEK"</i>	
Dynamic Holography-based Vibrometry .....	38
<i>Supported by: BMBF (FKZ 13N9339)</i>	
<i>Project: "Holovib"</i>	
White-light interferometric method for secure data transmission .....	39
<i>Supported by: Graduate School of Excellence advanced Manufacturing Engineering GSaME</i>	
Surface Analysis of Honed Objects.....	40
<i>Supported by: AUDI</i>	
<i>Project: "SAHO"</i>	
Wavefront sensing for applications in adaptive optics.....	41
<i>Supported by: DFG (OS 111/29-1)</i>	
<i>Project: "SHAO"</i>	

## Stable 3D trapping using axially extended intensity distributions

S. Zwick, C. Schaub, T. Haist, W. Osten

In the course of the BMBi project "Präzisions-Charakterisierung von weißen LEDs und LED-Beleuchtungen", a simulation scheme for simulating a linear grating spectrometer with high precision and high speed was developed.

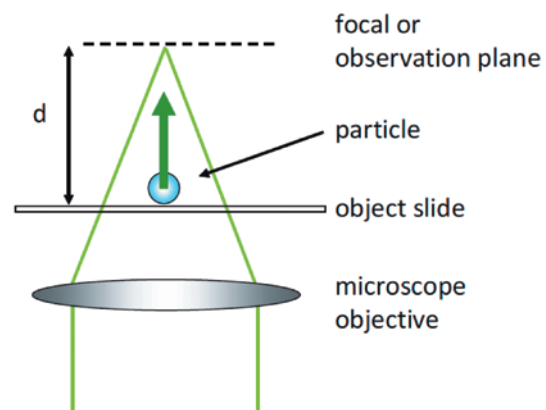
The performance of high end spectrometers is typically limited by stray light in the optical system. Figure 1 shows the optical setup of a typical array spectrometer in Czerny-Turner configuration. Figure 1 also shows the ray paths for monochromatic illumination of seven diffraction orders of the grating. All the rays hitting the spectrometer housing will be scattered diffusely and may ultimately still reach the detector.

In order to model this behaviour of the spectrometer with high accuracy, a RCWA simulation using an AFM scan of the grating surface was used to rigorously calculate the efficiencies of the diffraction orders in dependence of the wavelength of the illumination. Furthermore stray light measurements were conducted to phenomenologically account for the diffuse scattering of the grating and the spectrometer housing.

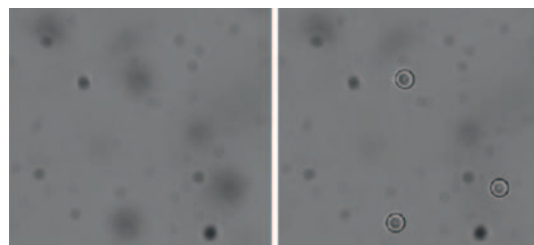
This data was used to create special reflectance functions for the grating and the housing parts for a non sequential ray tracing model of the spectrometer system. However in order to simulate intensity distributions with a SNR of 104, that are typical in spectrometers, at least 108 rays are required to reach the detector.

Tracing times for raysets of that size manifest a serious bottleneck in the systematic optimization of spectrometers. Therefore a non sequential ray tracing tool was developed that is highly specialized for simulating intensity images. The tool can be executed using either a single CPU, multiple CPUs in parallel or modern graphics processing units (GPU). Figure 2 shows the computation times of this tool in comparison to the commercial software ASAP. At a raynumber of 108 the developed tool running on GPU is about 400 times faster than the commercial tool. E.g. the simulation of monochromatic illumination that took a little more than 3h with ASAP on an Intel i7 machine with 3.2 GHz could be done in about 30 s using a GTX460 graphics card.

Future work will elaborate on possibilities to use this kind of high speed simulation for automated stray light optimization of general optical systems.



**Fig. 1:** The particle is pushed to the focal plane by the forward scattering force. The axicon guides the object along the way.



**Fig. 2:** Experimental result for polystyrene beads. Left: Objects in the "wrong" plane, not trapped. Right: Switched on holograms (including axicon term) leads to trapping and movement of the particles into the focal plane.

Supported by: BMBF (FKZ 13N8809)  
Project: "AZTEK"

### References:

- [1] Zwick, S.; Schaub, C.; Haist, T.; Osten, W. "Light fields with an axially expanded intensity distribution for stable three-dimensional optical trapping" *Optics Express* 18, 19941-19950 (2010).
- [2] Zwick, S.; Haist, T.; Miyamoto, Y.; He, L.; Warber, M.; Hermerschmidt, A.; Osten, W. "Holographic twin traps", *J. Opt. A: Pure Appl. Opt.* 11, 034011 (2009).
- [3] Zwick, S., Haist, T., Warber, M., Osten, W., "Dynamic holography using pixelated light modulators," *Appl. Opt.* 49, F47-F58 (2010).

## Dynamic correction of aberrations using a combination of stochastic optimization and gradient-based measurement

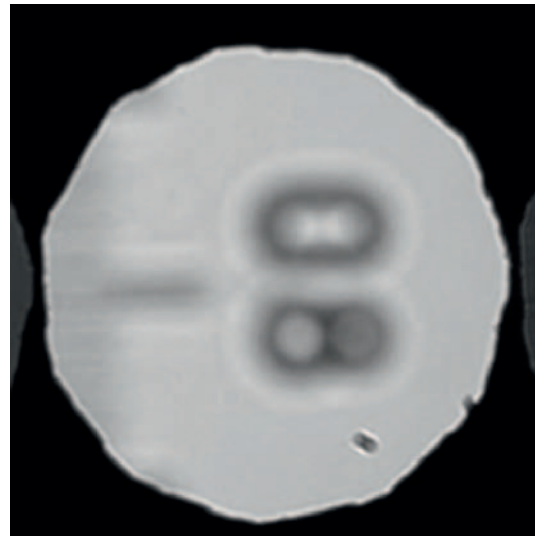
*M. Warber, S. Maier, T. Haist, W. Osten*

Typically, aberrations in high-quality microscopes that degrade the image are due to the specimen to be imaged or from the solution in which the specimen is embedded. Furthermore, aberrations might be introduced by the handling devices (cover slide, microfluidics, multiwell plates, etc.). Therefore, the aberrations are static for one setting, but variation of the specimen or the system will change the aberrations.

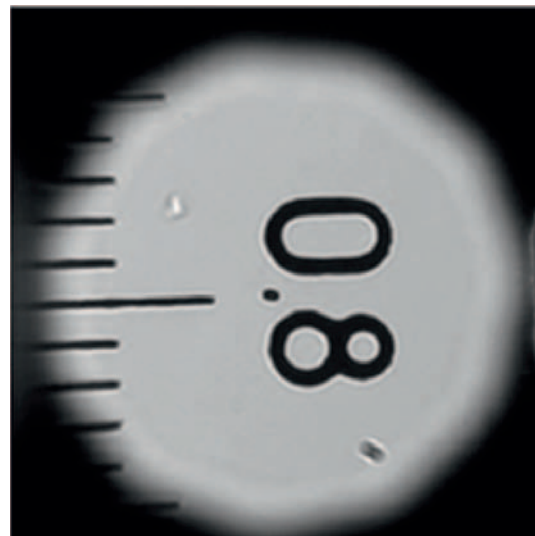
We use a combination of a gradient measurement system that is related to Shack-Hartmann sensing and stochastic optimization. The core element is the liquid-crystal display (LCD) that is already present in spatial light modulator-based microscopes. The LCD is located in a plane conjugate to the pupil of the microscope objective and in this plane the aberrations are corrected by writing the phase conjugate of the aberrated wavefront into the (phase-only) LCD. Before this can be achieved, the aberrations are measured. To this end, we first write different localized gratings into the LCD which lead to shifted (low resolution) copies of the object in the camera plane. Local wavefront tilts due to the aberration will lead to additional shifts of the corresponding copies and are detected by digital correlation of the image with reference images taken for the central part of the aperture. This way the local gradients in the pupil are determined and numerical integration (using SV-decomposition) finally leads to an estimate of the wavefront error.

In a second step, this wavefront is further stochastically varied until the image quality is optimum. The optimization criterion is the ratio between the high-pass and low-pass Fourier components.

To obtain impressive corrections, typically some hundred camera frames are necessary. Therefore a setup time in the range of 1 minute for a typical experiment would be necessary but the system can achieve the correction without additional hardware (an external wavefront sensor).



*Fig. 1: Without correction.*



*Fig. 2: With correction.*

*Supported by: BMBF (FKZ 13N8809)  
Project: "AZTEK"*

### References:

- [1] Haist, T.; Hafner, J.; Osten, W. "Scene-based wavefront correction with spatial light modulators" Proc. SPIE 7064, 70640M, (2008). [2] Warber, M.; Maier, S.; Haist, T.; Osten, W. "Combination of scene-based and stochastic measurement for wide-field aberration correction in microscopic imaging" Appl. Opt. 49, 5474-5479 (2010).

## Dynamic Holography-based Vibrometry

*T. Haist, S. Zwick, F. Schaal, M. Warber, W. Osten*

In the course of the BMBi project "Präzisions-Charakterisierung von weißen LEDs und LED-Beleuchtungen", a simulation scheme for simulating a linear grating spectrometer with high precision and high speed was developed.

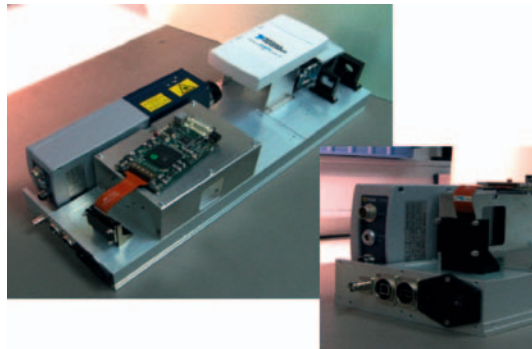
The performance of high end spectrometers is typically limited by stray light in the optical system. Figure 1 shows the optical setup of a typical array spectrometer in Czerny-Turner configuration. Figure 1 also shows the ray paths for monochromatic illumination of seven diffraction orders of the grating. All the rays hitting the spectrometer housing will be scattered diffusely and may ultimately still reach the detector.

In order to model this behaviour of the spectrometer with high accuracy, a RCWA simulation using an AFM scan of the grating surface was used to rigorously calculate the efficiencies of the diffraction orders in dependence of the wavelength of the illumination. Furthermore stray light measurements were conducted to phenomenologically account for the diffuse scattering of the grating and the spectrometer housing.

This data was used to create special reflectance functions for the grating and the housing parts for a non sequential ray tracing model of the spectrometer system. However in order to simulate intensity distributions with a SNR of 104, that are typical in spectrometers, at least 108 rays are required to reach the detector.

Tracing times for raysets of that size manifest a serious bottleneck in the systematic optimization of spectrometers. Therefore a non sequential ray tracing tool was developed that is highly specialized for simulating intensity images. The tool can be executed using either a single CPU, multiple CPUs in parallel or modern graphics processing units (GPU). Figure 2 shows the computation times of this tool in comparison to the commercial software ASAP. At a raynumber of 108 the developed tool running on GPU is about 400 times faster than the commercial tool. E.g. the simulation of monochromatic illumination that took a little more than 3h with ASAP on an Intel i7 machine with 3.2 GHz could be done in about 30 s using a GTX460 graphics card.

Future work will elaborate on possibilities to use this kind of high speed simulation for automated stray light optimization of general optical systems.



**Fig. 1:** Prototype of SLM-based scanning vibrometer.

*Supported by: BMBF (FKZ 13N9339)  
Project: "Holovib"*

### References:

- [1] Schaal, F.; Warber, M.; Rembe, C.; Haist, T.; Osten, W. "Dynamic multi-point vibrometry using spatial light modulators", Proc. Fringe 2009, 529-531 (2009)
- [2] Zwick, S.; Warber, M.; Haist, T.; Schaal, F.; Osten, W.; Boedecker, S.; Rembe, C. „Advanced Scanning Laser-Doppler Vibrometer with Computer Generated Holograms“ AIP Conf. Proc. 1253, pp. 279-290 (2010).

## White-light interferometric method for secure data transmission

*T. Haist, W. Osten*

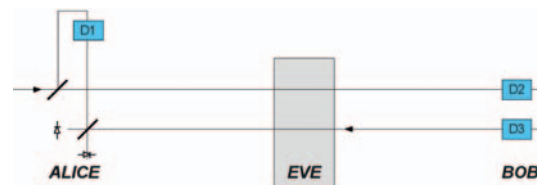
It is well known that secure data transmission can be achieved if a random key of adequate length can be securely interchanged between the two partners (typically called "Alice" and "Bob"). Once this secure key is distributed, simple encryption/decryption can be achieved, e.g. by the XOR operation.

Unfortunately, for a lot of application this is not feasible (e.g. ordering over the internet). In this case two methods to distribute the key between Alice and Bob are available. Public key cryptography using public known keys and mathematical methods (unfortunately with unproven security) might be employed. One example is the RSA public-key system which is based on the unproven difficulty of factoring large integers. Other methods rely on the similarly unproven difficulty of computing discrete logarithms. Even if the algorithms could be proven secure, this security still would be only given for the transmission of small messages and, even worse, quantum computing can be used to successfully attack them. The second and currently only (hopefully) secure method to generate a secret shared key between two parties that are separated by a certain distance is quantum key distribution (QKD). Different quantum methods have been proposed but the corner stones of these techniques are the no-cloning theorem of quantum physics, the non-commutativity of certain pairs of observables (e.g. different polarizations) and the use of single photon. Practical systems using QKD have been realized but the use of single photons over large distances is still technically challenging and expensive.

We propose to use a white-light interferometric approach as shown in Fig. 1 to achieve the secure key distribution. Alice randomly chooses the delay  $D1$  to be a natural number between 1 and  $N$ . Bob does the same for  $D2$ . Now, Bob sets the delay  $D3$  randomly to 0 or half of the wavelength. Alice then sends a short wavepacket with (on average)  $M$  photons ( $M < N$ ) and coherence length  $L < 1$  to Bob and measures at her interference detector if interference is present. If yes then she knows that  $D1$  was equal to  $D2$  and then she can find the unknown random bit of Bob,

namely  $D3$  by the measurement result. This process is repeated for a large number of Bits. Finally, Alice sends Bob the information which bits have been transmitted with  $D1$  being equal to  $D2$ . These bits, which are now known only to Alice and Bob, will be used as a secure key for classical data transmission.

Different possible attacks of an eavesdropper can be analysed and the simple basic protocol described above has to be changed in some minor ways to prevent these attacks [1]. Compared to quantum key distribution the main advantage is that the system achieves the security without the need for single photon operation. Therefore, potentially it should be much simpler to realize such a system. For the operation, "quantized waves" are necessary but no typical quantum features like entanglement or non-locality are necessary. Unfortunately, at the moment we do not have a sound prove of the security of the method.



**Fig. 1:** WLI-based method for secure key distribution.

Supported by: BMBF (FKZ 13N8809)  
Project: "AZTEK"

### References:

- [1] Haist, T.; Hafner, J.; Osten, W. "Scene-based wavefront correction with spatial light modulators" Proc. SPIE 7064, 70640M, (2008). [2] Warber, M.; Maier, S.; Haist, T.; Osten, W. "Combination of scene-based and stochastic measurement for wide-field aberration correction in microscopic imaging" Appl. Opt. 49, 5474-5479 (2010).

## Surface Analysis of Honed Objects

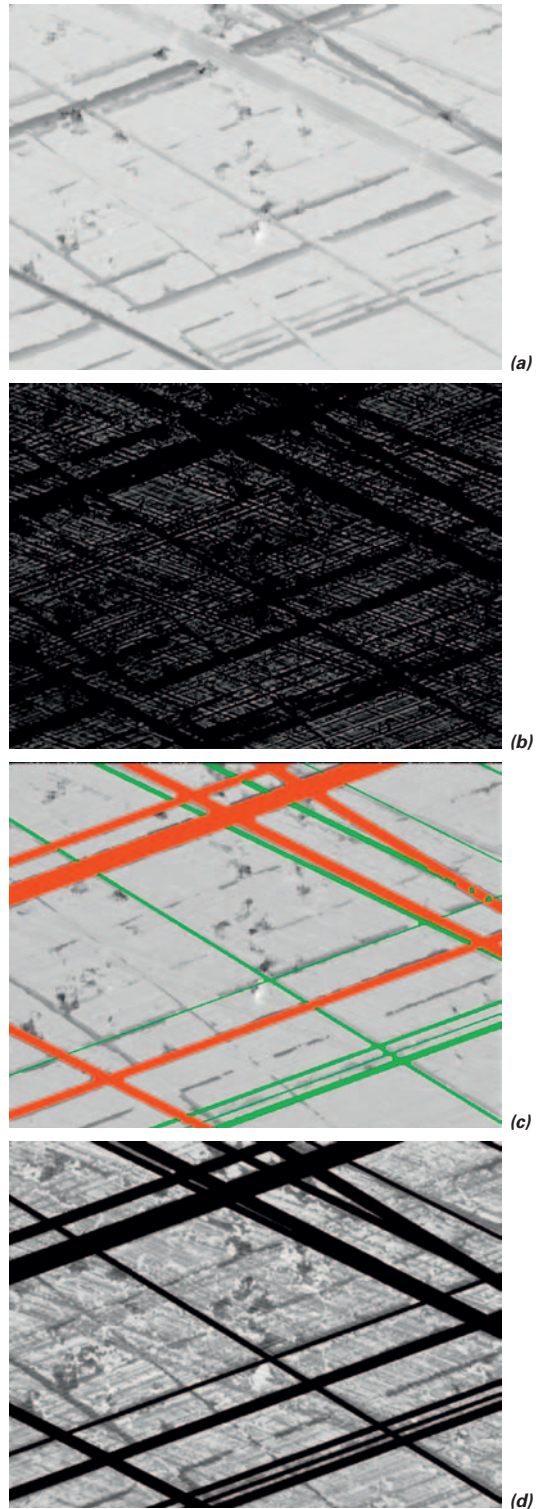
*A. Burla, T. Haist, S. Pehnelt, W. Osten*

Automatic surface analysis of honed objects (SAHO) is a software module developed to detect, separate, visualize, and analyse thin, medium, and thick grooves on honed objects. For this purpose, measurements of the specimen obtained using a white light interferometer have been used. The process involves taking into consideration several problems and constraints (e.g. poor contrast, complicated structures on the surface, curved or overlapping grooves, grooves in several arbitrary angles, etc). Existing methodologies use Hough transformations and Fourier based filtering to separate the grooves. This method is very sensitive and hence not flexible. Another Fourier based method uses only 2d projections of 3d data.

Using the Abbott Firestone curve (also known as material ratio curve), a preliminary separation of the thin grooves, from the medium and thick grooves of the image can be achieved. The Radon transform is used on the thin grooves image to estimate the thin groove angles. Based on these groove angles a filter mask is generated to separate the thin grooves using Fourier based filtering. (Fig.1b shows the resulting thin grooves) Similarly, the Radon transform is used to estimate the groove angles of the medium and thick grooves.

Unlike thin groove separation, thick and medium grooves are separated using a special groove detection algorithm that takes the groove angles as input. For every angle the image is scanned to find all corresponding grooves within the required constraints (e.g. minimum width, depth, groove quality factor etc.). The grooves can later be separated into thick and medium based on their widths. (See Fig.1c).

An average volume of the thin grooves is estimated using mathematical morphology. Also, several groove properties like primary groove angles, length, position, width, average depth, average volume etc are computed for the medium and thick grooves.



**Fig. 1:** (a) Measured surface image, (b, c) visualization of the thin, medium and thick grooves, and (d) visualization of the background after eliminating the grooves.

*Supported by: AUDI  
Project: "SAHO"*

## Wavefront sensing for applications in adaptive optics

*S. Dong, T. Haist, W. Osten, T. Ruppel, O. Sawodny*

The goal of DFG project "SHAO" is to develop a precise and real-time sensing and control system to increase the spatial and temporal resolution in adaptive optics. A combined optimization of the control strategy and the wavefront sensing is the cornerstone of the joint project of the Institute for Systemdynamics (ISYS) and ITO. One important task is the characterization of the dynamic response of the wavefront corrector (a deformable mirror (DM)). This response is used to create a feedforward control of the membrane allowing for faster settling time and reduced membrane vibrations. Fourier transform (FT) based interferometry is used to meet the measurement requirements of high speed and spatial sampling rate (SSR).

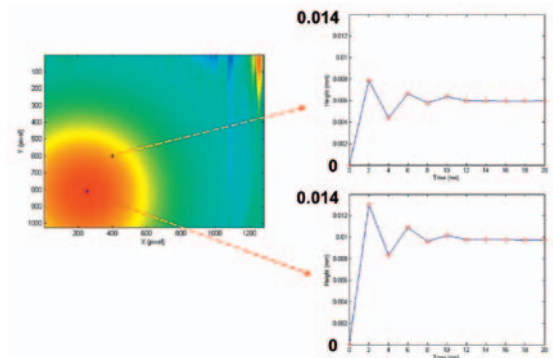
The interferometer is constructed based on a Twyman-Green geometry ( $\lambda = 633\text{nm}$ ,  $1280 \times 1024$  pixel, CMOS camera), and a Kepler telescope is employed to image the DM onto the CMOS sensor. The reference mirror is tilted to introduce a carrier frequency. The interferogram can be evaluated by the FT based carrier frequency method to extract the object height information. For eliminating the aberration introduced by the interferometer and unmodulated mirror and for removing the carrier frequency, the phase map of a reference surface where no voltage is applied to actuators is subtracted to obtain the final dynamic deformation.

Because the strongly curved DM brings dense fringes, only quarter of the DM can be tested in one shoot with speed of 500 fps in full resolution. Series of interferograms are recorded sequentially and processed afterwards to characterize the dynamic response of the DM. An exemplary result is shown in Fig. 1. The measurement results of four quarters of DM can be stitched at the end. With this technique, the surface of the DM can be measured with a resolution of 100 nm peak-to-valley. The setup is also used for static measurements (static influence function). In this case phase shifting with a piezocontroller is performed. In this case the whole membrane is imaged onto a  $2048 \times 2048$  pixel CCD camera.

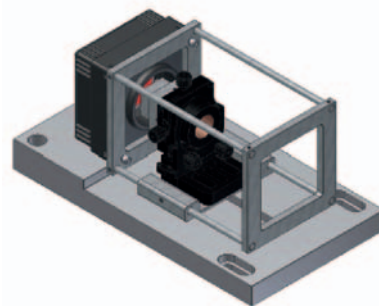
Apart from the modal wavefront sensor that is planned for the final control loop a fast Shack-Hartmann wavefront sensor (SHWFS) running at 1000 Hz has been implemented. The system parameters (NA of micro-lens, SSR of SHWFS)

are optimized with consideration of the typical wavefront aberrations that are caused by certain strength of atmosphere turbulence as well as the system bandwidth. The CAD model is shown in Fig. 2. The calibration strategy and image processing ensures the wavefront sensing accuracy of  $\lambda/50$  RMS. Using a quad-core CPU In C, the bandwidth of the SHWFS reaches 600 HZ with  $8 \times 8$  subapertures. This sensor is used for testing the control strategy of DM in closed-loop operation.

Future work will focus on the design and implementation of a high speed modal wavefront sensor. Efforts will also be made to improve the speed of SHWFS by performing the wavefront reconstruction on the graphics processing unit (GPU) of the PC.



**Fig. 1:** Dynamic response of the DM when one actuator is triggered with certain voltage.



**Fig. 2:** The CAD model of SHWFS in use. The micro-lens array is fixed on a Five Axis Lens Positioner from Newport.

Supported by: DFG (OS 111/29-1)  
Project: "SHAO"

Cooperation with: Institute for Systemdynamics,  
University of Stuttgart

