Hartmann-Shack sensor ASIC's for real-time adaptive optics in biomedical physics

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ABSTRACT

Hartmann-Shack wavefront sensors are widely used to measure wavefront aberrations. Their applications in biomedical physics are mainly in the fields, where lasers are used for diagnostics or treatment, especially in opthalmology. In a number of applications, e.g. retina scanning, the imaging performance is limited by temporal aberration fluctuations. A fast Hartmann-Shack sensor in combination with an adaptive micro-mirror allows real-time correction of these aberrations. Hartmann-Shack sensors consist of a lenslet array, which splits the aperture of interest into a matrix of subapertures and an image detector in the focal plane. The wavefront is calculated from the lateral shifts of the focal spots. We present application specific integrated circuits (ASIC), which perform the required image acquisition and processing in the 1 kHz range. The presented ASIC's detect the spots and their position and can substitute slow standard CCD camera-chips to allow real-time processing. A number of chips have been produced in standard industrial CMOS (0.6 μm and 0.35 μm) processes, with the number of detectors ranging from 3 x 3 to 16 x 16 spots.

Keywords: Hartmann-Shack-Sensor, ASIC, adaptive optics, biomedical physics, real-time.

I. HARTMANN-SHACK SENSORS

A. APPLICATIONS

A Hartmann-Shack sensor is a non-interferometric wavefront aberrometer. The exact knowledge of aberrations in optical systems is of importance, where the imaging quality is not diffraction limited, i.e. in the case of laser scanning of the human retina, when the pupil diameter is larger than 3 mm [1]. Hartmann-Shack sensors have been used at first in astronomy to measure and correct atmospheric fluctuations. In opthalmology these sensors are used to measure higher order aberrations of the human eye. The wavefront data can also be used to improve the quality of refractive surgery of the cornea and to achieve supernormal vision [2], [3]. The diffraction limit may be achieved in all applications, when adaptive optics are used to dynamically cancel the wavefront aberrations out. Such an adaptive optical system consists of a fast Hartmann-Shack sensor and an adaptive micro-mirror device. The repetition rate of the whole system should be in the order of 1 kHz, a speed which is not easily achievable with standard components of the shelf. A customized vision chip which includes image sensors and signal processing is necessary in this case. Fast Hartmann-Shack sensors with optical image processor have also been proposed [4].

B. WAVE-FRONT ABERRATIONS

A Hartmann-Shack sensor consists of a lenslet array and an image sensor in the focal plain. Each lenslet produces a focal spot, resulting in a grid of spots in the focal plane, fig. 1 shows a typical spot pattern. An ideal wavefront $W(x, y)$ will produce a rectangular grid of spots, whilst a deformed wavefront results in lateral shifts $\Delta x, \Delta y$ of the spots, according to the relations

$$\frac{dW(x,y)}{dx} = \frac{\Delta x}{f}, \tag{1}$$

$$\frac{dW(x,y)}{dy} = \frac{\Delta y}{f}, \tag{2}$$

where f is the focal length of the lenslets. The theoretical limit of the spot size is defined by the diffraction limit of the aperture of the lenslet, but non-ideal optics may lead to much larger spot sizes.

The task of the image processing is, first to detect, if a spot is present for each lenslet and second, to measure the lateral shifts of all found spots. The maximum of the intensity distribution of the spot can be used to estimate the spot position. Because the centroid of the intensity distribution is robust against noise and spot deformation, it is often used

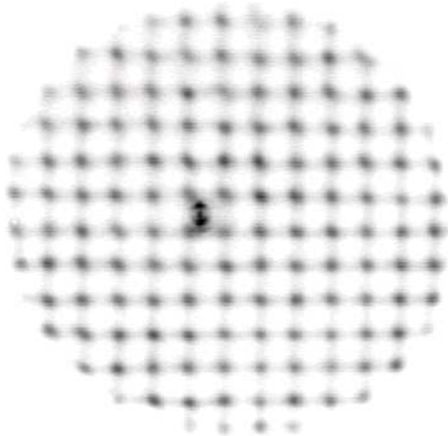

Fig. 1. Typical spot pattern of a Hartmann-Shack sensor (with cornea reflex).

as an estimator of location [5]. The third processing task is to calculate a common representation of the 2D-wavefront aberrations from the measured spot deviations, e.g. the Zernicke polynomials [6] Z_i with coefficients C_i

$$W(x,y) = \sum_i C_i Z_i(x,y). \qquad (3)$$

The reconstructed wavefront can be used to control an adaptive mirror, which shifts the deformed wavefront back into a plane one and thus to improve the imaging quality of the optical system.

II. AN ASIC CONCEPT FOR HARTMANN-SHACK SENSORS

The speed limitations of CCD cameras and software solutions may be overcome with a fast application specific integrated circuit (ASIC). We designed and produced ASIC's, which reach frame repetition rates of up to 1 kHz, whilst standard solutions are in the range of some tens of Hz. Our ASIC concept relies on standard CMOS technology. The ASIC's contain photo-detectors, analog image processing and digital read-out.

A. THE PHOTO-DETECTORS

The photo-detectors should have a quantum efficiency as high as possible for the desired wavelength. For opthalmological applications, photo-detectors with high quantum efficiencies at the longer wavelengths of the visible or near infrared spectrum should be used. Longer wavelengths are preferred, because the human eye has lower security levels for the intensity of red or near-infrared ligth than for blue one. The CMOS process offers some passive and some active photo-sensors. Active photo-transistors have much higher quantum efficiencies than passive photodiodes, but a much slower transient response and are more sensitive to noise.

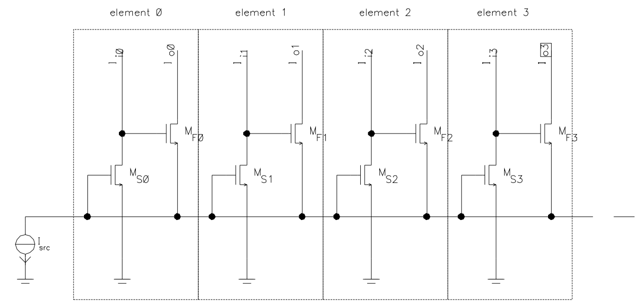

Fig. 2. Schematic diagram of a WTA circuit for finding the maximum of four input currents.

B. THE ANALOG IMAGE PROCESSOR

As much of the area of the chip should be covered with photo-sensors, because the incident power of one focal spot only amounts to some nW. Thus the required area for the signal processing has to be as small as possible. The analog winner-take-all (WTA) circuit [7] is appropriate, because in its basic form it only needs 2 x n transistors to detect the maximum of n input currents. The circuit is one of a number of analog circuits which have been extensively studied in recent years, because they show similarities with biological systems, i.e. they use certain non-linear device characteristics and perform nearest neighbor operations for signal or image processing tasks.

A basic position detector with a WTA circuit is shown in fig. 2. Each element of the WTA circuit consists of two MOSFET's M_S and M_F. The $M_{S,k}$ with the highest input current $I_{i,k}$ and the highest drain potential forces the adjacent $M_{F,k}$ to have the highest gate-source potential V_{GS}. Therefore most of the current from the current sink will be sunk by this transistor and forces the output current $I_{o,k}$ to be much higher than all other output currents. If this current is sunk through a resistor, the potential of the node is high, while all other node voltages are almost zero and a digital value is achieved, which assigns the position of the maximum current.

In its basic form the large junction capacitance of the photodiodes slows the transient response down. To speed the circuit up and reach transient responses in the millisecond range, the pixel capacitance was decoupled from the WTA-circuit with a cascaded current mirror. Further circuitry to speed the circuit up, has been implemented, an active feedback and an active initialization of the circuit.

B.1 THE ANALOG CENTROID DETECTOR

Analog circuits in CMOS technology often suffer from mismatching between identically designed structures. This

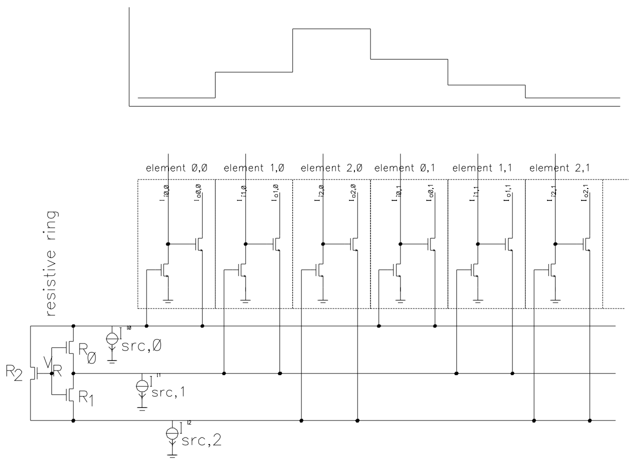

Fig. 3. Circuit diagram to find the three neighboring maximum currents. The circuit can be switched back to find the single highest current, when V_R and the transconductance of transistors R_1 and R_2 is high.

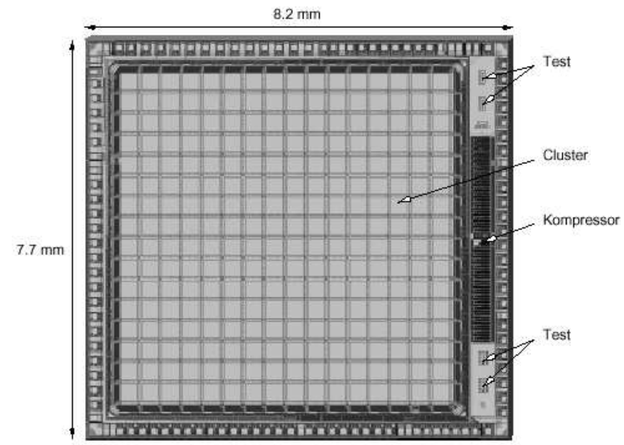

Fig. 4. Photograph of the HSSX.

leads to fixed-pattern noise in image sensors. To increase the resolution, the pixel width has to be chosen much smaller than the spot diameter. With decreasing pixel size, the differences of the photo-currents between neighboring pixels also diminish and effects of mismatching become dominant.

Analog centroid detectors suffer less from mismatching, because centroid operations include spatial averaging. Resistive grids perform the centroid operation [8] and have been evaluated, but the centroid here depends on the background noise level and is not suitable for our applications. We therefore chose a novel combination of WTA-circuits to perform an operation, which is close to the centroid operation. Instead of having all n elements of the WTA circuit connected through a common net, we split the n WTA elements into k groups with n/k elements each, where each group has its own current sink $I_{src,j}$, see fig. 3. The elements of the different WTA circuits are arranged inter-digitally. When a spot is present, the k largest currents will be detected instead of only one. For each WTA circuit, only one of the input currents will be large and the rest almost zero. The effect of mismatching is reduced to almost zero, by an appropriate choice of k.

The circuit can be easily switched back to find the largest currents of all, when the different nets of the WTA circuits are short-cut to form only one. When V_R is high, the switching $k-1$ MOS-FET's have high transconductance and the k current sinks form a single one, therefore only one of the WTA elements wins.

B.2 SPOT DETECTION

The digital bit-pattern from the WTA-elements serves to decide, whether a spot is present or not. When a spot is present, neighboring bits will be set. When no spot is present, the bits are randomly set, assuming a uniform background noise distribution. The false detection probability p is the probability of a random combination, which is mistaken as a detection, when no spot is present:

$$p = \frac{1}{(n/k)^k}(n-k+1). \tag{4}$$

It diminishes fast with a rising number of independent WTA circuits k.

III. ASIC PERFORMANCE

A. HSSX

The HSSX [9] ASIC has been produced as a maximum detector with 16 x 16 position detecors in CMOS 0.6 μm technology [1] for lenslet arrays with 400 μm aperture and 53 mm focal length. The position detectors consist of 19 x 19 pixels with p$^+$-nwell photodiodes of 17.6 μm pixel pitch. It has a total chip area of 7.2 x 8.2 mm^2 (figure 4). Position detection is feasible within 70 % of each 400 x 400 μm detector. The photo-sensitive array consists of 19 x 19 pixels with p$^+$-nwell photodiodes and has a resolution of 17.6 μm. The WTA circuit has been optimized for fast transient response by decoupling the large junction capacitance of the photo-diodes from the WTA elements. Further acceleration is achieved by active initialization and by an adjustable active feedback. The bit-pattern from the WTA-cells is serially directed to the periphery of the position detector matrix and read-out after data-compression.

A PC communicates with the chip via the parallel port and an FPGA [2]. The PC calculates the wavefront aberrations from the position data, which can be displayed with a graphical user interface.

[1] AMS (Austria Micro Systems) 0.6 μm and 0.35 μm triple metal, double poly technology has been used.

[2] Field programmable gate array.

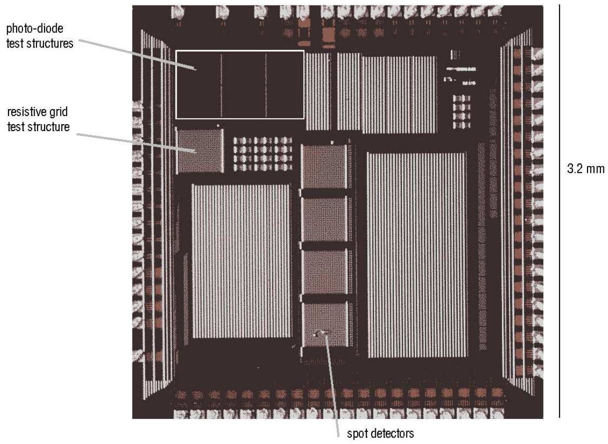

Fig. 5. Photograph of the prototype CENTHSSA.

The mismatching characteristics, which directly affect the position detection performance, were studied with a laser spot moving at constant speed over the array. The absolute error was 1.85 pixels at 1 kHz and 0.74 pixels at 250 Hz repetition rate at 1 nW spot intensity. Wavefront aberration measurements were conducted with standard astigmatic optical lenses. The relative errors were smaller than 7.5% relative to the full-scale dynamic range of 1 diopter.

B. CENTHSSA

The CENTHSSA chips are designed for centroid spot detection, but can also be switched back to maximum spot detection. A prototype with four position detectors has been produced in 0.35 μm CMOS technology (figure 5). The smaller minimum device size allows further diminishment of the required area for analog and digital circuitry and a larger dynamic range of focal spot movement and therefore larger wavefront aberrations are detectable.

The results from the prototype have been used to design a full-scale Hartmann-Shack sensor ASIC with 8 x 8 position detectors. The position detectors consist of 21 x 21 pixels with n-well/substrate photo-diodes of 17 μm pixel pitch. This diode-type has been chosen, because it has the largest quantum efficiency for longer wavelengths in the used CMOS process and its junction capacitance is the smallest, a fact that serves to speed up the transient response. Position detection is feasible within 80 % of each position detector.

The analog circuitry consists of five WTA-circuits which sense 21 input currents. When no spot is present, the data is rejected with $1 - p = 98.5\%$ probability, according to equation 4. Fig. 6 shows detection and tracking of a single spot moving over the detector array with 200 μm per second.

Fig. 7 shows the result from a spot of a lenslet array with very small spot intensity, as it moves over the detector. Despite the poorer optical quality of the spots from the lenslet array and the very small spot intensity of 1.6 pW, spot detection and tracking is possible.

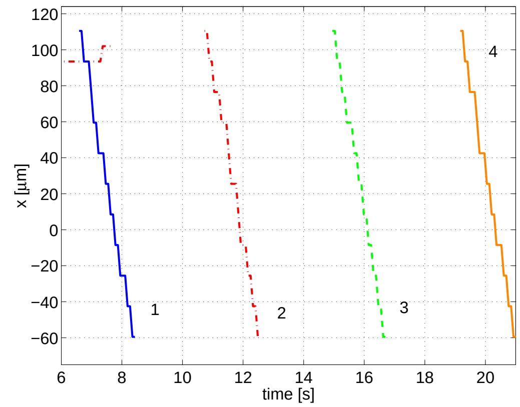

Fig. 6. Detection and tracking of one single spot, which moves over four position detectors.

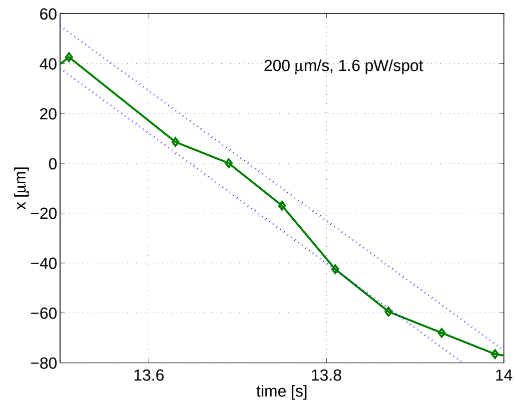

Fig. 7. Here a spot from a lenslet array is tracked with a single detector at a very small spot intensity.

Fig. 8 and 9 show the better performance of the centroid spot detector at small spot intensities. The error of the centroid detector stays below one pixel (dotted line). At 300 pW the standard deviation of spot position was 0.6 pixels in centroid mode and 1.6 pixels in maximum mode.

The digital read-out of the chip consists of addressing the detector to be read out. The data is transported via a tri-state bus to the periphery of the core and multiplexed to the pads. A commercial multi-functional PCI I/O-card serves as an interface between the ASIC and a PC. The card provides analog control voltages and addresses the position detector to be read out. The spot deviations are used to calculate a least-square solution of the Zernicke coefficients.

IV. CONCLUSIONS

Dedicated high-speed Hartmann-Shack sensor ASIC's have been developed to allow wavefront measurements in opthal-

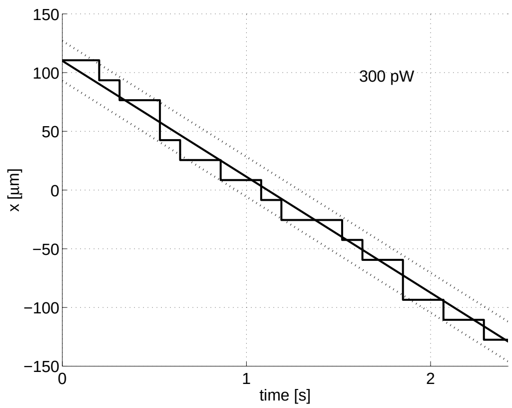

Fig. 8. Position detection in centroid mode.

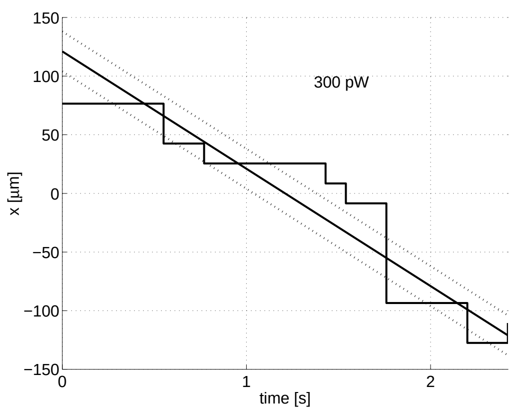

Fig. 9. Position detection in maximum mode.

mologic applications of up to 1 kHz frame repetition rate. The speed limitations of CCD camera chips and software solutions of some tens of Hz can be overcome. The sensor chips will be used in unison with an adaptive optical system for real-time canceling of wavefront aberrations. The ASIC itself relies on photo-sensors, analog and digital circuitry directly available in standard CMOS technology. The position of the spots may be detected with maximum or centroid spot detectors. Different chips of up to 256 position detectors have been designed and tested.

V. ACKNOWLEDGMENTS

The authors like to thank Perfect Vision GmbH for providing the lenslet array.

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