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Summary

Wave front sensor based on digital mirror matrix for functional characterization of freeform ophthalmic optics

Common functional testing of freeform optics, such as progressive eyeglasses, is usually carried out by means of measuring the refractive power pointwise at up to 10 measurement points and only 3 according to the *DIN EN ISO 21987* standards. Here a wave-front based test method is presented which allows to test the entire specimen by scanning the transmitted wave front with a micromirror array (DMD). This enables to increase the measurement range related to the maximum wavefront slope, compared to conventional Shack-Hartmann sensors.

1 Introduction

Shack-Hartmann sensors (SHS) are often used to measure wave fronts, for example in astronomy (adaptive optics), for topography and functional measurement of optical elements, for studying a laser's beam profile as well as testing the human eye in medicine. However, the sensor measurement range for wave front aberration, as well as the lateral resolution, significantly limit the application of these sensors in optical testing, since freeform optics and aspherical lenses frequently produce immeasurable wave fronts. Till now, cost-intensive deflectometric systems are often utilized in research and development to study an entire eyeglass lens surface. These work either in transmissive or reflective geometrical layout, but they also only offer a sufficient measurement range for a fraction of the production spectrum nowadays. The limited range of existing Shack-Hartmann sensors does not suffice for high-resolution, flexible eyeglass lens testing yet. Therefore, an innovative wave front measurement method utilizing a modified Shack-Hartmann working principle is developed in this work. It provides a higher lateral resolution as well as a larger measurable area, exceeding the measurement performance of currently available systems.

The developed measurement method will increase the dynamic range (ratio between maximum measurable wave front aberration to smallest change in wave front aberration) by theoretically as much as an order of magnitude compared to existing solutions. The dynamic range depends directly on the ratio between microlens quantity to pixel quantity: in existing SHS-based sensors, each microlens tyicacally corresponds to a fixed pixel area on the imaging sensor. Therefore, the light spots on the sensor correspond one-to-one to the microlenses above them. The new system will overcome the typical limitations of wavefront sensors by uniquely identifying each subaperture with the help of a reflective mask and assigning each of them without ambiguity to the light spots on the sensor.

The measurement performance of the new developed system is accomplished by utilizing micromirror arrays - a small chip with more than 1 000 000 micro mirrors, of which each can be controlled individually (this is referred to as DMD-based wave front measurement, with DMD standing for Digital Micromirror Device). The developed system will thereby be able to measure entire surfaces, as well as the optical function of complex lenses, such as strong aspherical lenses, and freeform lenses. In principle the proposed method can be utilized in both a transmissive as well as reflective measurement mode and with unprecedent lateral resolution determined mainly by the pixel pitch of 10.80 µm of the DMD and the magnification factor of the utilized telescope.

A number of ideas have been pursued in order to exceed the limits of classical Shack-Hartmann based setups. Transparent Liquid Crystal Displays (LCD) represent one important approach: an advanced setup using the SHS working principle utilizes a LCD instead of a microlens array. Behind the LCD, there is a single lens with a large numerical aperture. The LCD allows for scanning the wave front by dividing it up in pieces (so-called subapertures) and analyzing each subaperture. The single lens is the imaging optics for all subapertures [OLH00]. The advantage of this concept is the number of measurement points, as well as the variable sensor space available for each measurement.

Another setup, referred to as "adaptive Shack-Hartmann Sensor" (aSHS) also uses a LCD to enhance the SHS. The LCD serves as configurable aperture, as well as diffractive imaging lens [SLT03, LSTO04]. For each subaperture, the LCD shows a diffractive gray-tone pattern, which acts as a holographic lens. These diffractive lenses can be adjusted in all their parameters, and their total number can be scaled up. This special version of the SHS is very flexible due to the variable focal length. Theoretically it can therefore measure a broad range of wave front aberrations. The setup also allows for scanning the wave front, by individually turning single subapertures/lenses on or off. This also widens the measurable range.
For both of the concepts presented above, the number of subapertures - and thus, the number of measurement points - is significantly limited. In order to exceed the CCD sensor's minimum intensity threshold, and in order to achieve a working diffractive lens, each subaperture requires approximately 40×40 pixels on the LCD. Therefore, the two methods both typically yield less than 1,000 measurement points.
First, the developed system is compared to commercially available Shack-Hartmann sensors as well as adaptive Shack-Hartmann sensors in Table 0.1. One can easily recognize the potential in the DMD-based setup since it offers distinctive advantages in a number of applications for optical testing, especially in case the production environment does not allow e.g. interferometric methods due to vibrations and alignment requirements or in case a measurement system needs to test all types of optics that occur in a production line.

2 Measurement Setup

The measurement method enhances both the lateral resolution and the dynamic range in comparison to available conventional Shack-Hartmann based sensors. Using a switchable micromirror array (DMD) and a PSD detector, it is possible to scan an entire wave front sequentially by directing only small subapertures of it to the sensor (see Fig. 0.1). By controlling individual micromirrors, single subapertures are reflected through a focusing lens onto the sensor. The rapid switching speed of the DMD allow to scan the whole wave front in less than 10 seconds mainly depending on the lateral resolution, detector sensitivity and the applied laser power. The maximum lateral resolution that can be achieved depends on

	SHS	Adaptive SHS (aSHS)	New approach ≈
No. of subapertures (corresponds approx. to lateral resolution)	116×116 (Microlenses)	16×12 (Diffractive lenses on 1024×768 pix. LCD)	Max. 1.000.000 (Micromirrors on the DMD)
Detector resolution	4 megapixels (Approx. 17×17 pixel/subap.)	Off-the-shelf camera (opt.: using entire detector for single subap.)	1µm steps on $22\times22\,\mathrm{mm}^2$ ≈61 MP
Max. measurable aberration	Approx. 2°	Approx. 10°	Approx. 10°

Table 0.1.: Comparison between DMD-based and SHS-bases wave front measurement.

the number of micromirrors and the mirror size of the DMD (Texas Instruments DLP Discovery 4100, 1024×768 pixels, pixel pitch: 13.68 µm; alternatively: 1920×1080, pixel pitch: 10.80 µm). Since the total sensor area is available for the measurement of each subaperture, the measurable range is significantly increased. Scanning also solves the problem of ambiguous spot assigning - the task of matching a light spot (or rather the center of an intensity distribution) on the detector to the subaperture it stems from, but which becomes even more challenging for diffractive intensity patterns. Due to the analog output of the PSD, the spot position is available with negligable retardation, with light intensity (and thus signal intensity) being the main limiting factor since the switching time of a DMD is ≈2 µs.

For the experimental investigations a demonstration setup based on a relatively simple telescope has been developed (Fig. 0.1) consisting of two high-precision biconvex achromatic lenses. Additionally, besides commercially available rail systems, a number of custom designed opto mechanics and mounting parts had to be designed and manufactured.

In the following, the characteristics of the real demonstration setup are summarized in brief, comparing it to the calculations and simulations carried out in the development. Furthermore, the actual measurement performance is determined in this work, and utilizing these parameters, calibration routines to quantify vital characteristics such as measurement range, resolution and dynamic range are developed. The demonstration setup is characterized with respect to repeatability, linearity, stability, and sensitivity to ambient environmental factors.

3 Measurement Performance

The calibration of the system is basically performed by a characterisation of its non linear behavior in case of defined plane and spherical wave fronts coupled into the system's telescope at defined angles. The results are processed to calibaration polynoms and utilized as error compensation routines for the following measurements.

In order to study the compliance of measurement and simulation more accurately, the ori-

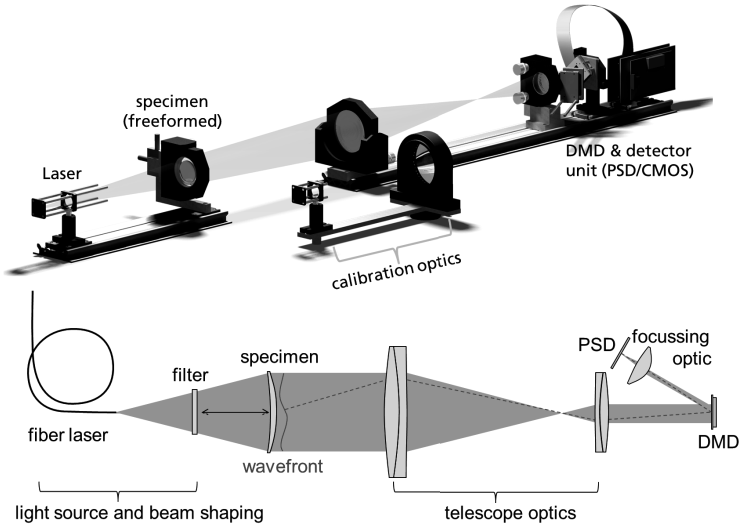

Figure 0.1.: Illustration of the measurement system applied in transmission using laser light and scanning the wave front employing a digital micromirror array (DMD). Top: 3D-CAD model of experimental setup. Below: schematic illustration.

entation and size of the angles is evaluated separately. This corresponds to using the local normal vectors in polar coordinates. The top of Fig. 0.2 shows the absolute value of the angle orientation (or φ), while the bottom shows the angle distribution (or θ). The analysis of the simulated wave front is to the left, the actual measurement data is on the right side.

Both evaluations basically show an accordance between simulation and real data. The existing deviations can partly be explained with differences between the real model and the simulated optical model, also with regard to the measurement error of the form of the specimen since it has been determined with a tactile coordinate measuring machine (*Zeiss F25*). A further contribution to deviations depends on the limited precision of the PSD based particularly on diffraction effects.
Various test measurements on varifocal eyeglass lenses ranging up to 5 diopters in dioptric power (corresponding to radius of curvature R by $1/R$) are performed. Evaluating the data, one can conclude that - considering the measurment statistics - the demonstration setup can basically fulfill the desired measurement capability in most aspects that are required for inline metrology in the production process of progressive eyeglasses. Figure 0.3 shows an example of a topographical display of the difference between simulated wavefront data and real measurement data. The peak to valley deviation in the current development state of the

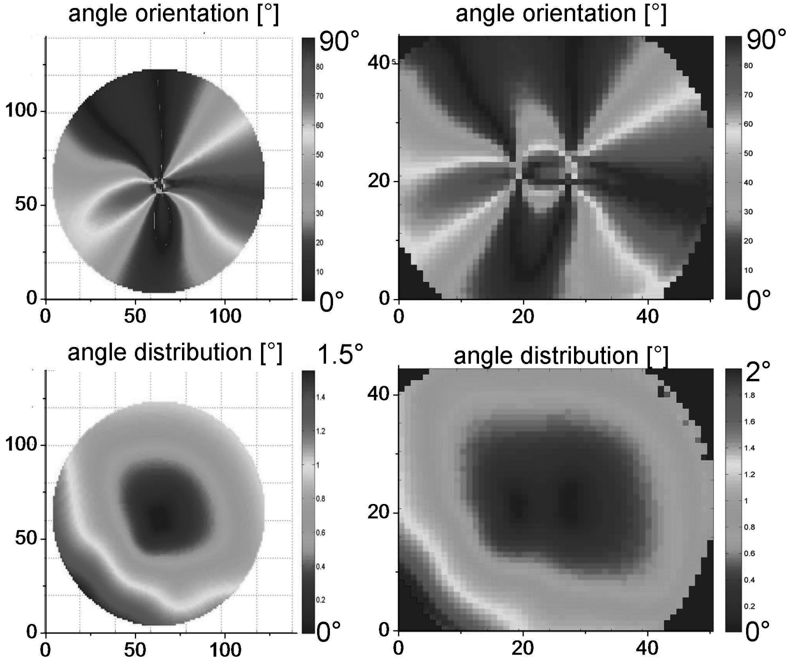

Figure 0.2.: Absolute values of angle orientation and angle distribution for simulated wave fronts (left side) and real measurement data (right side).

system is typically approximately (1.8±0.2) µm when neglecting stronger deviations at the edge of the measurement field which range up to approx. 5 µm. A significant contribution to the measurment uncertainty is caused by the integration of the measured slope distribution, the CAD-based alignment procedure for calculating the difference and the fact, that the tactile reference measurements serving for calculating the theoretical wavefront could not be performed in such a high lateral resolution that its error could be neglected (*Zeiss F25*, MPE according to DIN EN ISO 10360-2: 0.25 µm). A freeform calibration specimen with a higher precision is thus desirable for a better system characterization, but not commercially available.

4 Conclusion and Outlook

The current state of this research - funded by the BMBF joint research project "VariScan" - shows the applicability of DMDs for wave front measurements and thus for a functional testing of progressive eyeglasses. Within less than 10 seconds (highly depending on the laser power and detector sensitivity), the developed optical testing system enables to measure the

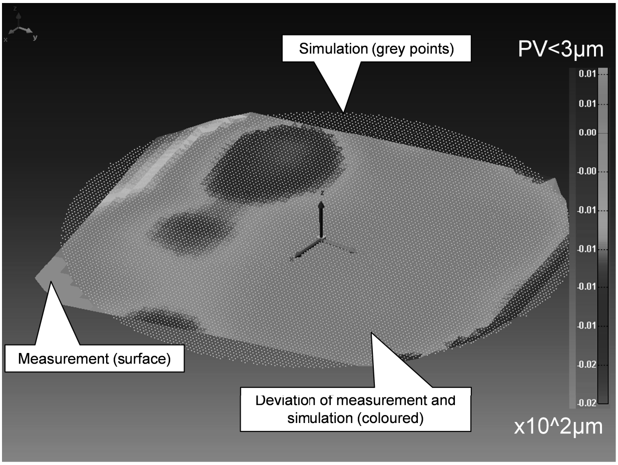

Figure 0.3.: Exemplary deviation topography: 3D-representation of difference of simulated and measured wave front (deviation indicating color).

function of an entire lens with a lateral resolution of less than 0.5 mm. A laser beam is directed through the lens, and the aberration of the wave front allows us to draw conclusions on its physical properties, whether or not it fulfills its specifications, and whether or not there are manufacturing imperfections.

The wave front measurement can be improved by using a camera-based detector rather than a PSD, since the PSD only offers limited precision mainly due to the diffraction patterns. The camera-based detector allows us to use the entire intensity distribution for a precise determination of the central spot position. However, the measurement time increases by a factor of $\approx$2 up to 10 due to the limited frame rates of imaging sensors (e.g. 75 fps) depending on the technology and resolution. Till now, the lateral resolution and the measurement duration are limited mainly by the available light power. Increasing it from approximately 30 mW to over 200 mW significantly improves the sytem's performance with regard to speed ($<$3 sec). The range of measurable slope can be increased with a more complex telescope objective transferring the wave front from the specimen plane to the DMD plane. Design studies are performed, but it turns out that many special lenses would lead to high costs. A further mean to improve the measurable slope is the use of the whole tilt range [-12, 12]° of the micro mirrors and not only the discrete states $\pm$12° which allows for compensating steep areas of the wavefront in that way, that the light rays are still collected by the detector optics. Furthermore, a concept for a galvo mirror based setup for scanning of eyeglasses with a singular beam is developed which fulfills the desired requirements of full-field inline production metrology.

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