Shack-Hartmann sensor and ophtalmology

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Shack-Hartmann wavefront sensor was designed in 1960s by Roland Shack and ben C. Platt (Platt&Shack 2001 [1]), based on the original telescope testing (as a physical ray-tracer) system invented in 1900 by Hartmann. The original sensor was designed to determine the maximum exposure time for the satellite tracking telescope.

The device is used behind the focus and consists of a colimator, which makes a parallel wavefront from the optical system, array of microlenses, creating a grid of images on an image sensor. The shift of every image against reference, samples the wavefront distorsion in the given sector. The wavefront can be reconstructed and completely described by a linear combination of Zernike polynomials [5] $Z_0, Z_1 \ldots Z_{\mathrm{N}}$ and their tied coefficients $a_0, a_1 \ldots a_{\mathrm{N}}$.

$$\begin{aligned} W(r,\vartheta) &= a_0 Z_0(r,\vartheta) + a_1 Z_1(r,\vartheta) + \ldots = \\ &= \sum_{i=0}^{N} a_{\mathrm{i}} Z_{\mathrm{i}}(r,\vartheta) \end{aligned}$$

This set of polynomial is useful, because they represent optical aberrations that are independent each other. The a_1 coefficient in front of Z_1 polynomial depicts a wavefront Tilt over x axis which has no relationship with a_2

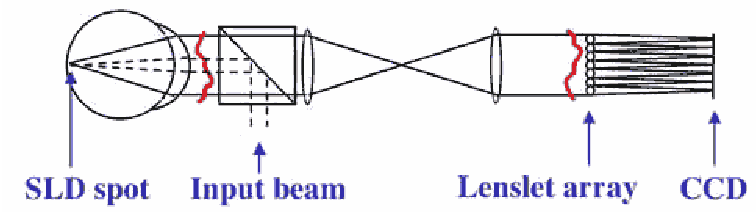

Figure 1: Simple schematic of an aberrometer.

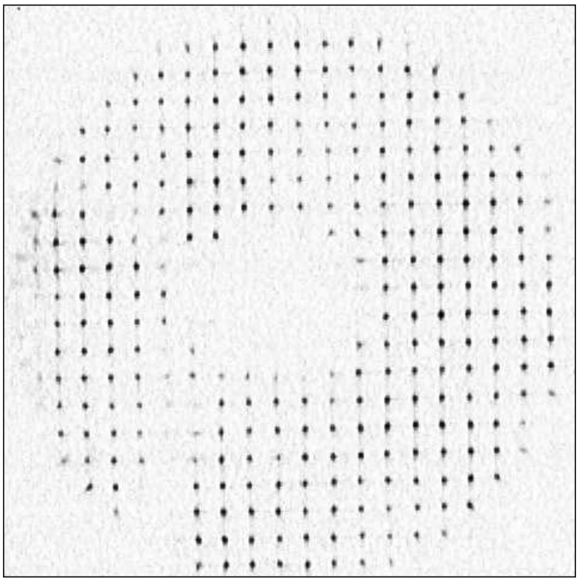

Figure 2: Example of Hartmannogram. [4]

of Z_2, the later being a Tilt over y axis. The a_3 coefficient that weights Z_3 is regarded as Defocus, that has no relationship at all with a_1 and $a2$. Coefficient $a_0 \ldots a_{\mathrm{N}}$ sets the strength coefficient for different aberrations. This way of wavefront reconstruction using Zernikes polynomials is called *modal reconstruction*.

Since mid-1970s, the Shack-Hartmann sensor was used in astronomy and air force, to test the optics and later (early 1980s, with the introduction of CCDs and powerful computers) also as a crucial part of adaptive optics system to compensate for the earth atmosphere.

In the mid-1980s, Josef Bille from the University of Erlangen-Nurnburg, was first to use the Shack-Hartmann sensor in ophtalmology — first to measure the profile of the cornea and then to measure the aberrations of the eye using a point source projected to the retina. His first published paper is from 1989.

aberrometry Using the aberrometer, see Fig. 1, the optical defficiency of the human cornea may be sampled and expressed in terms of Zernikes polynomials. In consequence, not just astigmatism and defocus may be described, but also most of the higher-order optical aberrations. Making

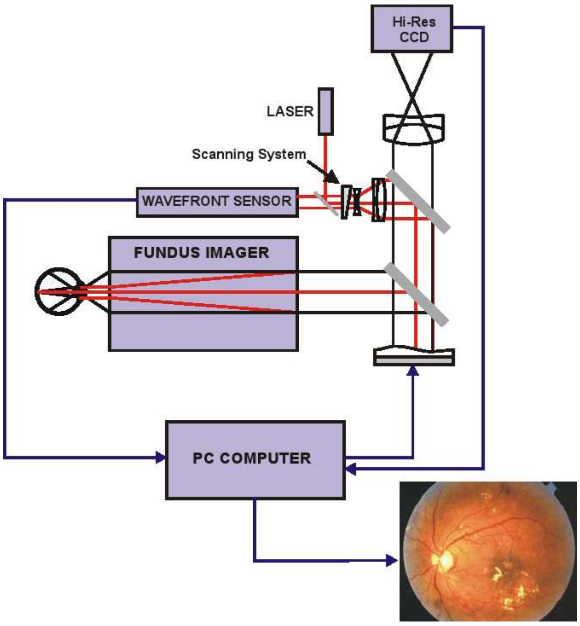

Figure 3: Schematic of the adaptive optic system used to study the human retina. From [6].

such an information available does not just serve as a diagnostic tool — saying how distorted the given optical system actually is.

adaptive optics in ophtalmology In ophtalmology, an important diagnostic method is the retina inspection. Due to the instant movements of the human eyeball, and due to inhomogenity of the (so to say) eye's material, a good quality image is impossible to be formed.

By combining the deformable mirror with Shack-Hartmann sensor, an adaptive optic system can be built (first by David Williams in late 1980s) to obtain otherwise inachevable retina image, allows ophtalmologists to improve the resolution with which the back of the eye is seen allowing to detect pathologies much earlier than it has ever been possible.

Further improvement, even down to the diffraction limit, is possible using numeric deconvolution.

Laser eye surgery It is now generally known, that it is possible to correct for an eye focusing error using *laser surgery*. To be precise, two distinct

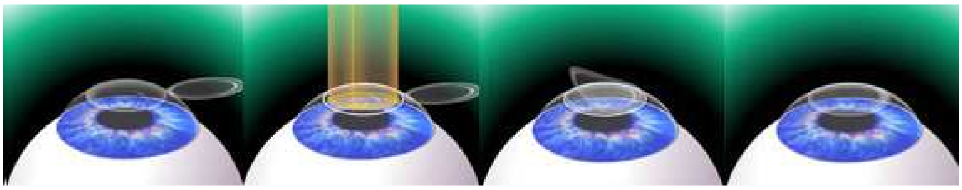

Figure 4: Lamellar surgery process. From [7].

types of laser surgery exist: *surface treatment* also known as PRK, Custom Surface, ASA or LASEK – is a process, where the very top layer of the front surface of the eye (cornea) is removed and the laser reshapes the exposed layer immediately below. The top layer then grows back over the newly shaped surface. On the other hand, *Lamellar surgery* also known as LASIK, is a technique having the advantage of not disturbing the very top layer of the cornea. Instead, a flap is created and lifted away to expose the layer immediately below, which is reshaped by the laser. The flap is then replaced on top of the reshaped surface.

Traditionally non custom laser, LASIK or PRK, fires many hundreds of small spots which overlap by different amounts to create a new surface to replicate the focusing pattern of the glasses or contact lenses. This system is called PLANOSCAN.

Using aberrometer, all the detectable optical aberrations of the eye may be detected and then applied to reshaping of the eyes cornea by the laser. It also allows for more detailed study of the cornea curvature, effectively allowing for a larger diameter of corrected area and reducing vision problems in low-light conditions. This approach is demarked as *custom* or *personalised* LASIK,

Ultimately, the adaptive optic concept may be partially applied also to the laser guiding — tiny movements of the eye may be real-time monitored and backfed to the laser beam pointing to improve the operation accuracy. This process is then known as *wavefront guided LASIK*.

Generally, this personalised system has the advantage of the possibility of correting the problems of much higher order. This way, even serious visual problems may be solved.[3] Furtermore, as less tissue is removed, the risk of complications is reduced, also (thanks to the guiding) the lielyhood of glare and halos at night is reduced.

References

[1] Platt B.C. & Shack, R., Journal of Refractive Surgery, 17/2001.

[2] http://www.cvs.rochester.edu/williamslab/r_shackhartmann.html

[3] http://research.opt.indiana.edu/Library/assessTransplant/assessTransplant.html

[4] http://www.astrosurf.com/cavadore/optique/shackHartmann/Shack-Hartmann.htm

[5] http://www.astrosurf.com/tests/roddier/zernike.html (in french)

[6] http://www.optics.ru/info/AO_in_opthalmology_2.pdf (in russian)

[7] http://www.aucklandeye.co.nz/index.asp?pageID=2145835604