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A Camera with analog adaptive Photoreceptors for a tactile Vision Aid

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ABSTRACT

A camera system to be used in a tactile vision aid for blind persons has been built and tested. The camera is based on individual adaptive photoreceptors modelled after the biological example and realized in standard CMOS technology. The system exhibits a large dynamic range of approximately 7 orders of magnitude in incident light intensity and a pronounced capability to detect moving objects. It is planned to connect such a camera to a set of mechanical actuators which will transmit processed information about the image to the skin of a person. This paper describes simulations and measurements carried out with single adaptive pixels as well as results obtained with two complete prototype camera systems.

Keywords : tactile vision, adaptive photoreceptors, adaptive cameras, analog neuromorphic electronics, single chip camera

1 CONCEPT

About 25 years ago first experiments were carried out at a hospital in San Francisco with a novel type of orientation aid for blind persons.[1] A commercial state-of-the-art TV camera was mounted on the persons shoulder. The image was processed by a mini-computer and a reduced information was transmitted back to the persons skin. The tactile transmission was based on electromechanical actuators vibrating at a frequency of 60 Hz. The results of those first attempts were encouraging. The test persons were able to recognize simple objects. The system was plagued however by its very inconvenient size. The processing mini-computer, for example, had to be moved with the help of a chariot and the camera itself was a rather heavy object to carry. Technology has progressed since then in particular with respect to image acquisition and processing. This fact is the major motivation for a new approach to this concept.[2] The camera systems developed within the framework of this project are based on the *Complementary Metal Oxide Silicon (short : CMOS)* technology. The availability of basic circuit elements like diodes and transistors suggests to use the intrinsic photoelectric effect in the depletion zone of CMOS structures for light detection. At the same time the possibilities for further signal processing on the same silicon wafer can be used. This is the basic idea of CMOS photoreceptors (*Vision Chips*). Apart from the integration of sensor elements and signal processing single CMOS photoreceptors are characterised by a huge dynamic range of 1 : 1 million or more. This performance comes close to the biological model and is far better than that of conventional CCD systems. This is of great advantage for the application in mind, because such a system can operate under a large range of different illuminations without the need for additional aperture corrections. In practical applications however, the use of the large dynamic range is difficult. A linear transfer of many orders of magnitude in incident illumination requires an unrealistic range of output voltages. A way out of this problem also realized in biological systems is a logarithmic compression of the output signal. Such a compression permits the acquisition of scenes with extremely high contrasts. The obvious disadvantage of such a flat logarithmic transfer curve is that pictures of normal scenes without extreme contrasts appear essentially grey. Biological system on the other hand can handle large and small input contrast because of their capability of adaptation. In the language of analog electronics an adaptive photoreceptor represents a bandpass filter. The response to static or very low frequency input signals can be described by a low gain logarithmic transfer characteristics (*static response*). Rapidly changing signals see a much higher logarithmic gain (*transient response*). The biological system adapts with time constants of typically seconds (minutes or more for dark adaptation). The bandpass characteristics causes a prounounced capability for motion detection. This paper describes the electronic realization of biologically motivated adaptive photoreceptors based on an analog feedback circuit. The photoreceptors have been used to build two prototype camera systems.

2 BIOLOGICAL MODEL

Fig. 1 shows the measured membrane potential of a turtle cone (red sensitive) as measured by Normann and Perlman.[3] The static response of this system is characterised by a rather flat logarithmic slope of about 1.8 mV/decade. The steep curves describe the response to rapid changes of incident illumination. Their slope is much higher (about 9.5 mV/decade).

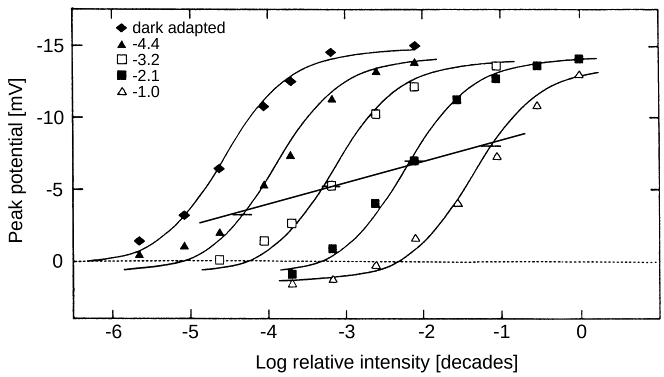

Figure 1: Response curves of red sensitive cones in the turtle retina.[3] The measured membrane potential (relative to the dark potential represented by the dotted line) is plotted as a function of the intensity of the incoming light. The 0. decade corresponds to an intensity of about 20 W/m^2. The full straight line describes the static response of the system two minutes after it was first exposed to a constant illumination. The measured points connected by the steeper lines show the response to light pulses of 0.5 s duration. The light pulses rise from a given lower intensity written next to the symbol table in the figure.

This adaptive behaviour allows the receptor to operate with high logarithmic gain over a wide range of light intensities without suffering from saturation. The output signal mostly represents the actual changes in incident illumination. Static signals are highly suppressed. The high gain response to transient signals causes increased sensitivity to moving objects as well as an enhancement of edges since moving objects show changes in intensity predomionantly at their edges.

3 TECHNICAL REALIZATION

The electronic circuit for the adaptive photoreceptor described here closely follows a suggestion by T. Delbrück and C. A. Mead.[4] Basically an internal model makes a prediction about the level of the input signal. The output signal is then generated from a comparison between the prediction and the actual input. Finally the circuit corrects its internal model in order to improve the prediction. For details about the adaptive circuit we refer to[4] and.[5] Based on the adaptive pixel concept two CMOS chips have been designed, produced and tested. The design has been carried out using the 1.2 μm CMOS technology of the company AMS (Austria Micro Systems). This CMOS process offers two metal layers and two polysilicon layers.

The first chip contains single adaptive photoreceptors (pixels) with various sets of design parameters and a matrix composed of 20 x 20 pixels. The matrix is used to record and process pictures with a spatial resolution of 400 pixels. Fig. 2 shows a microphotograph of the produced chip with a size of 3.5×2.5 mm^2. The layout is divided into two separate regions. The left part contains various versions of single adaptive photoreceptors as well as some optoelectronic test structures. The right part shows the 400 pixel matrix arranged in 20 rows with 20 pixels each.

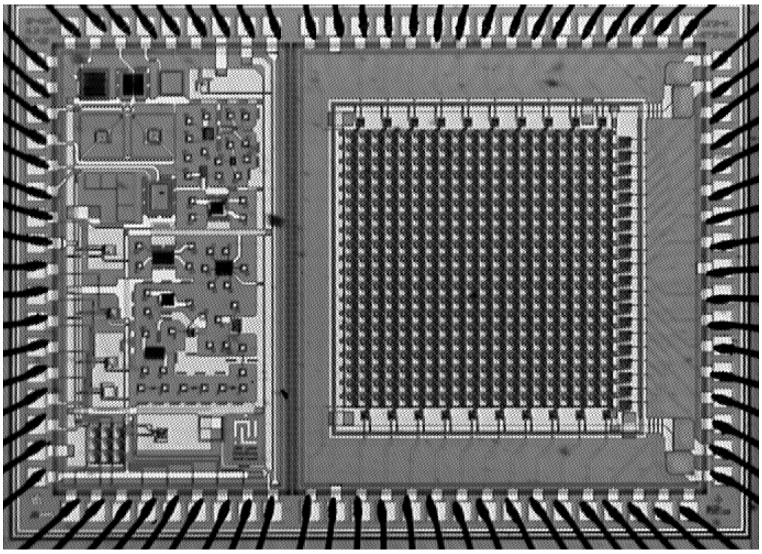

Figure 2: Microphotograph of the produced vision chip with a 20 x 20 pixel matrix

The layout of a single adaptive pixels occupies a surface area of approximately 50×50 μm. It is dominated by a capacitive divider necessary to obtain a RC time constant of a few seconds. At the top edge of each pixel design a quadratically shaped n$^+$-substrate photodiode has been implemented. This type of diode is close to the surface of the silicon wafer. At the same time the diode extends far into the weakly doped substrate so that the diode exhibits a rather large quantum efficiency for visible light. The photodiode itself has a surface area of 15×15 μm^2. Apart from the photodiode all other pn-junctions on the chip are also sensitive to light. For this reason the adaptive electronics has to be shielded. The second metal layer of the AMS process has been used for this purpose. The metal layer covers a major fraction of each pixel. The pixels in the matrix arrangement are somewhat modified compared to the standard pixel described before. Here the photodiode is surrounded by a strucure of contacts to the substrate forcing the substrate to ground potential. This way photocurrents travelling across the substrate can be carried away by the metal layer with very low impedance. Structures at large distance from the photodiode are thus well protected against such currents. For the readout of the matrix pixel rows are activated via transistor switches set by external control signals. The readout proceeds columnwise through 20 readout amplifiers. All required readout circuitry like switching transistors, logic level converters and readout amplifiers is located on-chip. Digitization is carried out externally for this version of the chip.

The second chip has been produced after the successful test of the first version described before. Apart from a much improved spatial resolution based on a total of 4096 adaptive photoreceptors arranged in a 64 x 64 pixel matrix it features on board 8-bit digitization and serial data transmission for the 4096 pixels. The entire system occupies an area of approximately 25 mm^2 of silicon. The largest part of this area is covered by adaptive pixels of the type described before. Digitization is carried out by 64 single slope ADCs composed out of 64 comparators and a programmable ramp generator. Data from each individual pixel are grouped into 8 parallel bits which are serially transmitted to the outside. The data are recorded directly by the parallel port of a personal computer which can also execute image processing algorithms like edge detection. The system represents an adaptive single chip camera well suited for the application in mind. A detailed description of this system can be found in.[6]

4 RESULTS

4.1 Simulations of single pixels

All simulation have been carried out using the program *Spectre*.[7] Since *Spectre* does not offer the possibilty to simulate the intrinsic photoelectric effect in pn-junctions the photodiode has been replaced by a current source for this purpose. The photcurrent I_{ph} can be related to the light intensity J via the following relation :

$$I_{ph} = e\ Q\ n_{Photon} = e\ Q\ \frac{J\ A}{h\nu}. \tag{1}$$

Here A is the diode surface area, Q the quantum efficiency and e the electron charge. The number n_{photon} arriving at the diode per unit of time can be calculated from the total energy per unit of time $(E/t = P = J\ A)$ and the energy carried by a single photon $(E_\nu = h\nu)$. As an example light with a wavelength of 600 nm and an intensity $J = 1$ W/m^2 corresponds to a photocurrent of $I_{ph} = 42pA$ in a diode with a surface area of 15×15 μm^2 and a quantum efficiency of $Q = 0.5$.

Fig. 3 shows the results of the simulations. The line with the flat slope of $\simeq$ 100 mV/decade represents the static response of the system. The vertical axis gives the output voltage level corresponding to full adaptation. The steeper curves describe the transient response. To obtain these curves the maximum output voltage in response to sudden changes of the photocurrent has been recorded. The slope of the transient curves is approximately 1.3 V per decade. The ratio of logarithmic slopes from static and transient response is 13 : 1. The biological model shown in Fig. 1 has a corresponding ratio of 5 : 1. This difference turns out to be a useful feature for motion detection. The higher relative gain for transient signals increases the sensitivity of the system for moving objects which appear clearly separated from the static background. The contrast for static scenes is very weak because of the flat response curve. In general the qualitative agreement between the simulation in Fig. 3 and the biological model in Fig. 1 is remarkable. Both sensor systems exhibit the same characteristic behaviour over a large dynamic range of input signals.

4.2 Measurements of single pixels

Measurements with the produced adaptive pixels have been carried out over a large range of input intensities corresponding to 11 decades in incident illumination. The experimental set-up consisted of a diode laser emitting at a wavelength of 675 nm and a set of removable neutral density filters. The laser beam could be focused to a spot size of 5 μm giving access to small structures on the chip. The chip could be positioned with a remotely

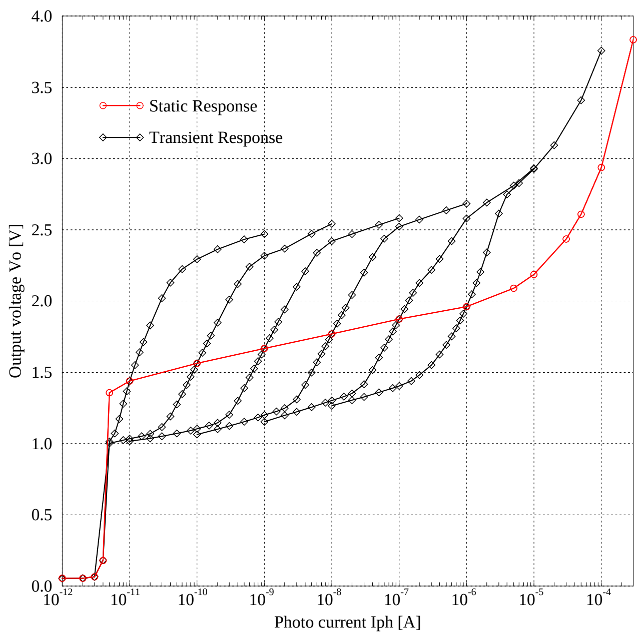

Figure 3: Simulation of the response of the adaptive photoreceptor.

controlled scanning table to a precision of 1 μm. An absolute calibration of light intensities was provided by a photometer. Fig. 4 shows the results for the response of an adaptive pixel presented in the same way as for the biological measurements and the simulations.

Over a large dynamic range of about 7 decades ($10^{-5} - 10^{2}$ W/m^2) the produced pixel exhibits qualitatively the same response characteristics than the simulation shown in Fig. 3 and the biological model shown in Fig. 1. The ratio of logarithmic slopes between static and transient response differs even more than the simulation from the biological retina. The produced pixel has a static slope of about 20 mV per decade and a transient slope a about 600 mV per decade. This corresponds to a ratio of 30 : 1 for the chip compared to 13 : 1 in the simulation and 5 : 1 for the turtle cones. The difference between measurement and simulation is well understood by the fact that the system has been simulated without taking parasitic effects (capacitances) of the actual process dependend layout into account. Such parasitic capacitances influence the transient gain. The standard pixel is therefore characterised by a very pronounced sensitivity to motion. This effect is desirable for the envisaged application as it has been demonstrated with the camera system (see next chapter).

Fig. 5 shows a measurement of the adaptation time which is defined to be the time at which the pixel output voltage has settled to the adapted level within the precision of the instrument reading (approximately 5 mV). The adaption time has typical values of about 20 - 30 s but exhibits a clear dependence on intensity. The two curves in the figure describe the intensity dependence for dark and bright adaptation separately. For intensities below 10^{-2} W/m^2 the measured times are essentially constant. The small drop at very low intensities ($< 10^{-5}$ W/m^2) is caused by the small transient gain in this region. Static response is reached faster in this case. At large intensities the adaptation time drops rapidly to values as small as milliseconds. The reason for this behaviour can be traced to the light sensitivity of the adaptive electronics. Light penetrating through the metal shield generates parasitc photocurrents which lead to faster discharge of the storage capacities and in turn cause a smaller adaptation time.

Of particular interest for complex analog VLSI designs are variations of system parameters like offsets, gains and noise among a large number of formally identical elements. Such variations are expected to arise from

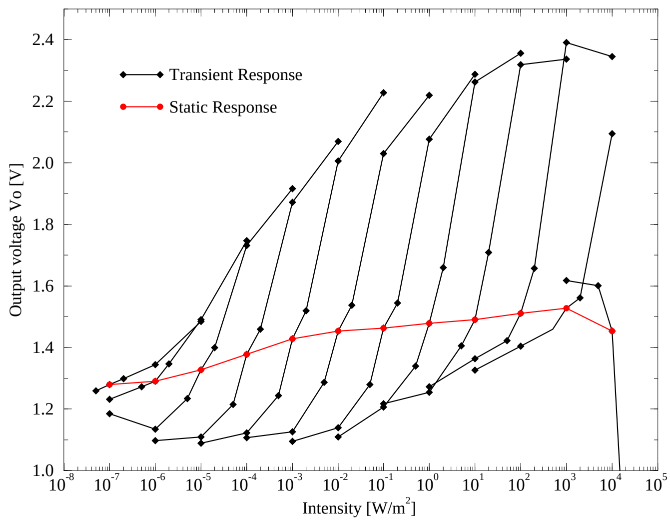

Figure 4: Measured response of the adaptive photoreceptors over 11 decades of incident illumination.

fluctuations of characteristic parameters in the production process like the doping level und structure sizes. A detailed study of parameter variations has been carried out for a large statistics of matrix pixels. In order to judge the relevance of the quoted numbers they should be compared to a typical slope of the static response (20 mV per decade of incident illumination). The following numbers are based on a statistics of 800 pixels from two 20 x 20 matrices. The noise per pixel amounts to 2-3 mV. This value has been determined with an integration time of 200 ns. The number is small compared to the static slope und could be reduced even further by increasing the time of integration. The variation of logarithmic slopes from pixel to pixel is about 0.4 mV per decade. This number is even smaller than the noise but does not average out in time and leads to visible effects in scenes with very large contrasts. Offset variations from pixel to pixel are typically 8-12 mV corresponding to half a decade in incident illumination. The last two effects can be compensated after signal digitization by a calibration algorithm.

4.3 Experiences with the adaptive camera systems

The 20×20 matrix together with an imaging optical system has been mounted in a camera casing. Due to the analog switching carried out on the chip the number of necessary cables amounts to 20 analog signals, 20 control lines and power supplies. The analog output signals are digitized with 20 external 12-bit ADC channels and read out by a single board computer running under the real time operating system OS9. The computer also generates the control signals for the camera and carries out a calibration of ADC channels and pixel to pixel variations. The digital image data are sent via Ethernet to a personal computer. The PC displays the images in real time on the screen and provides tools to record movies on mass storage devices. Also, some basic image processing algorithms based on digitized data have been implemented.

Fig. 6 shows a sequence of 6 camera pictures. Although the spatial resolution of the 400 pixel system is moderate the sequence clearly demonstrates the adaptive properties of the camera. The pictures show a hand moving into the scene and then held motionless for a while. The pictures directly recorded by the camera are shown in the first and the third row of Fig. 6. During the movement the hand can be seen with large contrast against a bright background (1. and 2. picture). After stopping the movement the pictures loose contrast. (3. - 5. picture). The pixel matrix adapts to the static response curve. In the last picture the hand starts to move

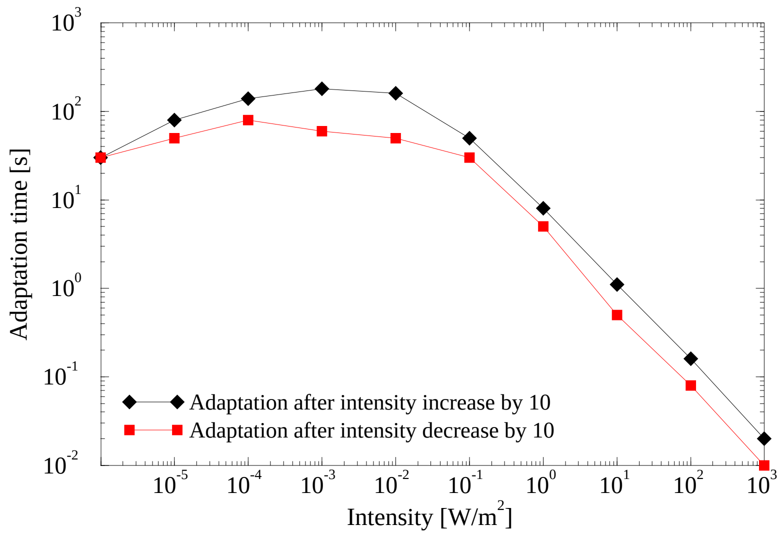

Figure 5: Adaptation time as a function of incident illumination.

again and is immedeately visible. Below each individual camera picture the result of a conventional edge detection algorithm is shown. The algorithm implements a simple filter based on a folding with a 3x3 matrix. The moving edges are recognised very clearly.

The second camera chip has been mounted on a small board (1.5×1.5 cm^2) together with a single lens optic of 6 mm focal length. Connected directly to a laptop PC the system has been used extensively to record real life scenes. Fig. 7 shows a moving car as an example. The four rows in this figure represent a temporal sequence of four images. The first row shows a car moving in from the left side. In the second row the car has just stopped. The third row has been recorded a few seconds after the car has stopped. Finally the car accelerates in the fourth row. The three columns of Fig. 7 represent three different levels of image processing. The original image recorded by the adaptive camera can bee seen in the first column. The second column shows a histogram of the pixel pulseheights. The digitized data of each pixel are plotted on the horizontal axis ranging from 0 to 255 ADC counts. The corresponding frequency is displayed in a logarithmic scale on the vertical axis. Each histogram has 4096 entries corresponding to the number of pixels. The third row demonstrates the output of a digital edge detection algorithm executed on the laptop PC after receiving the digital data. The sequence has been recorded under typical daylight conditions corresponding to approximately 1 W/m^2. The characteristic features of the adaptive camera system can be clearly seen. The original camera images are essentially grey. Only the moving car appears visible. The pulseheight distributions show a sharp peak around 100 counts corresponding to the grey level and a broad underlying distribution with output levels much above or below the static response. This underlying distribution corresponds to the moving car. The few fluctuating pixels at the lower horizontal matrix rows are due to a readout problem which has been fixed in the meantime. The result of the edge detection algorithm in the third column corresponds to the type of information which will be transmitted to the electromechanical skin stimulators. The information has still to be adjusted for the spatial resolution capability of the skin. This question is currently under investigation.

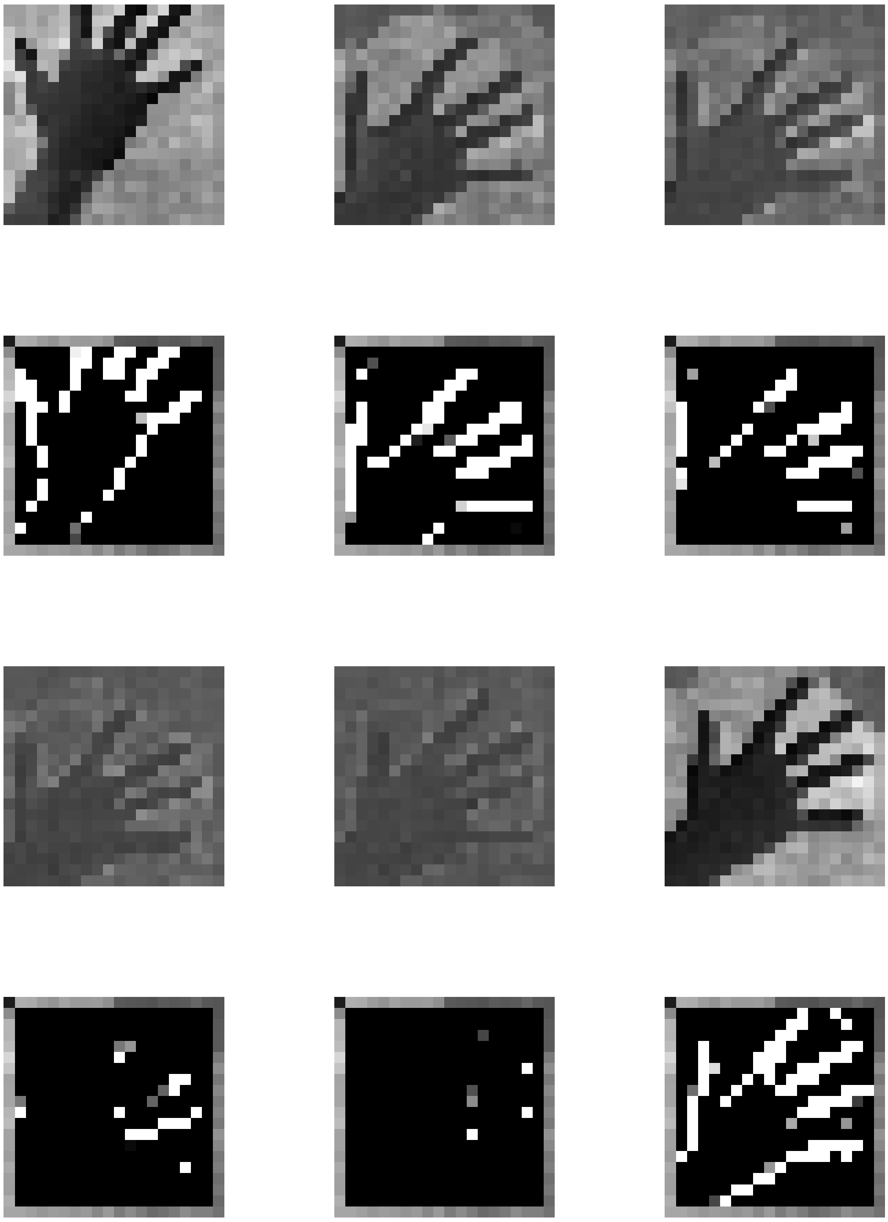

Figure 6: Simple moving object recorded with the 400 pixel adaptive camera. The first and the third row show a sequence of pictures recorded with the adaptive camera system. A hand is moving into the picture and held in position for a while. After pixel adaptation the hand is moved again and appears on the picture. The second and the fourth row show the output of a digital edge detection algorithm.

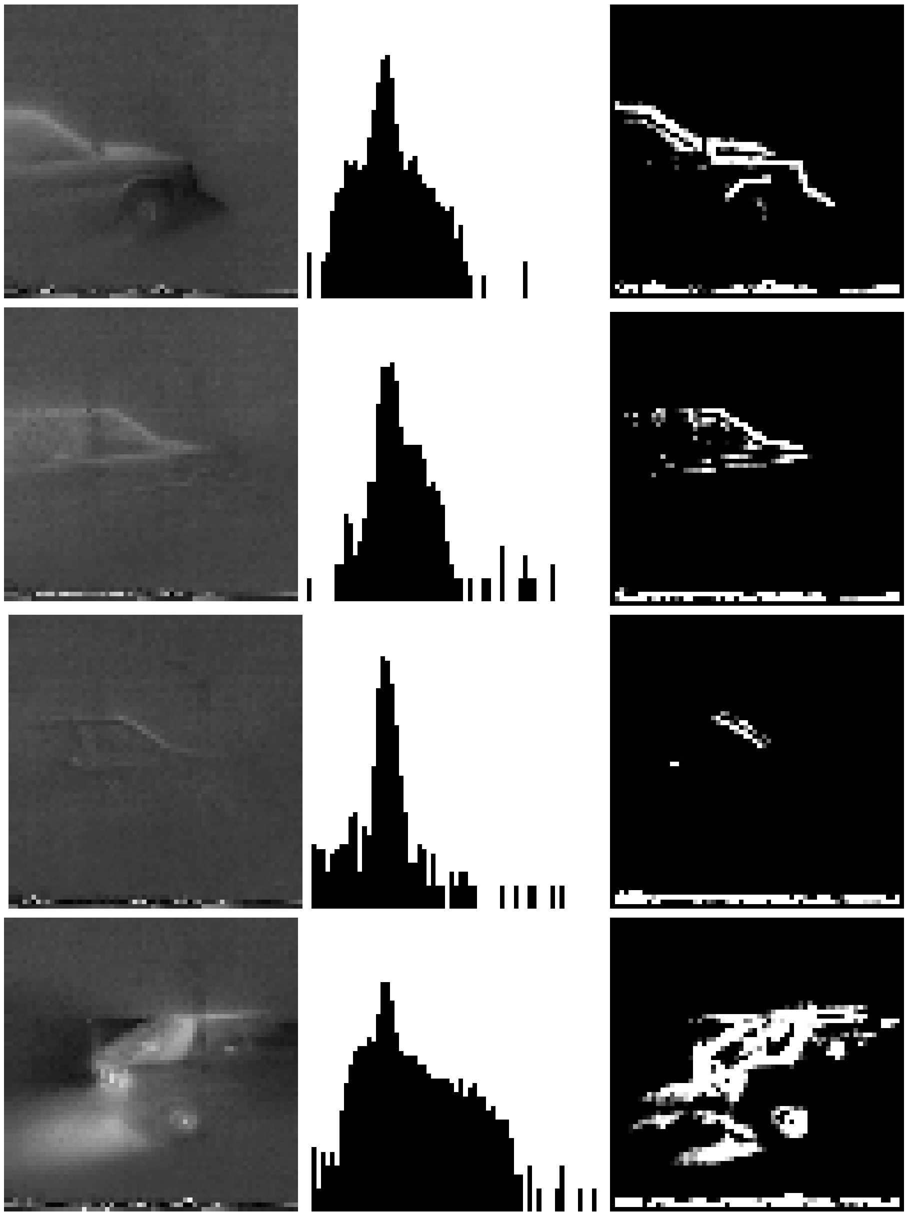

Figure 7: A car recorded with the 4096 pixel adaptive camera. The left column represents the original camera pictures. The histograms in the second column show the distribution of digitized pulse heights for all 4096 pixels ranging from 0 to 255. The third column demonstrates the effect of an edge detection algorithm. The four horizontal rows are a time sequence of a moving car stopping in the second row, standing motionless in the third row and accelerating in the fourth row.

5 PROSPECTS

The system of adaptive photoreceptors presented here shows a behaviour very similar to the biological model over a wide dynamic range of about 7 decades of incident illumination ($10^{-5} - 10^{2}$ W/m^2). It is planned to use the pronounced capability of motion detection together with conventional edge detection algorithms in an application as a tactile vision aid for the blind. First tests with blind people are being planned for this year.

6 ACKNOWLEDGEMENTS

The financial support from the Ministerium für Wissenschaft und Forschung Baden-Württemberg (Stuttgart, Germany) for this project is greatly acknowledged.

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